USE OF PETRI NET MODELLING TECHNIQUES AND SUSTAINABILITY INDEXES TO EVALUATE PERFORMANCE IN INDUSTRIAL PRODUCTIVE SYSTEM

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Abstract— Currently, the productive systems (PSs) performance must be concerned to sustainability indicators related to environmental (for reduction of negative impacts in conservation of energy and natural resources), technological (for best management in use practices of equipment and tools), social (for safety assurance of employees, communities and consumers) and economical (for business feasibility and profitability). However, industrial standards do not explicitly consider how to treat sustainability indicators in PS design and its control system. Therefore, this paper proposes a framework to systematize the performance evaluation process for industrial PS considering indicators that qualify and quantify its sustainability. The framework adopts Petri net technique and its extension named production flow schema (PFS), and extensions of the standard ANSI/ISA95. Simulation-based analysis, decision making techniques and a PS´s classification based on product green seal are also considered. Furthermore, the framework considers the information processing, storing and access of each component using a Cyber Physical Technology (CPT) due the trend of PSs to be, in fact, a network of companies that are, in general geographically dispersed.

Keywords— Sustainability indexes, Petri net, performance evaluation, modelling techniques, cloud computing, sustainable productive system

Resumo— Atualmente os Sistemas Produtivos (SPs) devem se preocupar com os indicadores de sustentabilidade relacionados aos fatores ambiental (para redução de impactos negativos em conservação de energia e recursos naturais), tecnológico (para gerenciamento das melhores práticas no uso de equipamentos e ferramentas), social (para garantia de segurança aos trabalhadores, comunidades e clientes) e econômico (para acompanhar a viabilidade e lucratividade dos negócios). Como, as normas industriais não explicitem como tratar indicadores de sustentabilidade em projeto de SP e seu sistema de controle. Assim, este trabalho propõe um *framework* para sistematizar o processo de avaliação de desempenho considerando os indicadores que qualificam e quantificam a sua sustentabilidade. O *framework* adota a técnica de Rede de Petri e sua a extensão PFS (*Production Flow Schema*), e extensões da norma ANSI/ISA-95. Também é considerada a análise baseada em simulação, as técnicas de tomada de decisões e um modo de classificação do SP baseada em um selo de produção sustentável. Além disto, o framework considera o processamento de informações, armazenamento e acesso a cada componente usando a *Cyber Physical Technology* (CPT) devido a tendência dos SPs serem, na verdade, uma rede de empresas, que estão geralmente geograficamente dispersos.

Palavras Chave— Índices de Sustentabilidade, rede de Petri, avaliação de desempenho, técnicas de modelagem, computação na nuvem, sistema produtivo sustentável

1 Introduction

Industrial Productive Systems (PSs) have been modified over time to include innovation (Goldstone, 2002), such as serialization, standardization and reconfiguration capabilities. From the mid-80s, due to tendency scarcity of raw materials, non-governmental organizations, such as Roman Club, have warned about the need to include sustainability in the PS design (Goldstone, 2002) (Senge *et al*., 2001) (McDonough and Braungart, 1998). Thereby arose governmental initiatives through the United Nations (UN) such as World Commission on Environment and Development (WCED, 1987), and events as Rio 92, Kyoto 97 and more recently Doha 2015. Currently, the PSs performance must be concerned to sustainability indicators, such as reduction of negative impacts in conservation of energy and natural resources, management practices for safety assurance of employees, communities and consumers and best practices business feasibility and profitability). However, industrial standards like ANSI/ISA95 do not explicitly consider how treat sustainability indicators into the PS design and its control system (ANSI/ISA, 2005). Therefore, this paper proposes a framework to systemize the PS sustainability performance evaluation. The framework considers enhancement of PS design requirements related to sustainability, adoption of Production Flow Schema (PFS) and Petri Net (PN) modelling techniques, extensions in the ANSI/ISA95 standard in order to include sustainability indicators. To evaluate the sustainability of PSs, a set of indicators must be measured to quantify and qualify the PS performance related to them. In the adopted approach, the modelling process describes a practical and systemized way of assessing the performance of a sustainable PS by monitoring the indicators in accordance with four dimensions: environmental, economical, social and technological, which is usually considered three dimensions called Triple Bottom Line (TBL) by Elkington (1997). In turn, these indicators must be used to guarantee certain grade of sustainability for PSs, positive impact on the environment, satisfaction of the employees, proper use of technology and profitable manufactured products. Thereby the framework also supports product classification based on sustainability seal. The performance and sustainability evaluation is based on computational environment of Cyber Physical Systems (CPS) with cloud computing infrastructure, where data processing, storing and accessing is done in wherever geographical location.

The text is structured in sections: section 2 shows a list of sustainability indicators defined for general PSs. Section 3 shows the framework considered for the systematization of performance evaluation process and presents a green seal to register sustainability in PSs. Section 4 describes an example of use the simulation and analysis techniques. Section 5 reports the conclusions and further works.

2 Sustainability Indicators Metrics

Sustainability in PS, according to the US Department of Commerce (US, 2009), involves the creation of manufactured products that use processes that minimize negative environmental impacts, saving energy and nature resources and to be safe to employees, communities and consumers. Also, this provides benefits to the company from an economic point of view. According to WCED (1987), sustainable manufacturing can be understood as all types of productive activity that minimizes diverse business risks inherent to any manufacturing operation, while maximizing new opportunities that increase results of its processes and products results. In its operations is adopted the 6R methodology (Javal, 2010) over product´s life-cycle since the production until discharge by market, the 6Rs cycle is following:
1- Reduce is related to the reduced use of energy and materials during manufacturing and the reduction of waste during the use stage;
2- Reuse is related to the reuse of product or its components to reduce the usage of new raw materials to produce new products;
3- Recycle refers the process to convert material considered waste to build a new product;
4- Recover refers in disassemblies for collecting and utilization obsolete products;
5- Redesign refers to simplify pos-use processes with application of techniques to make a more sustainable product;
6- Remanufacture involves re-processing of already used products for restoration to their original characteristics.

Figure 1 shows the evolution of different manufacturing concepts and their contributions to stakeholder value, and the proposed closed-loop system involving 6Rs. The production activities are:

- Enterprise Resource Planning (ERP) – Management function of all company business activities,
- Production Control and Planning (PCP) – Production planning activities according to a demand schedule,
- Warehouse of materials with identification code – Stores materials separated for attending production line,
- Reception of materials and checking – Preparing and checking materials to be sent to production line,
- Productive System (PS) – System arrangement to produce products,
- Warehouse of products – Stores traceable products to be sent to market,
- Distribution – enterprises network to put products at the market,
- Disassemble products – Dismounts products received from external agents,
- External products collection – Product´s entry from a external collection system,
- Discard materials – Faulty materials and,
- Treatment/Disposal – Treats materials before disposal.

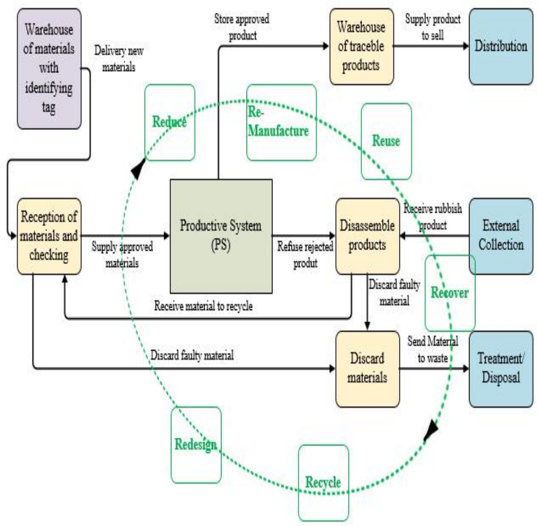


Figure. 1. Sustainable Production Cycle

According to (Veleva, 2000), sustainability indicators have three main objectives: raise awareness and understanding, inform decision-making, and measure progress toward established goals. These indicators are qualitative or quantitative values used to evaluate the sustainability aspects of a system (O'Brien, 1999). However, according to (Amrina and Yusof, 2011), the measure of the sustainability is more than just a set of indicators and there are different approaches to be considered, such as the definition of the actions set, in which the indicators must be verified. For e.g., (Joung *et al*., 2013) states that the result of this measurement should support the identification of specific areas to apply enhancements related to sustainability in PS activities. Analyzing the data achieved and its interpretation is other fundamental phase, since the difficulties are due to the complexity related to definition of several indicators (OECD, 2001) (OECD, 2011). Interrelationships may bring the conclusions about the level of sustainability and decisions of future improvements.

Based on (Tan *et al*., 2015) and other references, thus, a new list of indicators was defined and it is showed at table 1(a, b, c, d). A list of indicators which can be used to any PS in general, considering sustainability in four dimensions: environmental, economical, social and technological. For example: through the table 1 (a) in the sub-category resource consumption is possible to determine the "Energy intensity index" by dividing energy consumed and unit of product (kWh/unit). Thus, for each indicator chosen it is necessary to determine the index based on demand of the production.

TABLE 1

(a) PS Sustainability indicators – Environmental aspect

Sub-category	Indicator	Quantification Method
Emission and Pollution		
	Greenhouse gas emissions	Mass of CO_2 equivalents emitted
	Waste Water discharged	Volume of waste water discharged
	Waste material	Any type of material that is discharged
Resource Consumption		
	Reused/recycled materials used in products	Unit of product 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 that is directly attributable to the manufacturing process
	Energy intensity	Energy consumed/Unit of product
	Water intensity	Volume of water consumed/Unit of product
	Water reused	Total volume of water reused

(b) PS Sustainability indicators – Economic aspect

Sub-category	Indicator	Quantification Method
Financial Performance		
	Carbon footprint benefit	Financial gain in reduction of quantity of carbon gas emission
	Reused Material economy	Financial gain in quantity of reused material
	Disposal waste economy	Financial gain in quantity of disposed material
	Recycled material economy	Financial gain in quantity of recycled material
	Renewable Energy Benefit	Financial gain in quantity traditional energy economy in relation renewable
	Traditional energy reduction	Financial gain in quantity traditional energy economy
Manufacturing cost		
	Material costs	Costs of acquiring materials (including water and packaging) used within manufacturing process
	Energy costs	Costs of energy used in production process
	Labour costs	Costs of labour used during manufacturing process
	Operational and capital costs	Costs of operation and capital used during manufacturing process

(c) PS Sustainability indicators: Social (Well-being) aspect

Sub-category	Indicator	Quantification Method
Employee		
	Lost workdays	Number of missed workdays due to accidents.
	Job satisfaction	Labour humor survey during hours
	Labour Accidents	Number of occurrences during workday
	Labour productivity	(Total revenue/Total labour costs)
	Training in sustainability	(Employees trained in sustainability/ Total number of employees)x100%
Customer		
	Customer complaints	Total number of customer complaints related to sustainability performance
Community		
	Sustainability reports publishing	Total number of published assessments and reports and % of completion of these sustainability assessments.

(d) PS Sustainability indicators: Technological aspect

Sub-category	Indicator	Quantification Method
Productivity		
	Sustainable TI Policy application	Total number of actions complaints related to sustainability performance
	Employee environmental suggestions	Total number of employees' suggestions regarding sustainability improvements
Performance		
	Update of software and hardware version	Number of product updated/Number of product installed
	Innovation & R/D investments	Total amount of R&D investments for sustainability efforts
	Environmentally certified service providers	(Number of providers with EMS/ Total number of providers)x100%
Production line		
	Maintenance program policy	Number of equipments inspected/Number of equipments installed
	Avoid line stops due to safety concerns	Monitor security around manufacturing machineries
	Fail prognosis police	Monitor equipment work cycle/wear during manufacturing process

According to (Joung *et al*., 2013), the grade of sustainability may be used as a metric to evaluate the performance of PS. There are a pattern set of processes performance indicators, called Key Performance Indicator (KPI), which are measured to quantify and to qualify process performance evaluation. In the ISO standards (ISO, 2010) (ISO, 2014), the performance measure is treated as part of an industrial process creation value.

3 Performance Evaluation Systematization

According to organizational structure of a industrial company (ANSI/ISA, 2005), the production information is processed at level 3 Manufacturing Execution System (MES). The results from the production performance analysis executed at MES are sent to the business level (upper level) that assists managers to make decisions (Figure 2, on the left side). The proposed innovation of this work are: the level 3 are reviewed and re-interpreted to include a Sustainability Management System (SMS) module to treat sustainability, which is responsible for processing the data collected from the lower levels to calculate the sustainability indicators through information from PS infrastructure. In case of any indicators discrepancy, the SMS acts close to the existing MES modules in order to indicate and notify the higher level and to send commands for lower levels in accordance to directive established by the business level.

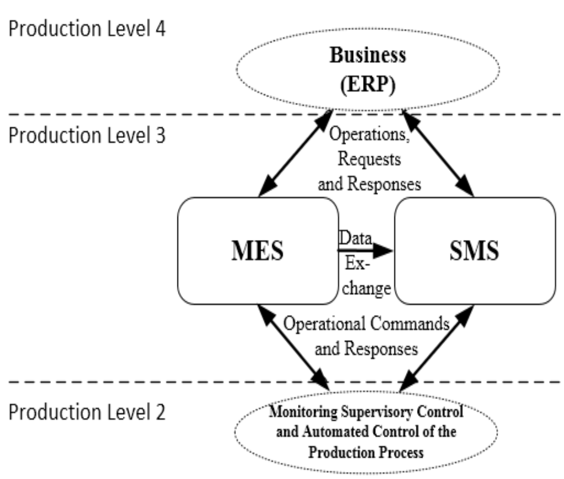


Figure 2 – ANSI/ISA-95 norm and the proposed SMS module.

The SMS is composed by sub-modules:
- "sustainability indicators data collecting", that stores the PS indicators data;
- "sustainability performance analysis", that calculates the performance of the PS based on data received from both the MES and PS sustainability indicators;
- "sustainability indicators definition", that deliveries the interface of a performance and a evaluation of sustainability indicators from other PSs that compose the disperse system to ensure compatibility among them;
- "execution management", that coordinates interactions among the SMS sub-modules and equipment located on inferior levels.

3.1 A Framework

PSs can be approached as a Discrete Event System (DES) (Miyagi, 2001) (Morales *et al*., 2007) (Villani *et al*., 2007) and based on this, Petri Net (PN) technique (Silva, 2013) can adopted as a tool to systematize the modelling procedure, analysis and control specification (Figure 3). In fact, there are other techniques to model DES, but when the implementation of control solutions in industrial process are relevant, the models based on PN are considered the most effective and easy way to program industrial controllers (Leitão and Colombo, 2006; Lira, D. et al., 2008). Even though, the introduction of the sustainability concept does not change the nature of PS, its consideration at the system design stage is not trivial. Therefore, is presented in Fig. 3 the framework for the performance evaluation of sustainable PS. This Figure also shows a simplified flow of information.

The proposed framework (Figure 3) to perform evaluation of sustainable and dispersed PSs (Da Silva, R. M. et al., 2015). considers:

1. Data survey about the physical machine operations and types of technologies involved in the processes. Based on this information, indicators are defined. The environmental resources data, materials and processes compose the environmental information and are previously defined.

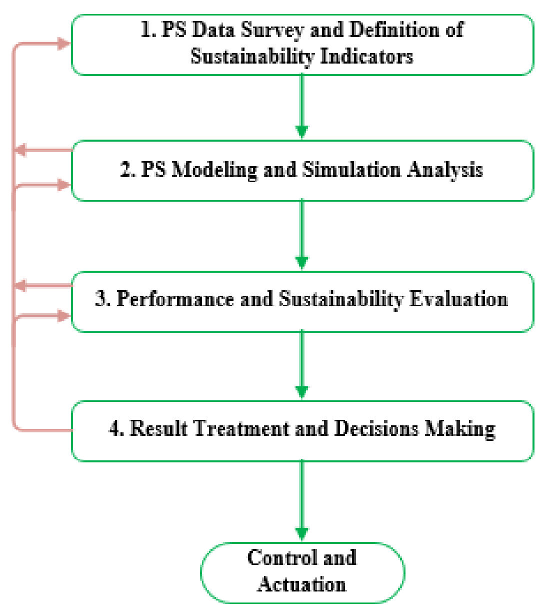


Figure 3. Framework for the analysis procedure of performance in sustainable PSs.

2. Processes in the PS described by PFS and then detailed by PN models (Miyagi, P. E. (2001)). The PN models are analyzed including the simulation for quantitative evaluation for different scenarios.

3. The expected KPIs related to sustainability, which are obtained from the PN models are stored at SMS database and used to compare the information collected from the productive plants on-line. It is supposed that information about the current status of the productive plants is available at the MES database; however, there are cases where direct communication from SMS to the supervisory level (lower level) is necessary.

4. The evaluation of the differences among the expected values of KPIs and measured values are reported to superior level (level 4). Although there are cases where some activation commands are previously established (evidently derived from decision of upper level). In this case, a message must be send to MES to update the tasks to be carried out in the PS.

3.2 Disperse PS Architecture

The Cyber Physical System (CPS) technology can be explored in PSs to create an infrastructure for data processing and acquisition, connecting elements to monitor variables that will compose the sustainability indicators. According to a cloud computing vision, PS must explore CPS to assure a collaborative environment to (re)configure online productive processes that are excuted in disperse PSs independently of its geographical localization. These systems form the basis of emerging and future smart services, and improve quality of life in many areas (NIST, 2012) (Sundmaeker *et al*., 2013) (Colombo *et al*., 2013), providing the foundation of this proposal, including its critical infrastructure (Figure 4).

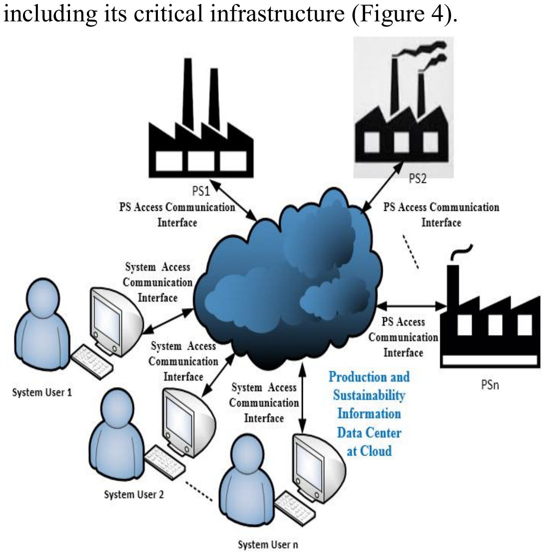


Figure 4 – CPS technology to disperse PS - productive systems.

The system users must access data of the PS to evaluate the performance, simulate a new scenario and implement improvements. All manufacturing data must be accessed wherever they are, via internet (Ferreira, 2013).

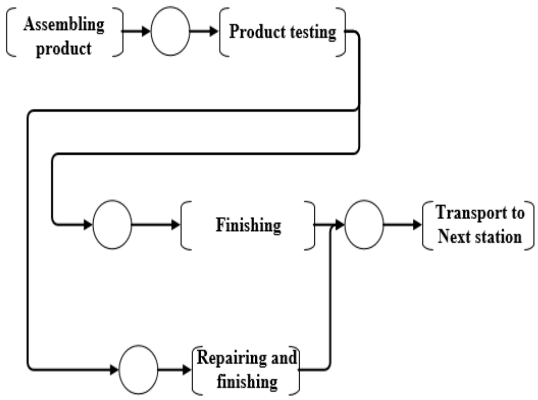
3.3 Green Seal

The "green seal" is an initiative to encourage industries to produce in accordance to sustainability factors, such as economical, social, environmental and technological. This seal is also a register that the framework is in working order. All customers that buy products with green seal must have the guarantee that they are helping to keep the world to be better to live. This way, the industry can show that is doing something for welfare of the people and the nature**,** and it produces an extra motivation for its employees and local community (Figure 5).

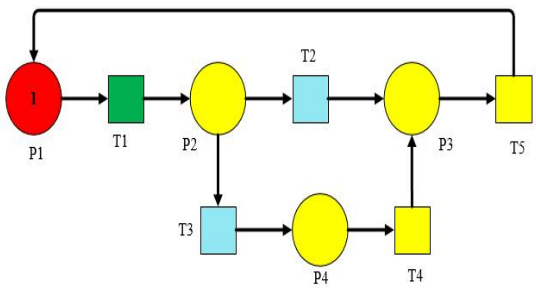
Figure 5 – Example of seals according with the green representation.

4 Simulation and Result Analysis

The proposed systematization makes the performance evaluation work easier because it specifies how to execute the evaluation process of sustainability indicators. The framework associated with the proposed systematization support the specification for a smart data acquisition system, well defined equipments, sensors and data network to facilitate flow of all information into the industrial infrastructure. The data acquisition systems work continually while the production is operating, then at any time the responsible staff of production administration can log in the system and evaluates performance in any system at network. As an analysis tool can be used Petri editors/simulators or any other discrete event tool. It is used IOPT (Input Output Place Transition) web tool (GOMES et al., 2007), Petri Net tool developed by a research group from Portugal. The analysis and reports are sent to the upper level system to make a decision.



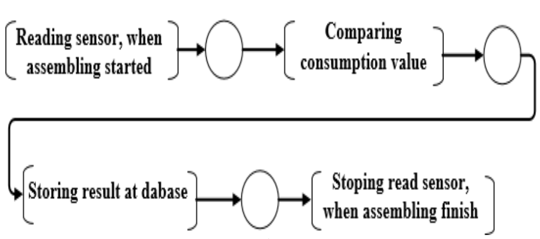
a)



b)

Figure 6 – a) PSF production model, b) Production representation using Petri Net in IOPT environment.

Figure 6 represents an example of production line where a flow of material goes through places indicating three different productive processes: P1-> P2 -> P3, at approved situation. In each place an operation is executed that demands energy consumption. If a fail occur in P2, the flow is switched to P4 to repair the material and then follows to P3. The arc between transition point T5 and place point P1 assures the sequence of activities. In parallel to production line, there is a measurement system working represented in Figure 7. The elements P5, P6, T6 and T7 represent a sensor that acts when P2 in Figure 6 starts operation, thus the sensor reads the energy consumption and the value read is compared with a pattern value stored in database. There are three possibilities for the index: low, normal and high. In all cases after checking the result it is stored in database. This is executed by tasks P8, P9 and P10 respectively. The results stored at database will be used to make decision at upper level system (level 4).



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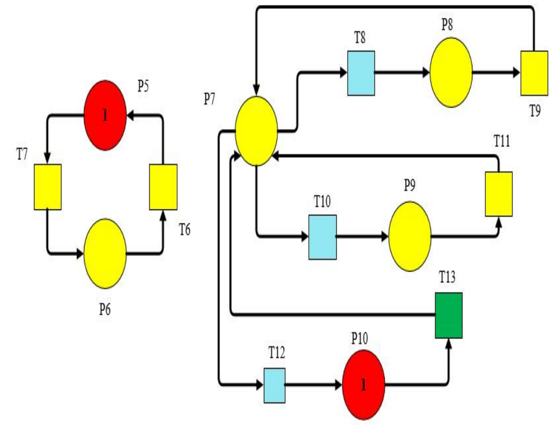

b)

Figure 7 – a) PFS measure model, b) Measure Consumption in P2 representation

This measurement structure is applied where the sustainability indexes values are relevant to evaluate the production line.

5 Conclusions and Further Works

The ANSI/ISA95 standard structure is reviewed to evaluate the performance of a productive system considering sustainability. This paper proposes a framework that considers these indicators and defines a list of indicators which can be used to qualify and quantify sustainability in PSs. The framework adopts the PN modelling technique and its extension PFS to consider the sustainable PS design, simulation-based analysis, decision making and classification techniques based on green seal of products. The seal is a register that the framework is in working order. In the adopted approach, the process modelling describes a practical and systematized way of assessing the performance of a sustainable PS by monitoring the indicators defined according to four dimensions of sustainability: environmental, economical, social and technological. This proposed systematization makes the performance evaluation work easier because it specifies how to execute the evaluation process of sustainability indicators. In the framework description is quoted the use of decision making tool, it needs to be better explored and also the case shown in section 4 is a small sample of simulation and analysis features that they will be detailed in further works.

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