



Framework to evaluate the performance and sustainability of a disperse productive system

Edson H. Watanabe^{1,2} · Robson M. da Silva³ · Mauricio F. Blos⁴ · Fabricio Junqueira¹ · Diolino J. Santos Filho¹ · Paulo E. Miyagi¹

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Abstract

In general, the performance of productive systems considers the efficient use of technological transformation resources (such as machines and raw materials), information processing, and handling/transportation operations. However, there are no normalized criteria or rules to evaluate the performance of a productive system in the context of sustainability. Thus, this paper introduces an approach to identify and evaluate the performance indicators related to the sustainability of productive systems, specifically for geographically dispersed cases, i.e., dispersed productive system (DPS), in which the processes are in a distributed and dispersive architecture. The proposed approach is based on a framework aimed to measure sustainability key performance indicators (SuKPIs) that evaluate the sustainability of a system. The framework considers the ANSI/ISA-95 standard, and the sustainability assessment methodology considers the balance of sustainability indicators, which depend on economic, environmental, social, and technological aspects. The Petri net and derived techniques are used to model and to verify the main functionalities of the proposed framework, and also to monitor the productive processes of DPS for data acquisition of the SuKPIs. An application example is also presented to show the feasibility and validity of the proposal.

Keywords Framework · Disperse productive system · Sustainability evaluation · Petri net · Sustainable indicator

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✉ Edson H. Watanabe
edsonh.watanabe@usp.br; edsonh@ifsc.edu.br

Robson M. da Silva
robsonms@uneb.br

Mauricio F. Blos
mauricioblos@unisanta.br

Fabricio Junqueira
fabri@usp.br

Diolino J. Santos Filho
diolinos@usp.br

Paulo E. Miyagi
pemiya@usp.br

¹ Escola Politécnica da Universidade de São Paulo, São Paulo, SP, Brazil

² Instituto Federal de Santa Catarina, Joinville, SC, Brazil

³ University of the State of Bahia (UNEB), Salvador, BA, Brazil

⁴ Santa Cecília University-UNISANTA, Santos, SP, Brazil

1 Introduction

Productive systems can cover a class of systems characterized by a chain of companies, service providers, and other required resources. This includes corporations and subsidiaries are generally geographically distributed to take specific socioeconomic advantages from different regions. It is fundamental to ensure the performance of this class of dispersed productive systems (DPS) and their sustainability. In fact, since the mid-1980s, due to the increasing scarcity of raw materials, non-governmental organizations such as the Roman Club warned of the need to include sustainability requirements in the design of DPS [23, 32]. Thus, United Nations initiatives arose, such as the World Commission on Environment and Development [40], besides events, such as Rio 92, Kyoto 97, Doha 2012, Paris 2015 and, more recently, Marrakech 2016. In this context, there is a consensus that DPSs should consider not only the conventional parameters of productivity, but also aspects related to sustainability, such as (1) the reduction of negative environmental impacts of the processes involved; (2)

conservation and adequate use of natural resources; (3) practices to ensure the safety of employees, communities and consumers; and (4) practices of feasibility and profitability of the business that ensure an efficient and safe use of production resources. In addition, works, such as Amrina and Yusof [1], Cannata and Taisch [4], Chen et al. [5], Joung et al. [20], and Kondoh et al. [22], highlight sustainability as an essential factor for evaluating the performance of a DPS.

Furthermore, works such as Verrier et al. [38] indicate that:

- There are already proposals for key performance indicators (KPIs) [16, 17] of productive systems; however, they do not deal with specific parameters of sustainability;
- Each company seeks to create its own metrics of sustainability and KPIs for analysis and decision-making, which hinders benchmarking between companies;
- There is no systematic procedure to consider sustainability as a criterion for selecting and calculating KPIs;
- Although standards such as ANSI/ISA-95 (ANSI/ISA, 2005) establish a structure for managing and controlling processes in productive systems, there is no explicit mention of the monitoring of KPIs for sustainability.

In turn, attempts are observed, as in the proposal in Jayal et al. [18], of a new business model that considers sustainability as a guide to productive activities for (1) improvement in trade and employment relations, (2) involvement with the local community, (3) improvement in environmental policies, and (4) promotion of technological innovation. However, from the technological point of view, a DPS should also be developed considering the standardization of products and processes, the customization of products, and the reconfiguration capacity of products and processes [2, 14]. Thus, the existing industrial standards, such as ANSI/ISA-95, cannot be ignored, mainly because existing companies already organize their management and control systems in accordance with these standards.

Therefore, to evaluate the performance of DPS based on sustainability indexes, this work proposes a framework that:

- (i) adopts a set of concepts, methods and tools organized such that it allows including the process of sustainability performance evaluation of a DPS;
- (ii) considers the management and control structure of industrial systems established in the ANSI/ISA-95 standard by reviewing the management and control functions of the standard, including functions of information processing for sustainability indicators;

- (iii) adopts a formal technique for process modeling, analysis and monitoring;
- (iv) considers the availability of information processing and communication infrastructure to explore on-demand access to a shared set of diversified and distributed manufacturing resources that form temporary and reconfigurable production lines to increase efficiency, reduce product life cycle costs, and allow an optimal resource allocation.

The text is structured into sections. Section 2 presents a concepts review and other premises adopted. Section 3 presents the proposed framework to evaluate the performance and sustainability of a DPS. Section 4 describes an example application. Section 5 presents the conclusions and suggests further works.

2 Concepts review and premises

In this section, the basic concepts, existing standard interpretations, versions, adaptations, and practices adopted for the approach to evaluate the sustainability performance of the DPS based on sustainability indexes are presented. Sections 2.1, 2.2 and 2.3 present the concept of sustainability and its relationship with DPS. Section 2.4 deals with the revision of the ANSI/ISA-95 for processing the system sustainability data. Section 2.5 deals with the physical environments and technologies available to implement the proposal, and Sect. 2.6 explains the modeling techniques for process analysis and generation of control solution specifications.

2.1 Sustainability

WCED [40] defines sustainable development as a process that meets current needs without compromising the ability of future generations to meet their own needs. Therefore, sustainable development seeks to improve efficiency in various aspects, to reduce environmental impacts, maintaining social equity and the viability of the business. According to the OECD [31], sustainability is a systemic term, that is, it includes a set of factors or aspects responsible for maintaining a system performing and its processes in a sustainable way. In such a context, sustainability can be approached in different ways, and traditionally considers three aspects: (1) economic, (2) environmental, and (3) social, forming the triple bottom line (TBL) [11]. These aspects are understood to derive from the fact that the impacts resulting from the lack of sustainability in a classical system are more visible in these prisms.

On the other hand, regarding the point of view of the DPS with high level of processes automation and communication, this work considers the need to include the technological aspect. That is, the review of concepts and procedures that provide technological innovation (in automation, information, communication, etc.) is indispensable to the sustainability of systems and must support the TBL. Thus, this work considers indicators according to four aspects of sustainability: (1) environmental, (2) economic, (3) social, and (4) technological, forming the quadruple bottom line (or 4BL).

Let sustainability S_{ust} of a DPS depend on the balance of the 4BL such that it can be expressed by Eq. (1):

$$S_{ust} = f(I_{Eco}, I_{Env}, I_{Soc}, I_{Tec}), \quad (1)$$

where I_{Eco} is the indicator of economic aspect, I_{Env} the indicator of environmental aspect, I_{Soc} the indicator of social aspect, and I_{Tec} the indicator of technological aspect.

The indicators are calculated based on parameters defined by specialists, the infrastructure, and on the dynamic evolution of the processes in the DPS.

2.2 Sustainability of a productive system

Esmailian et al. [12] describe a productive system as the combination of processes in which raw materials are converted into finished products, which in turn are placed in the market. These processes undergo constant innovations in function of the evolution of technology, the creation of new tools and manufacturing methods. By expanding this vision, a sustainable production system can be understood as a product-oriented system, as well as the services that must guarantee positive results related to 4BL. When analyzing the sustainability of a system, all the stages of production and product life cycle must be taken into account, from the acquisition of raw material and production resources to the end of the production process and the recycling of the product in its obsolescence.

The main goal of a sustainable productive system is not only to maintain environmental balance, but also to maintain the quality of life for the current generations, without causing irreparable damage to the ecosystem for future generations. By intelligently monitoring economic, social, environmental, and technological aspects, a balance is achieved. The 4BL requires somehow maintaining economic profitability through the efficiency of production processes. In this sense, Zhang et al. [44] and Jayal et al. [18] present guidelines for sustainable systems design called 6R—reduce, reuse, recycle, recover, redesign, and remanufacture.

However, in many countries, such as Brazil, there is still no regulation on reverse logistics associated with redesigning or remanufacturing. Even in more developed

countries, this regulation is still under discussion. Therefore, this work focuses on a 4R guideline (reduce, reuse, recycle, recover) for analyzing the sustainability of DPS.

2.3 Indicators of sustainability

Veleva et al. [37] state that sustainability indicators have three main objectives: (1) raising awareness and understanding the problem; (2) informing those responsible for decision-making; and (3) measuring progress toward the goals established. O'Brien [29] argues that indicators are qualitative or quantitative values used to evaluate the sustainability aspects of a system, and according to Amrina and Yusof [1], there are different approaches to be considered beyond the task of measuring a set of indicators, one of which is choosing a set of actions to ensure the correct measurement and to define which indicators should be evaluated.

Some researchers, such as Joung et al. [20], understand that measurement aims at identifying a specific problem to apply improvements related to sustainability in the activities of the productive system.

These aforementioned works indicate that the analysis and interpretation of the data obtained are obviously fundamental, but this is unfortunately not trivial. There is a difficulty deriving from the complexity related to the number of indicators to be considered and the nature of their quantification [30, 31].

Therefore, in this work, the reorganization and reclassification of the existing indicators are carried out based on the literature in this area [20, 35], taking into account the 4BL of sustainability, to facilitate data processing and the sustainability analysis of a DPS. Thus, Tables 1, 2, 3, and 4 are used as a guide to define the indicators to be considered in practice based on the specificities of each case.

2.4 Standard ANSI/ISA-95

Among the various existing standards for the structural organization of productive systems, ANSI/ISA-95 (2005) is one of the most widely known and commonly adopted. This standard establishes different hierarchical process management and control levels. At levels 1 and 2, there are the physical plant and the control devices of the productive processes, respectively. At supervision level 3, there is the manufacturing execution system (MES), which processes the information of the productive processes aiming at its operation sequence in the available resources (machinery and staff). Finally, at level 4, called business level, strategic decision-making is performed (see Fig. 1). Additionally, Fig. 1 shows the standardization organizations that define standard interfaces for communication among levels: International Society of Automation (ISA), International

Table 1 Sustainability indicators: environmental aspect

Sub-category	Indicator	Quantification method
Emission and Pollution	Greenhouse gas emissions	Mass of CO ₂ equivalents emitted
	Wastewater discharged	Volume of wastewater discharged
Resource Consumption	Waste material discarded	Mass of discharged material
	Reused/recycled materials used in products	Mass of reused/recycled materials used
	Packaging materials discarded	Unit of product mass of packaging materials discarded
	Packaging materials reused	Unit of product mass of packaging materials reused
	Total energy consumption	Total energy consumed directly attributable to the manufacturing process
	Water intensity	Energy consumed/unit of product
	Water reused	Volume of water consumed/unit of product
	Air quality	State qualification

Table 2 Sustainability indicators: economic aspect

Sub-category	Indicator	Quantification method
Financial performance	CO ₂ reduction benefit	Financial gain in quantity of CO ₂ reduction
	Reused material savings	Financial gain in quantity of reused material
	Disposal waste savings	Financial gain in quantity of disposed material
	Recycled material savings	Financial gain in quantity of recycled material
	Renewable energy benefit	Financial gain in quantity of traditional energy savings in relation to renewable energy
Manufacturing costs	Traditional energy reduction	Financial gain in quantity of traditional energy savings
	Material costs	Costs of material used in production process
	Energy costs	Costs of energy used in production process
	Labor costs	Costs of labor used during manufacturing process
	Operational and capital costs	Costs of operation and capital used during manufacturing process

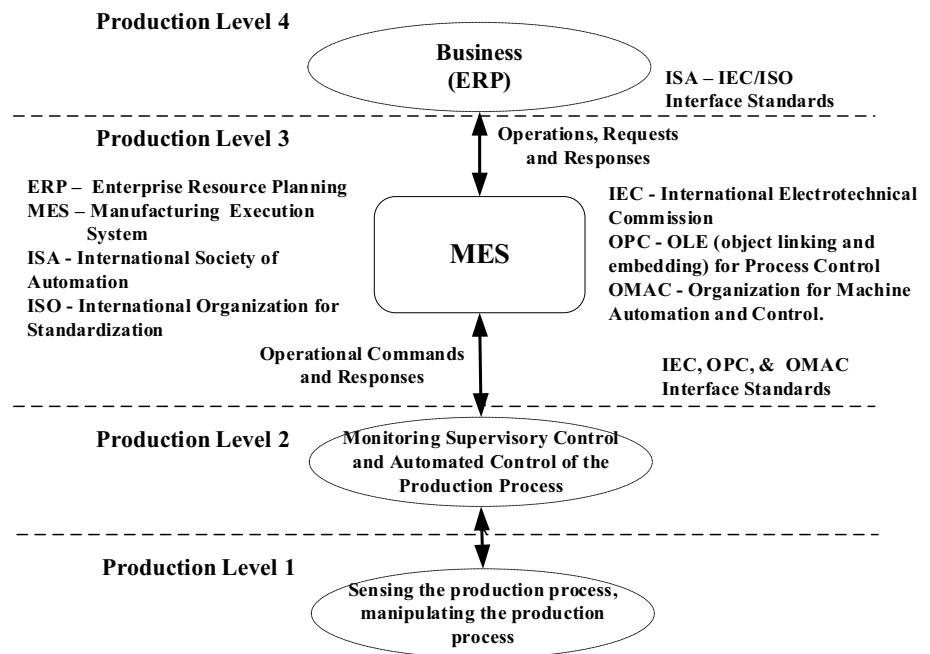
Table 3 Sustainability indicators: social (well-being) aspect

Sub-category	Indicator	Quantification method
Employee	Workdays missed	Number of missed workdays due to accidents
	Job satisfaction	Job satisfaction survey in work time
	Labor accidents rate	Number of occurrences on workdays
	Labor productivity rate	(Total revenue/total labor costs)
	Labor training in sustainability	(Employees trained in sustainability/total number of employees) × 100%
Customer	Employee environmental suggestions	Total number of employees suggestions regarding sustainability improvements
	Customer complaints	Total number of customer complaints related to sustainability performance
Community	Community sustainability suggestions	Total number of community suggestions regarding sustainability improvements
	Sustainability reports published	Total number of published assessments and reports and % of completion of these sustainability assessments
	Sustainability awards	Number of awards or references

Table 4 Sustainability indicators: technological aspect

Sub-category	Indicator	Quantification method
Security	Sustainable TI policy application	Total number of actions and complaints related to sustainability performance
	Protective equipment and personal safety	Total number of protective equipment for personal safety
	Software and hardware version updating	Number of products updated/number of products installed
Performance	Innovation R&D investments	Total number of R&D investments for sustainability efforts
	Service providers with environmental certification	(Number of providers with environment certification/total number of providers) × 100%
	Maintenance policy application	Amount of equipment inspected/Amount of equipment installed
Production line	Avoid line stops due to safety concerns	Monitor security around manufacturing machineries
	Open systems initiative	Total number of open system products installed
	Renewable energy systems	Total number of renewable energy systems installed
	Fail prognosis monitoring	Monitor equipment work cycle/wear during manufacturing process

Fig. 1 Management and control levels of productive systems according to ANSI/ISA-95 (adapted from ANSI/ISA, 2005)



Organization for Standardization (ISO), International Electrotechnical Commission (IEC), OPC Foundation (OPC), and Organization for Machine Automation and Control (OMAC).

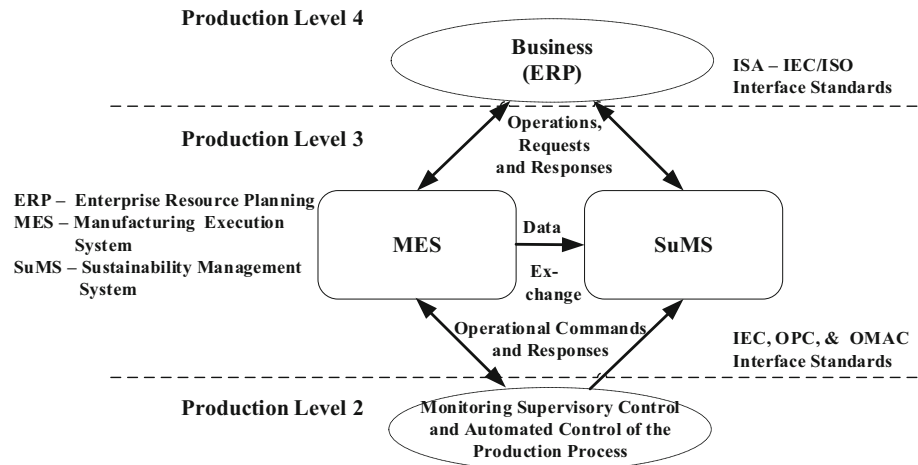
This work revises level 3 functionalities and reinterprets them to include a module for specifically addressing sustainability. This module is called sustainability management system (SuMS) and processes the calculations and evaluations of sustainability indicators. Information about the productive processes is assumed to be directly handled by the MES, but it can also be used by SuMS. However, there is information related to sustainability not considered by the control devices in the plant or in the functionalities for task execution/supervision. That is, in practice, there is

information necessary for SuKPIs (KPIs for sustainability) calculus not available in the MES. It is thus necessary to consider an interface in SuMS so that the information (about the environment, for example) is received directly from level 2 via a data acquisition system.

Based on the information of the process and of the environment, the current state of the productive system and its dynamics, the SuMS calculates the indicators of sustainability. SuMS informs these indicators of sustainability to level 4, whereby the strategic decisions are made. In addition, SuMS is ready to receive commands according to the decision-making procedures at level 4.

Figure 2 shows the proposed SuMS module in the context of the management and control structure of

Fig. 2 SuMS module proposed in the context of ANSI/ISA-95



productive systems of ANSI/ISA-95 (2005). SuMS works independently of the MES, but it can, and it should, exchange information mutually to ensure the sustainable operation of the DPS.

The SuMS is composed of sub-modules that execute the following functions:

- *Data acquisition* receives and stores the data required for calculating the indicators of sustainability. The environmental data, for example, are received from a dedicated data acquisition system at level 2, while other actual state data of the productive processes are received from the MES;
- *Data evaluation* processes the sustainability data and conforms the stored data to place them in appropriate formats and standards for calculating SuKPIs. It evaluates indicators based on comparison with desired values and/or set limits;
- *Communication with the level of strategic decision-making* makes a preliminary assessment of possible discrepancies with the values expected, indicating possible causes and/or possible improvements to be considered; these are communicated to the higher level.

2.5 Cyber-physical system and information technology

According to Colombo et al. [7], the term CPS (cyber-physical system) was coined around 2006 to “refer to the integration of computation with physical processes”. CPS can be described as smart systems that encompass hardware, software, and physical components, seamlessly integrated and closely interacting to sense and to control in real time the processes that include interaction with humans through various forms of devices/interfaces.

Then, NIST [28], Sundmaeker et al. [34], and Colombo et al. [6] declared the CPS as the basis of emerging and future

intelligent services, providing the infrastructure for interacting processes that may be geographically dispersed. In this environment, managers, operators, suppliers, customers, and stakeholders of a DPS operation could be able to independently (of their physical location) access their data, for example, to monitor processes, analyze data, and/or evaluate new scenarios of production systems. That is, information could be accessed from anywhere via Internet [13].

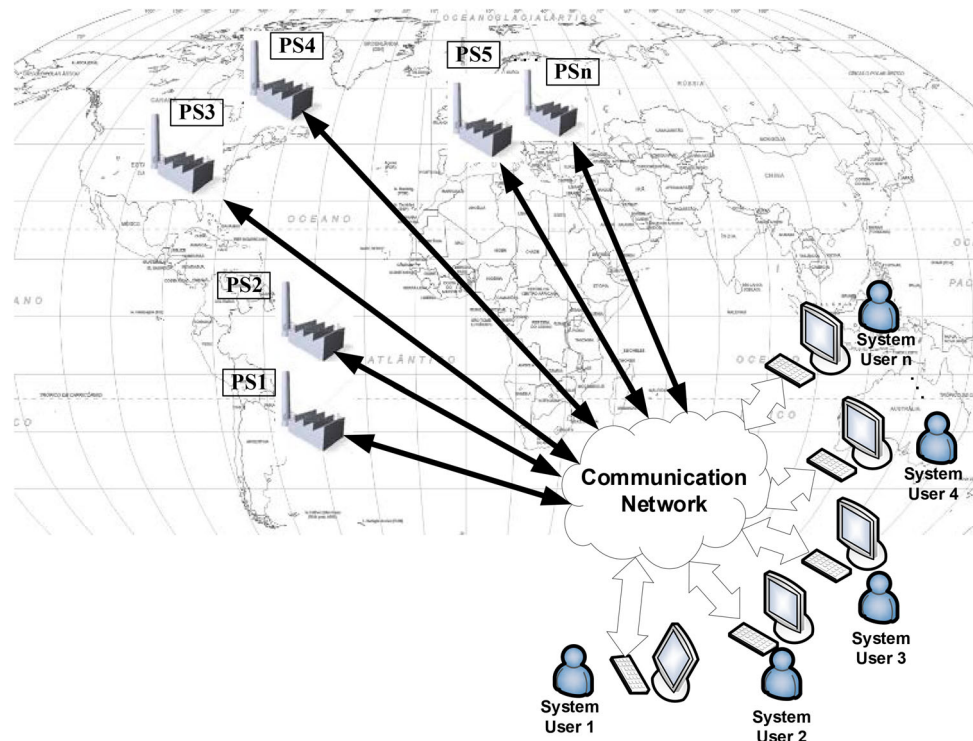
Despite some technological challenges still not completely overcome, CPS and a communication infrastructure of the network of entities that consider an enterprise level (private inter-enterprise cloud) and the public environment (public cloud) as presented in Wollschlaeger et al. [41] is also part fundamental of DPS operation and its sustainability management.

Figure 3 illustrates the way users (managers, operators, suppliers, customers, stakeholders) of a DPS see the system and interact with it independently of the physical location of the places where the plants (productive systems) are operating and, therefore, all SuMS interfaces (with level 2 and level 4 devices as well as MES) should consider this infrastructure.

2.6 Process modeling techniques

Real productive processes have several intrinsic indeterminations that do not allow an analytical evaluation, that is, it is not possible to predetermine when certain events happen, e.g., the instant of the occurrence of failure, or the (correct or erroneous) activation of an operation by a human being. However, it is possible to characterize the system based on the states between the occurrences of events. Thus, based on previous works, it is assumed that the DPS can be seen as a discrete event system; therefore, the Petri net is an adequate technique to model it [26, 33]. In fact, the Petri net has been widely used and several extensions of this formal technique have been proposed

Fig. 3 Communication network in the context of CPS where dispersed ‘system users’ can monitor the sustainability of each productive system (PS1, ... PSn), and of overall DPS system



according to specific applications. For example, da Silva et al. [8] use the production flow schema (PFS) technique together with the place/transition Petri net to: systematize the modeling procedure, perform the analysis, and control specification of reconfigurable productive systems. Mello et al. [25] address the orientation to services in DPS also using the PFS and Petri net. These studies have demonstrated that this combination allows an effective and relatively simple and transparent way of developing models of processes in Petri net. In this combined approach, the models in PFS are gradually refined, and the dynamics is represented only at the Petri net models, such as the place/transition type, which is derived from a PFS model.

PFS identifies “activities” carried out in a flow of items (information, materials, etc.) and also among its “activities”, at a relatively high level of abstraction. The PFS model can represent a flow considered primary (such as sequences of “activities” that process a workpiece) and secondary flows (such as those related to the tools or operators) according to the interpretation adopted. PFS representation has no explicit concern about the dynamic evolution of the system.

According to Miyagi [26], systematic system modeling with PFS must follow the following steps: (1) identifying the main “activities” of items transformation (materials and/or information); (2) detailing the flow of items between “activities”; (3) detailing the “activities” and identifying the “inter-activities”; (4) introducing control elements of resources, and (5) detailing the signals exchanged between the control system and the plant. Therefore, the PFS model is

gradually refined to Petri net models by detailing the states, events, and dynamic behavior of the processes. Figures 4 and 5 illustrate this modeling procedure.

The Petri net has a formalism that allows analyzing the structural and functional properties of the models [25, 27].

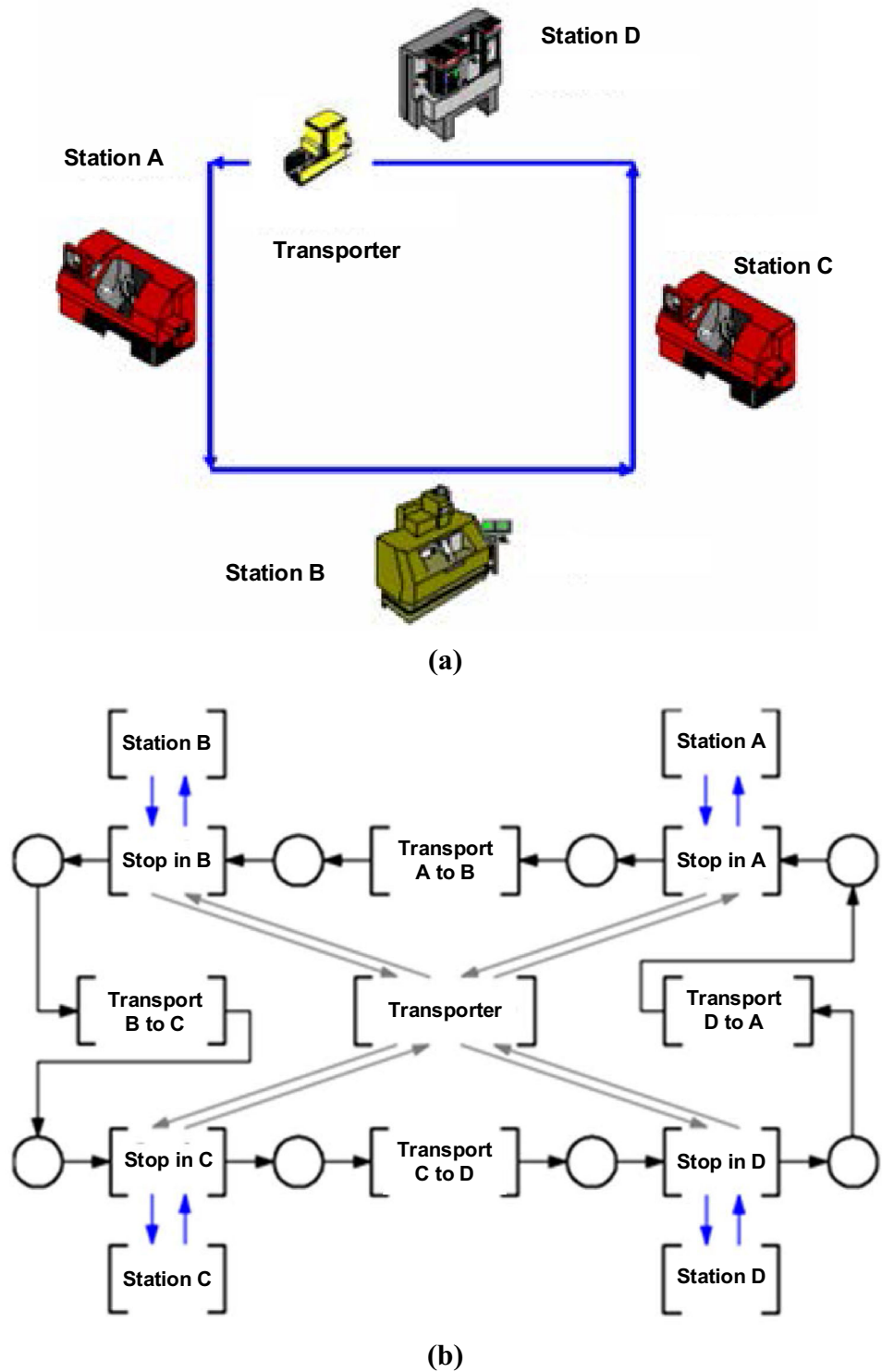
Figure 6 illustrates an example of a Petri net model, in which acquiring data and calculating for sustainability indicators is made explicit. That is, the graph indicates which devices (sensors) must be activated to collect data and where and when these measurements should be taken, using “enabling arcs” and “inhibitor arcs” (structural elements of Petri net models). SuMS uses this information for calculating the indicators.

The SuMS has the description of all DPS processes in its database, that is, SuMS has the PFS and Petri net models of the processes to monitor all the information concerning the sustainability of the system in any situation. Thus, the SuMS can carry out online investigation about discrepancy levels of the sustainability indicators and assess its effects conditions for forwarding the necessary information to the strategic decision-making level of the DPS.

3 Framework to support the sustainability performance evaluation

As defined in Cambridge dictionary online [3], a framework is a support structure around which a “thing” can be built. Adapting it to the present work, a framework can be

Fig. 4 Example of a productive process modeling in PFS: **a** transporter circular movement, going through the stations; **b** PFS model of the transport system Adapted from Junqueira and Miyagi [21]

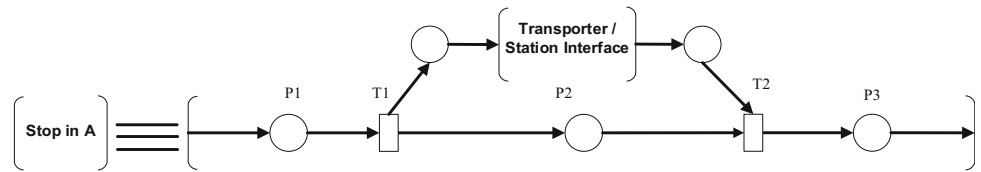


considered the implementation of a DPS performance evaluation system, in which this structure involves several physical and logical subsystems. In other words, a framework involves hardware and software with specific functionalities, as well as procedures for data initialization,

development representation, manipulation, and processing of information.

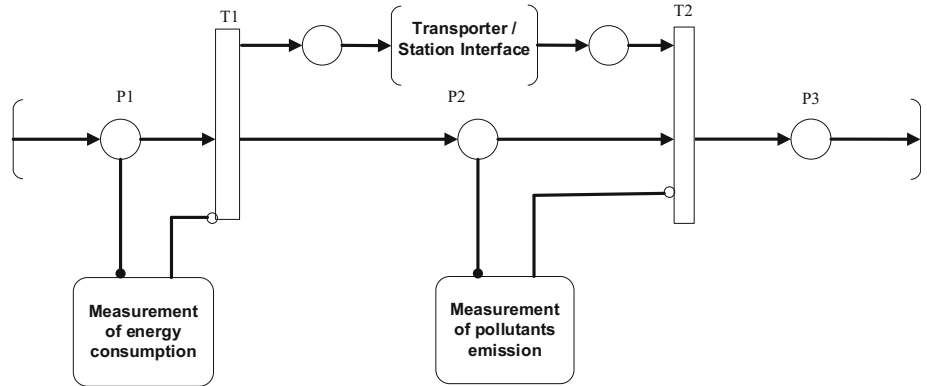
Introducing the concept of sustainability into the DPS does not alter its nature. However, considering this concept from the design phase of the system is not trivial, and a systematic procedure involving different techniques and

Fig. 5 Example of detailing, in Petri net model, one of the activities of the PFS in Fig. 4. Adapted from Junqueira and Miyagi [21]



P1 is a state that indicates when a transporter has entered station A
 P2 is a state indicating when the transporter is stopped at station A
 P3 is a state that indicates when a transporter is exiting station A
 T1 is an event that indicates the beginning of the loading/unloading activity of a transporter in station A
 T2 is an event that indicates the ending of the loading/unloading activity of a transporter in station A

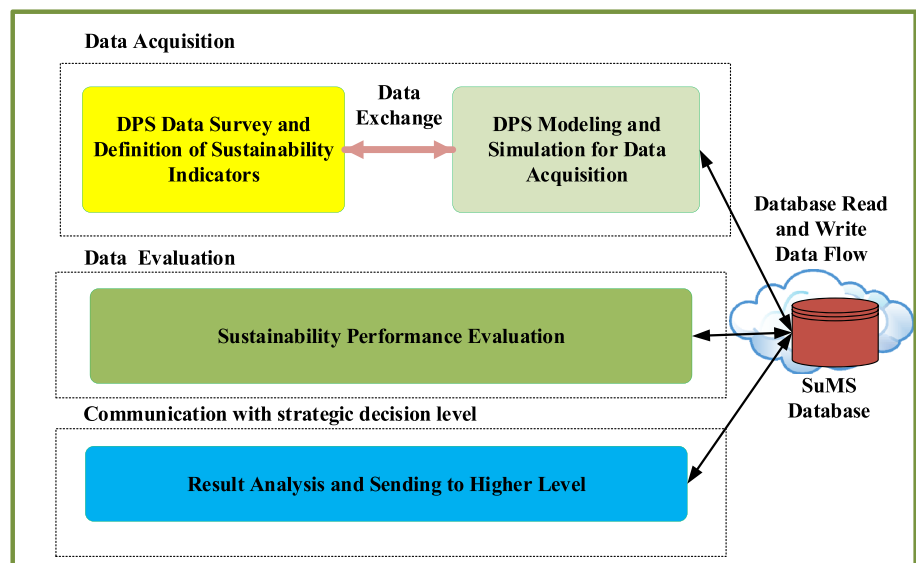
Fig. 6 Example of a Petri net model with indication of data acquiring for calculating sustainability indicators



their tools must be adopted to ensure the correct application of the requirements involved [9]. Figure 7 illustrates the main functionalities that should be considered to evaluate the sustainability performance of a DPS. In this figure, the arrows indicate the relationship between the functionalities, which derive from existing concepts, methods, and tools available and accessible to researchers, or which have been properly adapted to develop and evaluate sustainability in productive processes.

Figure 7 shows the functionalities to be implemented by hardware and software according to the revised management and control structure of ANSI/ISA-95 shown in Fig. 2. The functionalities correspond to the SuMS sub-modules. The SuMS database is the repository of process data (Petri net models used to monitor productive processes) and DPS sustainability information. The production process information specifically related to the productivity of the system is in a database managed by the MES. However, there are data solely related to sustainability,

Fig. 7 Schema with the functionalities to be considered for analyzing the sustainability performance of a DPS



which can be treated independently thus requiring an SuMS database.

To verify the proposed framework and its main functionalities, the PFS/Petri net technique was also used. Figure 8 shows an illustrative schematic of the main components (modules) of SuMS and the PFS models of the procedures to produce the functionalities. These models specify how to implement the SuMS module and the sub-modules: communication, data evaluation, data collection, and database. The exchange of data internally between the sub-modules is represented by “enabling arcs” and “inhibitory arcs” of the Petri net technique [25, 27]. The external arrows between modules indicate communication for data exchange.

The Petri net models of the SuMS functionalities was edited and analyzed considering Petri net properties, and simulations were carried out to confirm the dynamic behaviors of the proposed framework. In this verification, the IOPT tool was used [9].

The functionalities of the SuMS are detailed as follows.

3.1 Data acquisition

This functionality is associated with the productive system information survey (functional and operational characteristics) to define and calculate sustainability indicators, and store this information in the SuMS database. The four main activities are described as follows.

3.1.1 Productive system data survey

In the data initialization phase of the SuMS, the DPS information survey is carried out comprising the structure of the processes involved; the interactions between the processes; the resources involved; the interdependence relationships; and the restrictions involved.

The data survey is carried out based on the design and operation documents of the DPS, and complemented with information collected from questionnaires. Tables 1, 2, 3, and 4 of the previous section list the family of indicators forming the basis for choosing the specific indicators for the DPS, which may be used as a whole or parts thereof. Tables 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14 list preformatted questions for the survey. The information collected receives scores to define the DPS indicators to be monitored and is stored in the SuMS database.

Tables 5, 6, 7, 8, and 9 refer to technical issues of productive system infrastructure and sustainability aspects.

Tables 10, 11, 12, 13, and 14 are used to characterize the intensity of the company/employees involvement with the DPS sustainability. This questionnaire surveys the level of commitment of the people involved with the use of resources and how processes are conducted.

The data collected must be stored in the SuMS database and properly processed for defining the DPS sustainability indicators. At this moment, values are assigned to each indicator according to the information surveyed from the

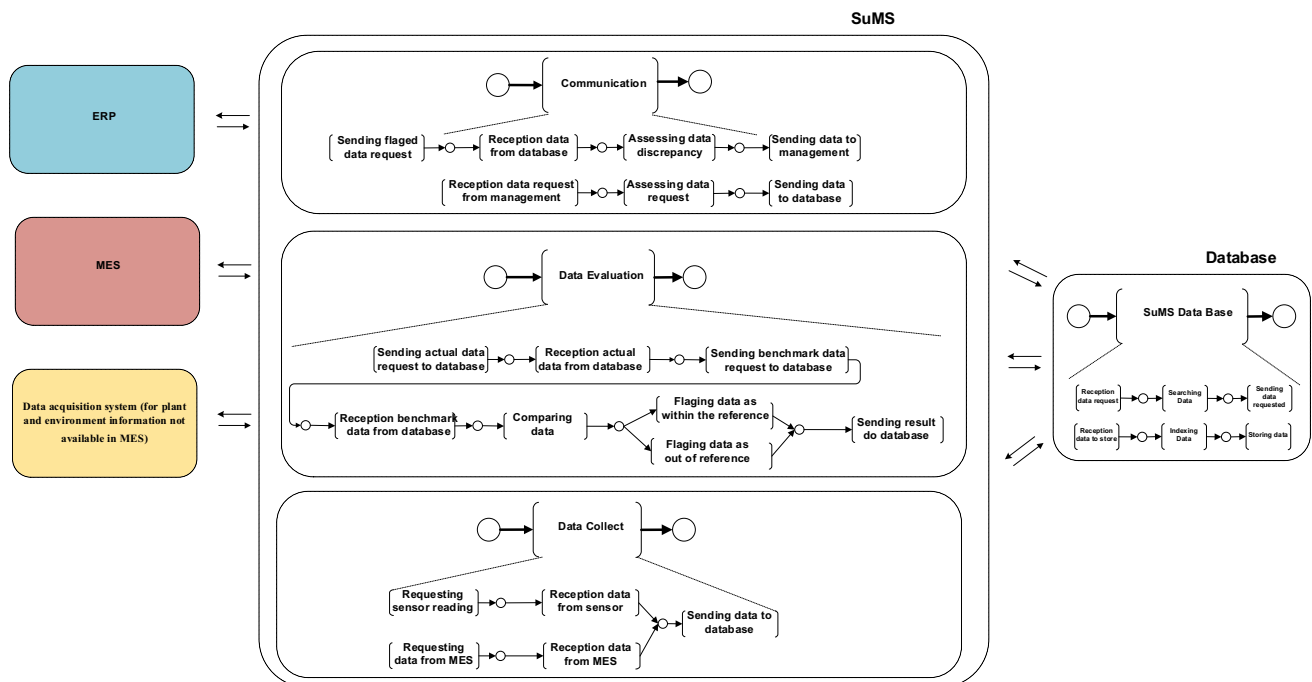


Fig. 8 PFS model of the functionalities of SuMS

Table 5 Questionnaire for data survey on productive system infrastructure

Item	Questionnaire on the production and infrastructure of the productive system		Results	
	Information	Description	Yes	No
1	How could the production be classified?	Traditional Flexible Lean Ecologic Sustainable		
2	How is the production classified?	Fewer than 50 employees Up to 50 employees Between 50 and 100 employees Between 100 and 1000 employees More than 1000 employees		
3	What type of production configuration is adopted?	Undefined Processes Cell Autonomy Positional		
4	What type of production transport is used?	None Fork lift Conveyor belt AGV Manipulator robotic		
5	What type of integrated management system is adopted?	None Local supervisory system (level 1) Control and supervisory system (level 2) Central management system (level 4) External data center (Cloud, WebServer)		

DPS by an environmental specialist. Thus, these values are the reference for calculating sustainability.

When the DPS sustainability indicators are defined, these surveys should be periodically reviewed to follow the evolution of the system, taking into account a sustainability assessment policy implemented and the pace of changes in the production system.

3.1.2 Definition of sustainability indicators

The information in Sect. 3.1.1 is used to determine the most adequate sustainability indicators. To support this process of choosing indicators, Tables 1, 2, 3, and 4 were elaborated with the most common indicators used in productive systems, taking into account the 4BL (economic, environmental, social, and technological), and complete lists or parts of them may be used. The criteria used should be the relevance of the indicators chosen, based on the sustainability information surveyed from the company's processes and infrastructure.

3.1.3 Modeling

In the SuMS data initialization phase, the modeling activity is responsible for describing all the processes involved in the DPS. Initially, this is carried out by surveying the specifications of the productive processes, identifying the "activities" and "inter-activities" involved, thus creating a graphical and conceptual representation of the processes based on the PFS technique.

The processes are initially modeled in PFS and are refined until a functional model in Petri net is obtained. The resulting model describes the functional characteristics, such as parallelism, competition, asynchronism, and non-determinism, besides when and where the signals (specifically related to SuMS) are considered in the evolution of the processes.

Table 6 Questionnaire for data survey on economic aspects

Item	Questionnaire on the production and infrastructure of the productive system: economic aspects		Results	
	Information	Description	Yes	No
1	What economic benefits are achieved by the production after the inclusion of sustainability?	Benefit from the ‘Carbon Footprint’ program Benefit from reuse of resources Benefit from waste disposal Benefit from recycling materials Benefit from renewable energy Benefit from traditional energy reduction		
2	Which manufacturing costs are monitored so as not to exceed the budget planned?	Cost of materials Cost of energy Cost of labor Operational and capital cost Cost with material disposal		
3	Which areas of the company have received investments?	Technological innovation for reducing energy consumption Generation of renewable energies Benefits to employees Development of reuse of materials Monitoring of the environment Material disposal process Customer monitoring Project with the community Communication with customers and the community		

3.1.4 Processes monitoring

The derived Petri net models are also used to monitor the systems and processes involved. Therefore, these models must be validated. Structural and behavior aspects are analyzed based on the Petri net theory.

In the data initialization phase of the SuMS, the modeling and analysis of the DPS processes aim to develop models that represent the real system with an appropriate degree of precision regarding the parameters related to its sustainability.

In the DPS operation phase, the models are used to follow the evolution of the processes in real time, that is, for monitoring sustainability indicators. The MES has the data related to the DPS productivity and the current state of the processes that are treated together with the information necessary for calculating the sustainability indicators of the system and which are accessible via SuMS database (as described previously, this information is updated by the SuMS module named “data acquisition”).

Note that support systems such as PIPE, HPSim, and IOPT Tools [9] are already available, which integrate tools for graphically editing Petri net models and for their

analysis, including the resources to perform model simulations. These support systems can be used to collect and to process DPS data so that process models (in Petri net) displayed on a screen indicate the evolution of the system and sustainability indicators online.

3.2 Data evaluation: processing sustainability data

As aforementioned, in the SuMS data initialization phase, different scenarios are analyzed and situations are simulated to define the SuKPIs. Once this is done, these data are stored in the SuMS database.

In Eq. (1), the sustainability of the DPS is a function of the indicators in the 4BL. However, this involves several parameters so that the relative importance of each one must be properly considered.

The data for calculating sustainability indicators under different aspects, i.e., I_{Eco} , I_{Env} , I_{Soc} , I_{Tec} , are measured directly with the system in operation. The results are also compared to the reference values and stored in the SuMS database.

Table 7 Questionnaire for data survey on environmental aspects

Item	Questionnaire on the production and infrastructure of the productive system: environmental aspects		Results	
	Information	Description	Yes	No
1	Which stages of collection of obsolete product are in operation?	Defined collection points Material transport system Collection logistics		
2	What stages of the disposal system are in operation?	Disassembling system Separation system Material transport system Locations of waste materials defined		
3	What sustainability solutions have been implemented?	Reconfiguration ISO 9000 implemented ISO 14,000 implemented Duplication of the production unit Multifunction machines Reverse logistic		
4	How can production be classified according to the following sustainability methodologies (rethinking, refusing, reducing, reusing, recovering, recycling)?	2Rs 3Rs 4Rs 6Rs		
5	What is monitored?	Water consumption Energy consumption Waste of material Air quality Pollutant emission Thermal confort control Emissions of toxic gases		
6	Which renewable energy sources are in use?	Solar energy Wind energy Biomass energy		

Based on works already published (for example: Davidsson et al. [10], Tracey et al. [36]), an indicator evaluation criterion is adopted, in which the current value must reach at least 70% of the reference value (previously defined by experts as mentioned in Sect. 3.1) with a tolerance of 10% for the sustainability analysis. In related studies, this value of 70% has been observed to be usually adopted as a desirable level of achievement in many areas. This type of criterion helps to quickly identify the condition of the indicator evaluated and allows the adoption of a binary classification of the result. There are methods of evaluation that consider arithmetic means of indicators, but the result does not specify the contributions of each

indicator. Thus, in the criterion adopted here, the participation of each indicator is clearly identified.

The result of this comparison is expressed by an integer in the interval [0, 1], according to the following relations:

- 0 = outside the area of expected value;
- 1 = inside the area of expected value.

The sustainability weights ($w_{Eco(k)}$, $w_{Env(k)}$, $w_{Soc(k)}$, $w_{Tec(k)}$) are defined considering their relevance in the system, as follows:

- 1 = irrelevant;
- 2 = not very relevant;
- 3 = relevant;
- 4 = highly relevant;

Table 8 Questionnaire for data survey on social aspects

Item	Questionnaire on the production and infrastructure of the productive system: social aspects		Results	
	Information	Description	Yes	No
1	What customer relationship policies are in operation?	Complaints and criticism management Customer relationship program Participation of customers with suggestions for improvements		
2	What is monitored in the workstation?	Measure of labor behaviors Measure of satisfaction Ergonomics Training in sustainability Training in security Monitoring accidents Box for suggestions and criticism		
3	What is monitored in the workstations?	Annual sustainability report (e.g., GRI—Global reporting initiative) Community integration program Partnership with local schools to encourage training Community development project		

Table 9 Questionnaire for data survey on technological aspects

Questionnaire on the production and infrastructure of the productive system: technological aspects			Results	
Item	Information	Description	Yes	No
1	What technologies are being used?	Research and implementation of renewable sources Product location by tracking Data center storage in the cloud Implementation of cyber-physical system technology Monitoring employee welfare Monitoring internal and external security Continuous monitoring of client and community needs		
2	What method is adopted for failure prognosis?	Predictive maintenance policy Preventive maintenance policy Material analysis technique Machine performance monitoring Machinery operation cycle monitoring Meeting the MTBF index (mean time between failures) Meeting the MTTR index (mean time to recovery)		
3	What is used to improve control systems?	Smart sensors Smart actuators Industrial controllers with energy consumption management Machinery with safety management		

5 = strongly relevant.

In Table 15, which is derived from Table 2, there is an example of calculating economic sustainability indicators.

The indexes achieved are calculated according to Eq. (2):

Table 10 Questions about involvement in economic aspects

Questionnaire about economic aspects of sustainability	Response	
	Yes	No
Items		
1. Does the production generate the necessary financial return to sustain itself?		
2. Is it necessary to reinvest in the company to ensure its growth?		
3. Is there investment in research and development of new products and technologies?		
4. Are costs being reduced by improving the productive processes?		
5. Do sustainability issues affect the business positively (1) or negatively (0)?		
6. Does the company have any future sustainable plans (strategic plans) for growth over the next 5-20 years?		
7. Is SWOT (strengths, weaknesses, opportunities and threats) (or similar) analysis a general practice for evaluating every part of the organization?		
8. Have sales increased after sustainability practices were implemented?		

Table 11 Questions about involvement in social aspect

Questionnaire on social aspects of industrial sustainability	Response	
	Yes	No
Items		
1. Are benefits offered to employees besides those provided by law?		
2. Are employees treated equally without biases regarding race, age, sex, or religion?		
3. Is the organization open to new ideas from employees?		
4. Is there a paid program of suggestions for improving production processes?		
5. Does the company have regular plans to increase the efficiency of the work process?		
6. Is the training of personnel well planned for all employees?		
7. Is the working environment equipped with safety and security mechanisms for employees?		
8. Are client claims treated with proper responsibility?		
9. Is there any channel for communicating with clients for suggestions on improvements?		
10. Does the company promote improvements in the community in which it operates?		
11. Does the offered product/service provide any guarantee of not being harmful to society or to the environment?		
12. Is there a program for the community to visit the company premises?		
13. Is there a current or future investment plan in the local community to improve/remanufacture some technologies?		
14. Are there partnerships with local universities for developing academic research?		
15. Is the community informed of a periodic report about the results regarding sustainability?		

$$\text{if } \left\{ \frac{av_k}{bv_k} \right\} \times 100 \geq \text{limit, then } i_{\text{achieved}} = 1; \quad (2)$$

$$\text{else } i_{\text{achieved}} = 0,$$

where $i_{\text{achieved}(k)}$ is the index achieved, av the actual value, bv the benchmark value, k the indicators sequence, and limit the 70% of reference value with a 10% acceptable variation.

For example, the index achieved referring to the “renewable energy benefit” indicator for the sustainability of the system is calculated as:

$$\left\{ \frac{33}{100} \right\} \times 100 \text{ is } < 100 \text{ then,}$$

$$i_{\text{achieved(Renewable Energy Benefit)}} = 0.$$

The weight of each sustainability aspect is calculated according to Eq. (3):

$$w_k = \left\{ \frac{L_{\text{imp}(k)}}{\sum_{i=1}^4 L_{\text{imp}(i)}} \right\} \times 100, \quad (3)$$

where $L_{\text{imp}(k)}$, level of importance of indicator in the sustainability aspect (1–5); k , sustainability aspect; i , amount of indicator considered.

For the example related to Table 15, the weight by importance of the “renewable energy benefit” indicator for system sustainability is calculated as:

$$w_{\text{amb(Renewable Energy Benefit)}} = \left\{ \frac{4}{36} \right\} \times 100 = 11\%.$$

Table 12 Questions about involvement in environmental aspects

Questionnaire on environmental aspects of industrial sustainability	Response	
	Yes	No
Items		
1. Does the company solve the problems concerning environmental pollution?		
2. Is there a strategy to reduce energy consumption?		
3. Has a new production process that consumes less energy been implemented?		
4. Have renewable sources of energy, and less polluting, such as solar, wind or other been used?		
5. Has the use of non-renewable resources in the company been optimized?		
6. Has the use of non-renewable resources been replaced with renewable resources?		
7. Are office materials and waste generated in the production sent for recycling, or reused in-house?		
8. Is recycled material used in the product packaging?		
9. Is there a concern about developing packages using less plastic/cardboard/etc.?		
10. Does the company find it feasible to reuse material from obsolete company products that are in the market (reverse logistics)?		
11. Does the company plan to implement a collection system, collection points for obsolete customer products?		
12. Does the company have waste management controls (i.e., emission control, CO ₂ reduction plan, firing regulations)?		
13. Has the company implemented an unused by-product disposal policy?		

Table 13 Questions about involvement in technological aspects

Questionnaire on the technological aspect of industrial sustainability	Response	
	Yes	No
Items		
1. Does the company invest in new technologies?		
2. Does the company train people to become familiar with the latest technologies?		
3. Does the company have its own technological know-how?		
4. Does the company plan to improve safety in operations?		
5. Are there any production security monitoring records in the company?		
6. Does the company follow the preventive maintenance system for plant equipment?		

Table 14 Questions about commitment to sustainability

Questionnaire on commitment to industrial sustainability	Response	
	Yes	No
Items		
1. How many employees in the company are committed to the economic aspects of industrial sustainability?		
2. How many employees in the company are committed to the social aspects of industrial sustainability?		
3. How many employees in the company are committed to the environmental aspects of industrial sustainability?		
4. How many employees in the company are committed to the technological aspects of sustainability?		
5. How many employees in the company are committed to economic, environmental, social and technological aspects of industrial sustainability?		

By applying a weighted sum of the values in Table 15, we have:

$$I_{Eco} = \frac{\{(0 \times 0.08) + (1 \times 0.08) + (1 \times 0.08) + (0 \times 0.08) + (0 \times 0.11) + (1 \times 0.14) + (1 \times 0.11) + ((1 \times 0.11) + (1 \times 0.11) + (1 \times 0.08))\}}{(0.08 + 0.08 + 0.08 + 0.08 + 0.11 + 0.14 + 0.11 + 0.11 + 0.11 + 0.08)},$$

$$I_{Eco} = 0.72.$$

Table 15 Example of indicators of economic sustainability

Item	Economic indicators	Actual value (unit)	Benchmark value (unit)	Indexes achieved	Weight by importance	Level of importance
1	CO ₂ reduction benefit	58	100	0	0.08	3
2	Reused material savings	70	100	1	0.08	3
3	Disposal waste savings	83	100	1	0.08	3
4	Recycled material savings	45	100	0	0.08	3
5	Renewable energy benefit	33	100	0	0.11	4
6	Traditional energy reduction	156	100	1	0.14	5
7	Material costs	75	100	1	0.11	4
8	Energy costs	80	100	1	0.11	4
9	Labor costs	72	100	1	0.11	4
10	Operational and capital costs	81	100	1	0.08	3

The result of the economic indicator I_{Eco} shows that 72% of its components (sub-indicators/parameters) are sustainable, i.e., have reached the established limit. Thus, there are sub-indicators/parameters that need to be improved.

The proposed framework supports different existing approaches and procedures to evaluate the sustainability of a DPS.

3.2.1 Sustainability considering “infrastructure questionnaire”

Information on the DPS infrastructure is processed based on the data from Tables 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14. Each item (question) is analyzed; a score and a weight are defined according to the level of direct influence of each indicator on the productive process.

For example, Table 16 illustrates the data collected for the questions in Table 5.

After completing the Tables (from Tables 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14), the quantitative result of each table is processed by a specialist. Then, based on the data collected, the calculation of indicators is conducted, and a spreadsheet, as shown in Fig. 9, can be used.

For example, Table 16 represents data on the infrastructure of the productive system (Table 5), which are the parameters to calculate the I_{Ips} (sustainability indicator related to infrastructure of the productive system). Each item receives an evaluation and an average of all the items in the table is calculated. The result is shown in Fig. 9. In this figure, the indicators are classified by their influence on

the system, and thus the weight by importance is calculated (Eq. 3). Therefore, by proceeding with the information from other tables, the results are transcribed in Fig. 9, where PS is the indicator of infrastructure derived from data from Table 5. A_{eco} is the indicator of the economic aspects of the infrastructure derived from data from Table 6. A_{env} is the indicator of the environmental aspects of the infrastructure derived from data from Table 7. A_{soc} is the indicator of the social aspects of the infrastructure derived from data from Table 8. A_{tec} is the indicator of the technological aspects of the infrastructure derived from data from Table 9. Commitment is the indicator of the commitment of the employees using the infrastructure derived from data from Tables 10, 11, 12, 13, and 14.

Infrastructure indicators	Indexes achieved	Weight by importance	Level of importance
PS	0.50	0.17	5
A_{Eco}	0.60	0.17	5
A_{Env}	0.55	0.17	5
A_{Soc}	0.40	0.17	5
A_{Tec}	0.60	0.17	5
Commitment	0.60	0.17	5
I_{Ips}	0.54		

Figure 9 shows a worksheet for evaluating the indicators of each table corresponding to the survey of the elements that define the I_{Ips} :

$$I_{Ips} = \left\{ \frac{(0.50 \times 0.17) + (0.60 \times 0.17) + (0.55 \times 0.17) + (0.40 \times 0.17) + (0.60 \times 0.17) + (0.60 \times 0.17)}{(0.17 + 0.17 + 0.17 + 0.17 + 0.17 + 0.17)} \right\},$$

$$I_{Ips} = 0.54.$$

Table 16 Questionnaire on the production system and its infrastructure

Item	Questionnaire on the production and infrastructure of the productive system		Results	
	Information	Description	Yes	No
1	How could the production be classified?	Traditional		
		Flexible	X	
		Lean		
		Ecologic		
		Sustainable		
2	How is the production classified?	Fewer than 50 employees		
		Up to 50 employees		
		Between 50 and 100 employees	X	
		Between 100 and 1000 employees		
		More than 1000 employees		
3	What type of production configuration is adopted?	Undefined		
		Processes		
		Cell	X	
		Autonomy		
		Positional		
4	What type of production transport is used?	None		
		Fork lift	X	
		Conveyor belt		
		AGV		
		Manipulator robotic		
5	What type of integrated management system is adopted?	None		
		Local supervisory system (level 1)	X	
		Control and supervisory system (level 2)		
		Central management system (level 4)		
		External data center (Cloud, WebServer)		

<i>Infrastructure Indicators</i>	<i>Indexes Achieved</i>	<i>Weight by importance</i>	<i>Level of importance</i>
PS	0.50	0.17	5
A_{Eco}	0.60	0.17	5
A_{Env}	0.55	0.17	5
A_{Soc}	0.40	0.17	5
A_{Tec}	0.60	0.17	5
Commitment	0.60	0.17	5
I_{Ips}	0.54		

Fig. 9 Worksheet for calculating the sustainability indicator related to the system infrastructure

Item	Indexes	Level of importance	Weight by importance
Economic	0.72	4	0.33
Environmental	0.70	3	0.25
Social	0.75	2	0.17
Technological	0.61	3	0.25
Evaluation of IPS	Evaluation of Sustainability	Sustainability Minimum Limit	Sustainability limit
54%	69%	63%	70%

Fig. 10 Worksheet for calculating sustainability

3.2.2 Sustainability considering 4BL

In Sects. 3.1.1 and 3.1.2, the indicators are chosen and reference values are assigned. Thus, the measured values are compared with the reference values. The result of the comparison must be stored in the SuMS database.

As previously mentioned, the definitions of weights are made by specialists, considering a scale of importance of each indicator in the productive system sustainability evaluation. The matrix method is used for calculating sustainability, and the method based on weighted average correlates indicators and sustainability aspects to obtain the degree of DPS sustainability. Thus, at the end of the evaluation, the system is classified as sustainable or not. Consequently, based on these evaluations, it is possible to verify which productive processes contribute to achieving the sustainability goal, and which ones should be improved.

Considering the items in Tables 1, 2, 3, and 4, each sustainability indicator related to economic, environmental, social, and technological aspects ($I_{Eco}, I_{Env}, I_{Soc}, I_{Tec}$) is calculated using a procedure analogous to the case of Table 15.

The results are placed in a worksheet as the one presented in Fig. 10. In this worksheet, the weight in column 4 is calculated according to Eq. (3). For example, for w_{Eco} , the following is obtained:

$$w_{Eco} = \left\{ \frac{4}{12} \right\} \times 100 = 33\%.$$

Item	Indexes	Level of importance	Weight by importance
Economic	0.72	4	0.33
Environmental	0.70	3	0.25
Social	0.75	2	0.17
Technological	0.61	3	0.25
Evaluation of IPS	Evaluation of sustainability	Sustainability minimum limit	Sustainability limit

Evaluation of IPS	Evaluation of sustainability	Sustainability minimum limit	Sustainability limit
54%	69%	63%	70%

In the last line of the worksheet in Fig. 10, the results of the sustainability calculations of the system in question are presented. The calculus of I_{Ips} has been presented previously, and the sustainability is calculated as follows:

$$S_{ust} = \left\{ \frac{\sum_{i=1}^n I_n \times W_n}{\sum_{i=1}^n W_n} \right\},$$

$$S_{ust} = \left\{ \frac{(0.72 \times 0.33) + (0.70 \times 0.25) + (0.75 \times 0.17) + (0.61 \times 0.25)}{(0.33 + 0.25 + 0.17 + 0.25)} \right\},$$

$S_{ust} = 0.69.$

The “sustainability limit” is 70%, and its variation is 10%, i.e., 63% is the acceptable “sustainability minimum limit”. Therefore, the system evaluated in this case, with the values of the indicators obtained according to the worksheet in Fig. 10, is considered sustainable.

The framework is developed so that sustainability indicators that can be general in the DPS, or for each productive system composing the DPS, can be used to compare the systems. The example presented illustrates how the system performance can be detailed under the 4BL of sustainability.

The literature also mentions that another important evaluation to be considered is the sustainability of a product or process during its life cycle. Then, the framework also considers the existing approaches for analyzing the impact of the product life cycle on the environment [15]. The functionalities of the framework must be applied at each stage of the product/process life cycle (prefabrication, manufacturing, use, and post-use) and then the set data must be treated.

Regardless of the purpose, all the results in the worksheets (Fig. 11) are stored in the SuMS database.

Figure 12 shows different formats to visualize the results of the sustainability evaluation (graph on the left

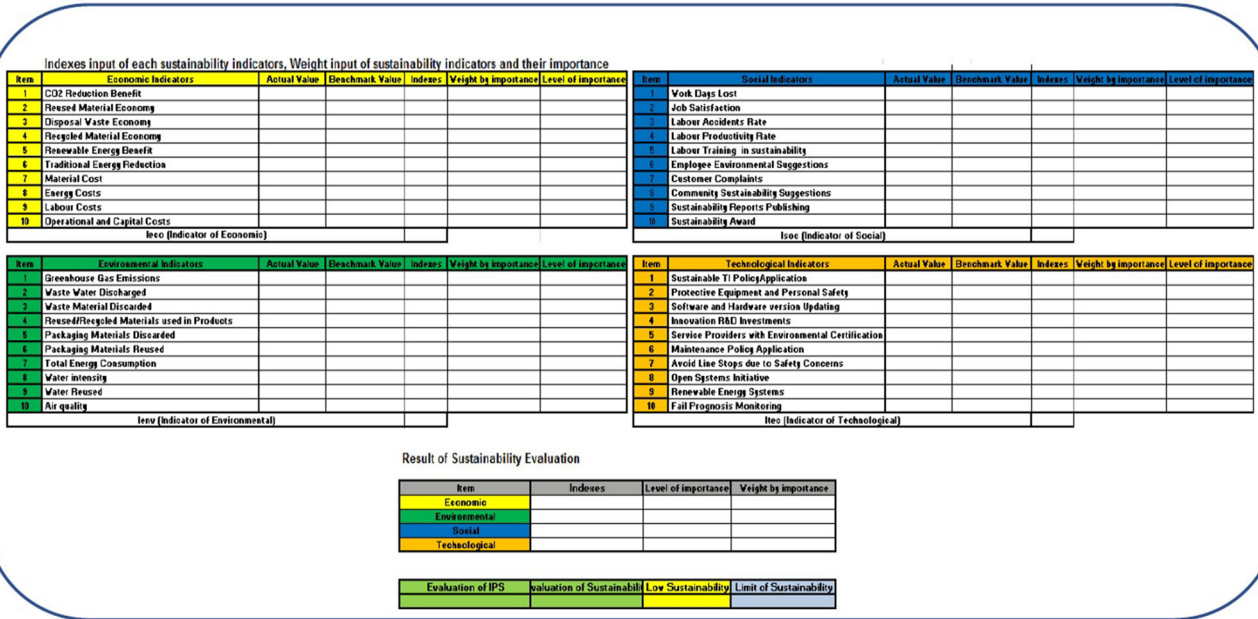


Fig. 11 Worksheet for calculating sustainability

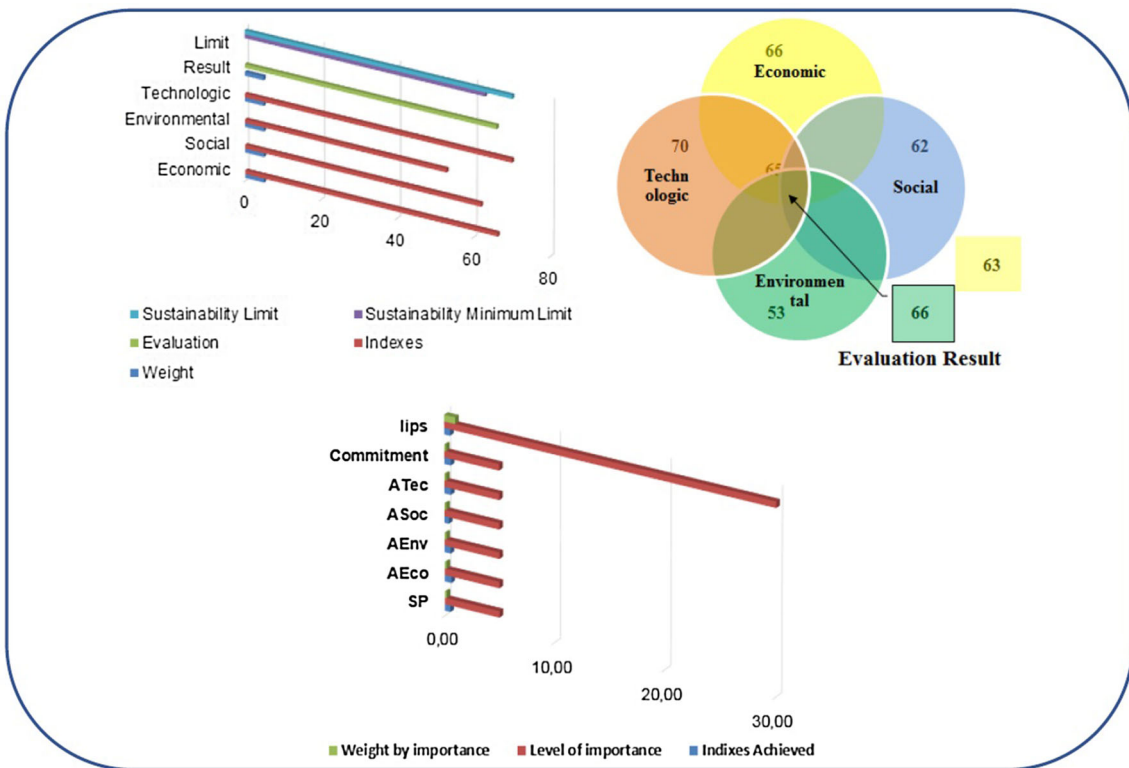


Fig. 12 Examples for visualizing evaluation results

and the Venn diagram on the right) and the productive system infrastructure indices (graph in the center).

3.3 Communication with strategic decision-making level

This functionality does not involve data initialization, i.e., it is activated only at the operation phase of the DPS. On

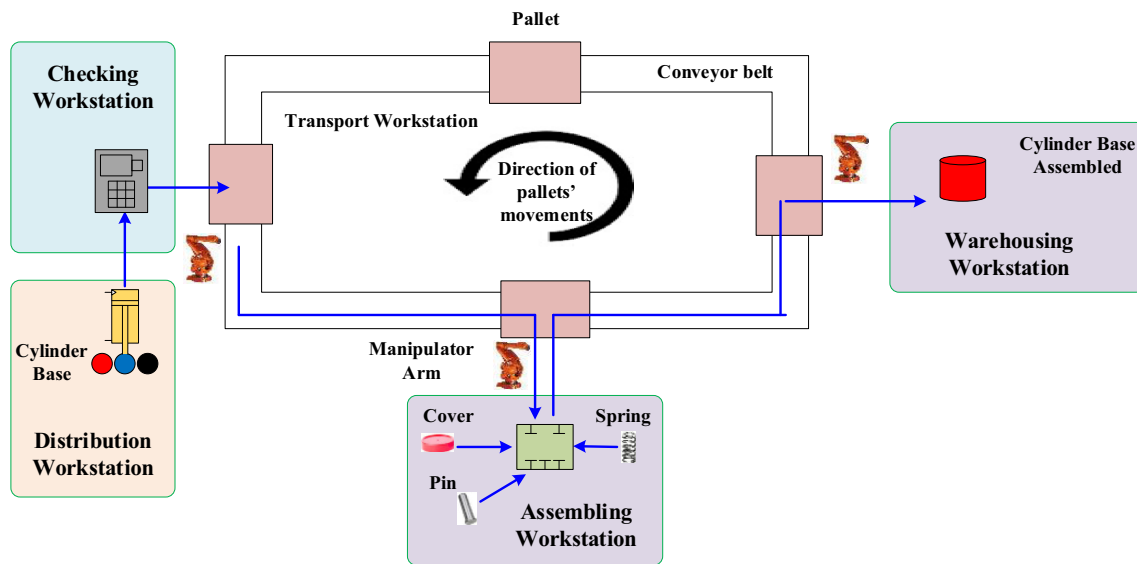


Fig. 13 Example of disperse productive system

the basis of sustainability indicators, using the parameters and variables considered in the calculation of these indicators, a report is generated for the upper level, following the hierarchical structure shown in Fig. 2. The procedure adopted for the proposed framework considers that if there are differences among the measured values and the expected values, these differences should be promptly reported to the upper level, where strategic decisions are made; in this strategic communication process, this SuMS functionality must satisfy possible requests for additional information about data related to the DPS sustainability.

4 Example of sustainability evaluation

Figure 13 shows a productive system in which the production flow follows a programmed order of manufacturing operations at different workstations. This system emulates the main characteristics of a DPS (in which each workstation acts as an independent productive system) and illustrates the proposed solution for evaluating its performance and sustainability.

In this case, the final product is a set composed of a cylinder base where a pin, a spring and a cover are mounted. The “distribution station” has a stack with several types of cylinders randomly stocked. Each cylinder has different characteristics, such as color and size. When a request (final product) is forwarded to the “distribution station”, a device withdraws one of the cylinders from the stack and positions it to feed the “checking station”. When the “checking station” receives the signal that there is a cylinder base to be inspected, a manipulator arm is activated to pick up the cylinder in the “distribution station”

and move it to “checking station”. To pick the cylinder base up, the manipulator arm has a suction device as its end effector. Thus, in the “inspection station”, the cylinder is positioned on a base where its color and dimensions are checked. If certain characteristics are not met, the cylinder is rejected and a device is activated to take it to the disposal compartment. If the characteristics are met, the cylinder is considered approved and another device is activated to take it to a pallet moved via a conveyor belt, which is controlled by the “transportation station”. When the pallet with the cylinder base arrives at the “assembly station”, it activates another manipulator arm, with a mechanical claw as its end effector, to remove the pallet from the conveyor belt and place it on the workbench. Then, the cylinder base is removed from the pallet and positioned on a mounting base. The same manipulator arm, with the aid of a special end effector, places a pin and a spring inside the cylinder and the tapping of a cover in its upper part. Finally, the manipulator arm places the cylinder base mounted on the pallet, and then the pallet on the conveyor belt that leads it to the “warehousing station”.

There is no space here to present all the documents generated and information processed for implementing the proposed framework for the DPS sustainability performance analysis. Thus, only part of the results and information that illustrate the feasibility and validity of the proposal are presented.

Firstly, the data acquisition functionalities are executed. Thus, according to Sect. 3.1, the DPS architecture is analyzed and a trained worker fills Tables 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14 with the information of the characteristics of the system and the processes involved. On the basis of this information, relevant sustainability indicators are defined

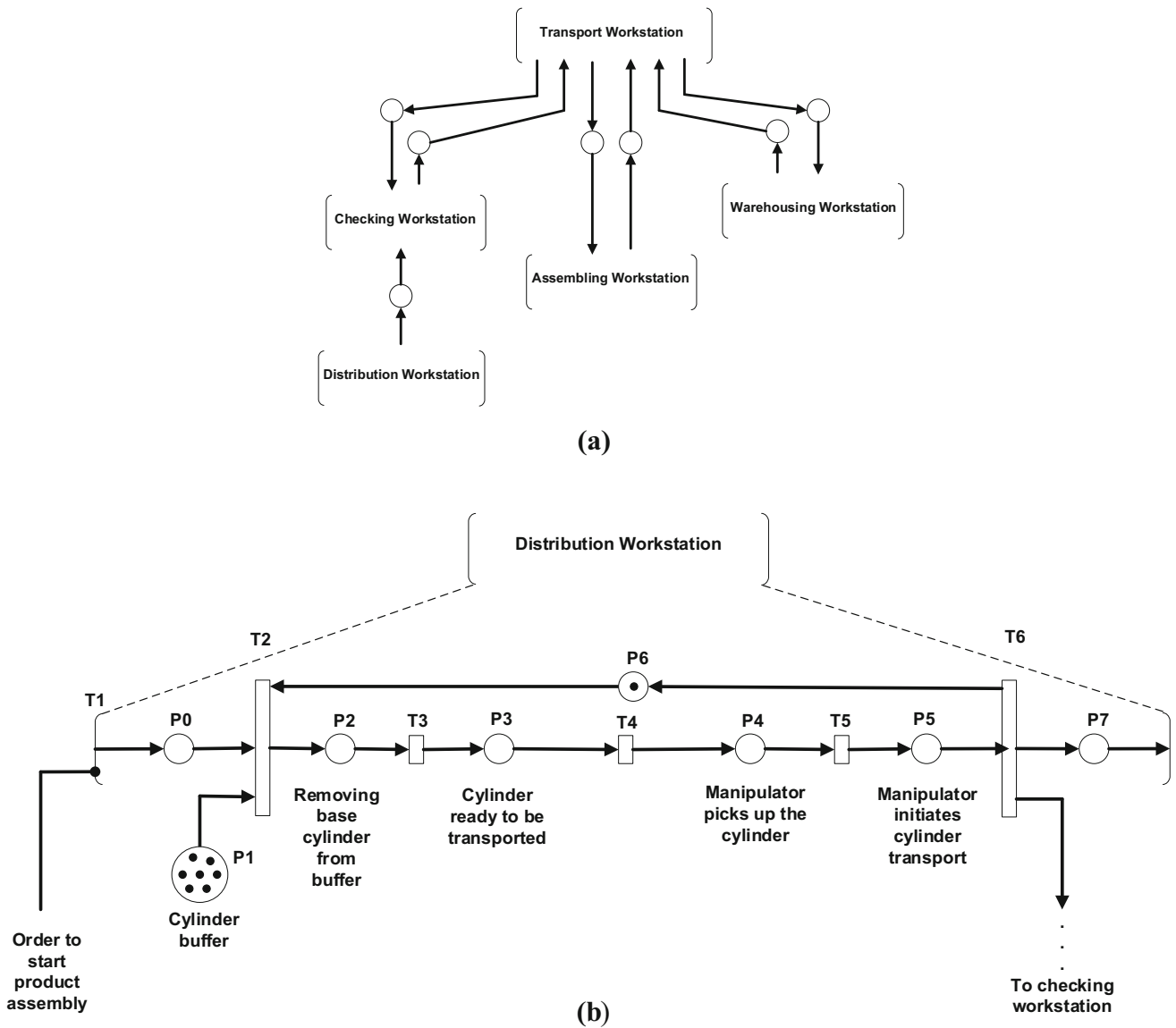


Fig. 14 Models of the processes in the DPS. a PFS model of the general process. b Model in Petri net of the process in “Distribution Workstation”

Fig. 15 Productive process of the “distribution station” and the “data acquisition” for the SuMS

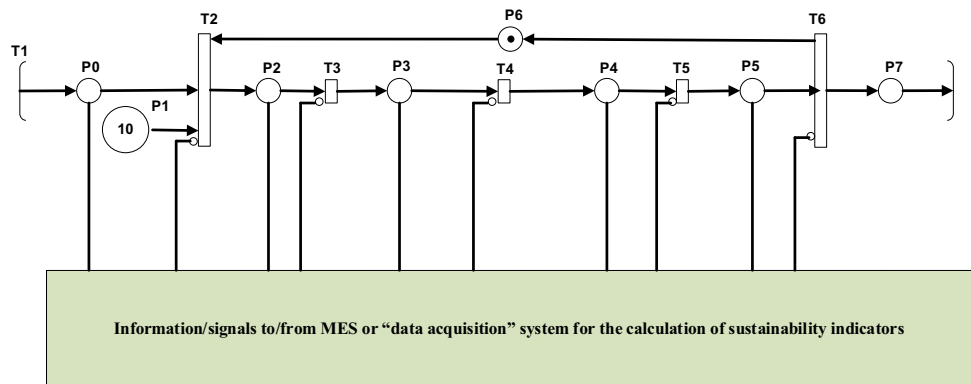


Table 17 Sustainability indicators according to economic aspects

Item	Economic indicators	Actual value	Benchmark value	Indexes	Weight by importance	Level of importance
1	CO ₂ reduction benefit	58	100	0	0.17	5
2	Reused material economy	70	100	1	0.10	3
3	Disposal waste economy	83	100	1	0.10	3
4	Recycled material economy	45	100	0	0.10	3
5	Renewable energy benefit	33	100	0	0.13	4
6	Traditional energy reduction	400	100	1	0.13	4
7	Material cost	75	100	1	0.07	2
8	Energy costs	80	100	1	0.03	1
9	labor costs	72	100	1	0.07	2
10	Operational and capital costs	81	100	1	0.10	3
I_{Eco} (indicator of economic aspects)				0.57	100%	30

Table 18 Sustainability indicators according to environmental aspects

Item	Environmental indicators	Actual value	Benchmark value	Indexes	Weight by importance	Level of importance
1	Greenhouse gas emissions	70	100	1	0.17	5
2	Waste water discharged	70	100	1	0.10	3
3	Waste material discarded	70	100	1	0.10	3
4	Reused/recycled materials used in products	75	100	1	0.10	3
5	Packaging materials discarded	33	100	0	0.13	4
6	Packaging materials reused	90	100	1	0.13	4
7	Total energy consumption	72	100	1	0.07	2
8	Water intensity	73	100	1	0.03	1
9	Water reused	63	100	0	0.07	2
10	Air quality	81	100	1	0.10	3
I_{Eco} (indicator of economic aspects)				0.80		

Table 19 Sustainability indicators according to social aspects

Item	Social indicators	Actual value	Benchmark value	Indexes	Weight by importance	Level of importance
1	Workdays missed	70	100	1	0.17	5
2	Job satisfaction	72	100	1	0.10	3
3	Labor accidents rate	73	100	1	0.10	3
4	Labor productivity rate	70	100	1	0.10	3
5	Labor training in sustainability	65	100	0	0.13	4
6	Employee environmental suggestions	58	100	0	0.13	4
7	Customer complaints	74	100	1	0.07	2
8	Community sustainability suggestions	83	100	1	0.03	1
9	Sustainability reports publishing	75	100	1	0.07	2
10	Sustainability awards	45	100	0	0.10	3
I_{Soc} (indicator of social aspects)				0.53	100%	30

Table 20 Sustainability indicators according to technological aspect

Item	Technological indicators	Actual value	Benchmark value	Indexes	Weight by importance	Level of importance
1	Sustainable TI policy application	72	100	1	0.17	5
2	Protective equipment and personal safety	70	100	1	0.10	3
3	Software and hardware version updating	83	100	1	0.10	3
4	Innovation R&D investments	75	100	1	0.10	3
5	Service providers with environmental certification	80	100	1	0.13	4
6	Maintenance policy application	75	100	1	0.13	4
7	Avoid line stops due to safety concerns	68	100	0	0.07	2
8	Open systems initiative	54	100	0	0.03	1
9	Renewable energy systems	63	100	0	0.07	2
10	Fail prognosis monitoring	40	100	0	0.10	3
I_{Tec} (indicator of technological aspects)				0.73	100%	30

for the DPS, using Tables 1, 2, 3, and 4 as a reference. In this example, all indicators are considered.

The next step involves SPD process modeling. Initially, the conceptual model of the system is developed using PFS. Once these models are verified, the functional models of the processes involved are derived in Petri net. The structural and behavioral verification of the models in Petri net and the dynamic analysis of the system are performed to validate the models.

The models are used to identify where (in the processes) the data collection for calculating sustainability indicators should be performed. Different scenarios are also tested to confirm what information is actually feasible to be collected in practice, including assessing the time limits to be considered, etc.

Figure 14 shows the model of the productive processes of DPS. Figure 14a is the PFS model of the general process (note that each workstation is modeled as a relatively autonomous subsystem and the interaction between them is described as a secondary flow of items) and Fig. 14b shows the Petri net model of the “distribution station” with functional details of the process.

Figure 15 shows the production process of the “distribution station”, that is, the Petri net model, edited in the IOPT tool [9]. Sensors to obtain data through measurement of electrical signal (i.e., gas emission, energy consumption, etc.) and data input device to obtain estimated data (CO₂ reduction benefit, job satisfaction, etc.) are considered according to indicators defined in Tables 17, 18, 19, and 20 to obtain sustainability information, that is, since this information is not available in the MES, a data acquisition system was installed in the plant, but connected directly to the SuMS. The Annex provides a brief explanation of the

data acquisition system developed for this application example.

In the data evaluation functionality, the indicators are initialized with assignment of reference (benchmark) values and the definitions of the indicators’ importance levels. An index is obtained by comparing the actual and reference values, if the result is within the established support limit; the index receives value 1, otherwise, 0. Weights are calculated based on importance level and indexes results. The actual values are obtained via MES and through specific acquisition systems. Thus, these values are used to calculate the DPS sustainability level. Tables 17, 18, 19, and 20 present the resulting data.

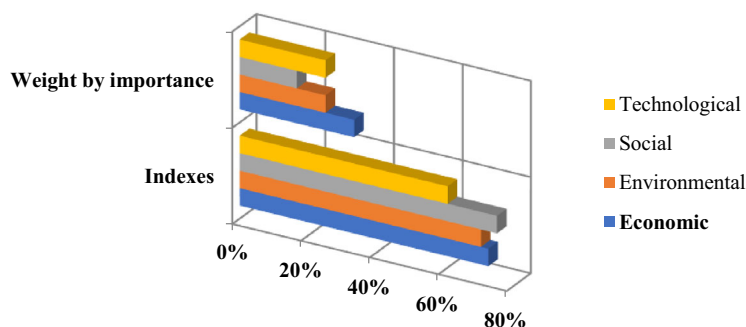
Figure 16 illustrates part of the evaluation results from this example. As aforementioned, a limit of 70% sustainability with a 10% variation is adopted. The weights classify the importance of the indicators and the values are calculated from the data measured and collected directly from the DPS plant. The results can be presented in graphical form, from which improvements to be made to the system, regarding its sustainability, are more easily identified.

Item	Indexes	Level of importance	Weight by importance
Economic	0.57	4	0.33
Environmental	0.80	3	0.25
Social	0.53	2	0.17
Technological	0.73	3	0.25
Evaluation of IPS	Evaluation of sustainability	Sustainability minimum limit	Sustainability limit
54%	66%	63%	70%

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Economic	0.57	4	0.33
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Evaluation of IPS	Evaluation of Sustainability	Sustainability Minimum Limit	Sustainability Limit
54%	66%	63%	70%

(a) Evaluation summary



(b) Bar chart representation

Fig. 16 Results of the sustainability evaluation

Figure 16 indicates that the economic and social aspects are below the value considered as a limit, and when consulting the indexes of each indicator that composes these aspects, the parameters that need to be improved are identified.

As indicated in the framework description, the worksheets shown in Fig. 10 are then used to improve the system. This information is stored in the SuMS database and is available to the DPS strategic decision-making level according to the functionality related to the communication with the upper management and control level of the DPS.

This example presents how the main functionalities of the proposed framework can be implemented and serves as a proof of concept. That is, the framework proves to be an effective solution to implement a system of data collection and processing of indicators of a DPS. The latter allows monitoring sustainability indicators and provides detailed data on different aspects of sustainability that are relevant to strategic decision-making.

5 Conclusions and further works

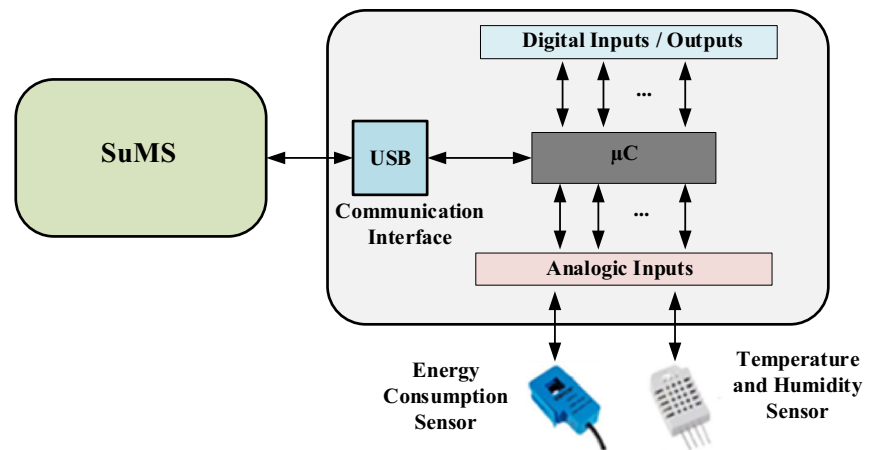
The proposed framework for assessing DPS performance based on sustainability indexes considered concepts, techniques and tools, in addition to the so-called “good

practices” reported by researchers in the area. The framework considered a structure of management and control of productive processes based on the ANSI/ISA-95 standard, and adopted the Petri net as a formal tool to describe the processes involved. Thus, the Petri net models of the processes are used to verify the functionalities of the proposed framework and also to describe the productive processes so that the module dealing with information related to DPS sustainability can monitor the system evolution online.

An example was presented to illustrate the application of the main functionalities of the framework, besides confirming it is an effective solution to monitor and collect data on the sustainability of the system under different aspects, which are fundamental for making strategic decisions.

In the work developed to design and assess the framework, in addition to the example presented, several cases were studied considering an environment with Web services for integrating the sustainability database among the DPS components. The cases studied were based on data provided by Brazilian companies, which did not authorize the disclosure of information, thus posing a difficulty in generalizing the evaluation of the results. However, the studies carried out were considered to indicate that the structure of processes could be very common in developing countries, and that the framework was clearly effective in these cases.

Fig. 17 Operation diagram of the data acquisition system



This work proved that the Petri net models were effective in monitoring the processes and in collecting data for calculating the sustainability according to the existing procedures. Another fundamental step to investigate is whether it is possible to characterize a system as sustainable based solely on the models of the processes in Petri net.

In the framework presented, the module dealing with sustainability at the level of supervision of productive activities, i.e., the SuMS, interacts with the module of execution of productive activities (MES) only to collect data on the processes so that there is no conflict between their functions. The paradigm adopted herein is that, even though sustainability is relevant to the company's strategic decision-making, the performance and productivity parameters of the system are determinant. However, when considering another production paradigm in which sustainability may play a more decisive role, the interaction between SuMS and MES must be reviewed.

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Annex: Data acquisition system

To carry out case studies regarding the calculation of the sustainability of production systems, it is necessary to monitor data related to the environment, which in turn are not usually treated or are not available from the controllers of machines and equipment. Thus, a data acquisition system working independently of the equipment is installed in the plant. In practice, the acquisition system is implemented with an embedded system, that is, a dedicated microprocessor system with a program that performs the data acquisition and communication management functions with the sensors for signal collection. As shown in Fig. 17,

the communication here was developed for “SuMS data collection”.

The sensors are connected to the analog inputs; a program reads the signal and converts it into digital values, which are processed and sent via USB communication interface to the SuMS. The readings are updated in real time.

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