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Back to Intuition: Proposal for a Performance Indicators Framework to Facilitate Eco-factories Management and Benchmarking

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Abstract

In the current competitive and regulated landscape, manufacturing enterprises struggle to improve their performances, encompassing environmental as well as economic objectives, towards sustainable manufacturing and the future Eco-factories. Experts and scholars have developed more and more indicators, usually referred to as Key Performance Indicators (KPIs), as a mean for steering and controlling the complex factory systems, characterized by dynamic interdependencies among different subsystems and external variables. The present study proposes a synthetic framework to bring back hundreds of environmental and economic KPIs to a few sound intuitive categories, in order to reduce duplications, recuperate meaningfulness and consciousness, facilitate inter and intra-organizational benchmarking. The approach, based on input-output modelling of physical flows (products, materials, energy, emissions, etc.) in manufacturing systems, can be used at different hierarchical levels in the plant and in different factory life-cycle phases (design, operations and re-design). The application of the framework is demonstrated on an extensive review of performance indicators gathered in industrial cases and in the literature.

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Keywords: Sustainable Manufacturing; Environmental Conscious Manufacturing; Manufacturing KPIs; Manufacturing Benchmarking.

1. Introduction

The concept of sustainability emerged at the end of the eighties with the World Commission on Environment and Development report [1]. This report, instead of assessing the state of natural resources, highlighted possible ways to combine economic growth with environmental and societal issues. In particular the following definition of sustainable development was provided: development that "meets the needs of the present without compromising the ability of future generations to meet their own needs". This very wide and abstract concept has been developed and detailed in the years along three main streams: environmental, social and economic dimensions.

Global competition and climate change phenomenon represent some of the key challenges that force industrial players to reconsider their strategic objectives and priorities.

Economic development and environmental protection together are now being considered by industrial leaders as the basis for competitive advantage, thanks to the double impact that resource efficiency can have both on operating costs and on company brand image. The motivations for corporations to pursue sustainability have been extensively researched [2]. According to a recent McKinsey report [3], positive effects on Return on Capital of manufacturing companies might come from i) marketing resource efficiency attributes, ii) improving product value propositions with low environmental impacts, iii) reducing operating costs through improved internal resources management (energy, waste, water, hazardous substances).

In this context, therefore, European manufacturers have to fundamentally change their approach to competition: they need to deliver high quality and increasingly customized products and services, with minimum cost and environmental

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impact. Production systems requirements therefore entail improving energy and resource efficiency, reducing waste and emissions, while pursuing all the other manufacturing performances [4]. Enterprises need methods and guidelines to support decision making to design, operate, manage and "fine-tune" their manufacturing systems, aiming at economic and environmental objectives to achieve the so called eco-economy with their future factories, the eco-factories.

Therefore, there is the need for evaluation of sustainable manufacturing performance (see for instance [5]. Development of appropriate metrics is critical to enable designers, engineers and managers to orientate their decision processes, from the factory planning, to operations, management and control.

An organization such as a manufacturing company has a mission, a set of stakeholders, and some specific objectives. Once these items are clear, Key Performance Indicators (KPIs) are those measurements that support the organization decision makers towards the defined goals and missions and can be monitored by the stakeholders for different purposes. In this context, KPIs can be used to set performance targets for the future, driving change and development, to describe and review historical performance [6] [7].

More precisely, a Key Performance Indicator is, during Operation, an item of information collected at regular intervals to track performance of an organization or system at any level (such as production machine or plant, or unit) that produces output (products or services) using resources of different types. During design process, KPIs can be used to compare the performance of alternative technologies or manufacturing systems and the trade-off with quantities and costs of the relevant resource usage. It has been recognized that future sustainable eco-factories must be seen as a complex network of interdependencies among the various products/materials and resources flows with the factory management and control systems [8] [9] [10]. We consider here as resources all the flows needed by the manufacturing system to produce final goods/services, such as raw materials, parts, energy, manpower, and even time.

Measurement of KPIs has no meaning per se but acquires different meaning when compared with appropriate reference points:

- with defined targets, to assess the implementation of strategy and plans;
- with historical values, to assess progress/improvement;
- with similar manufacturing systems (benchmarking), to identify and adopt best practices.

From literature and practice we can get a multitude of key performance indicators concerning management of energy and resource efficient manufacturing systems, given the complexity of the manufacturing systems and of their management and control structure. It is widely recognized that a general framework is needed to support an integrated and systems-oriented assessment of the future sustainable factories. According to many authors (such as [11]) to incorporate the company strategic goals within an organization and to ensure that all activities are aligned with the strategic path defined, it is crucial to implement a Performance Measurement System (PMS) with specific Key Performance Indicators (KPIs) at each level (strategic, tactical, operational). There is therefore the need to research towards KPIs, integrated in a performance system with the management and control layers of the company to allow systematic performance evaluation of sustainable manufacturing.

2. Related work

2.1. Sustainable manufacturing metrics

Sustainability indicators have been addressed by a lot of international initiatives, at different scales: global, national, regional, supply chain, company, factory, process and product scope, aiming at providing the relevant information to the different levels of decision making [12]. Various publicly available indicators sets, such as Global Report Initiative, OECD Core Indicators, GM Metrics for sustainable Manufacturing and a few others, have been listed in [13]. Within the classes of indicators identified by the National Standard Institute of Standards and Technology (U.S.A.), two categories mainly address eco-economy: Economic Growth, including costs, profits and investments; and Environmental Stewardship, including emission, pollution, resource consumption and natural habitat conservation [12].

2.2. Indicators frameworks

As new metrics are developed in order to address global and specific sustainability dimensions, there is an increasing interest in the potential for synthetic, comprehensive indexes.

Environmental intensity, consisting in environmental impact per unit of economic performance, is proposed as a measurement for measuring eco-efficiency of different industry classes [14].

Other composite indexes are proposed for technology assessment [15].

An interesting contribution for assessing environmental performance, sustainability and associated competitive advantage of individual firms and their suppliers is provided by [16]: the framework can be used at firm, location and product level, extended to the supply chain and to the product lifecycle; the indicators are calculated on the basis of reference values.

Furthermore, there is a rich literature concerning aggregation of sustainable performance indicators through balanced scorecard methods, as, for example [17].

2.3. Common view for sustainability indicators

As summarized in the previous sections, a great variety of indicators related to sustainability in manufacturing have been identified, specified, analyzed and collected in publishable and restricted repositories.

Researchers and practitioners have dealt with the complexity of the theme: addressing different scales from the product process to the planet; different dimensions, economic, environmental and social; different perspectives for internal and external stakeholders; different time references, from periodic evaluation to lifecycle assessment.

Criteria for the usability, principles and best practices for the measurement process [18] have been studied in order to provide full support to all the roles that can influence the decision making processes towards manufacturing sustainability.

However, to the knowledge of the authors, whether they refer to a whole industrial sector, a firm or a factory, sustainability indicators share a common external view of manufacturing, based on the measurement of the different types of environmental and economic relevant flows, such as material, energy and other resources; emissions, wastes and other polluting output, costs, etc.. Sustainability indicators in fact are calculated by gauging, comparing, correlating these quantities during a specified period of time, blind to the dynamics of the manufacturing processes in that period of time.

3. Holistic KPI framework

We propose in this section a high level KPI framework that enables a thorough and systematic assessment of performance of manufacturing systems along multiple dimensions in terms of production performance, economic performance and environmental impact, suited for the design and management of future sustainable eco-factories.

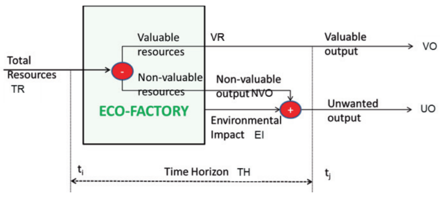

Figure 1 Holistic KPI framework schema

Focusing on the physical flows in the system, in Figure 1 we show how Total Resources (TR) can be:

i) valuable resources (VR), to produce non-defective final products, becoming valuable output (VO);

ii) non-valuable resources NVR, wasted i) during non-productive time or ii) to produce defective products, becoming "non-valuable" output (NVO).

These wasted resources NVO can be considered "unwanted" output (UO), together with all environmental impacts (EI).

Splitting resources in valuable and non-valuable needs a proper information structure aiming at highlighting resource wastes, and is essentially enabled by identification of usage of resources in valuable or non-valuable manufacturing states (such as non-productive time of a machine tool or Technical Building Service kept switched on while the corresponding production line is off-line for maintenance (more details in [19]).

Table 1. Holistic KPI framework

Indicator	Description	Formula
Resource Productivity (RP)	$RP = \frac{Valuable\ Output}{Total\ Resources}$	$RP = \frac{VO}{TR}$
Eco efficiency (EE)	$EE = \frac{\text{Valuable Output}}{\text{Unwanted Output}}$	$EE = \frac{VO}{UO}$
Energy / Resource Efficiency (ERE)	$ERE = \frac{Valuable\ Resources}{Total\ Resources}$	$ERE = \frac{VR}{TR}$
Resource Intensity (RI)	$RI = \frac{Total\ resources}{Time\ Horizon}$	$RI = \frac{TR}{TH}$
Output Intensity (OI)	$OI = \frac{Valuable\ Output}{Time\ Horizon}$	$OI = \frac{VO}{TH}$

Under these assumptions, we propose five high level holistic indicators (see Table 1), related to cumulated sums over a specific time horizon TH of the above mentioned flows:

- Resources Productivity (RP) = VO/TR
- Eco-Efficiency (EE) = VO/UO
- Energy-Resources Efficiency (ERE) = VR/TR {0..1}
- Resources Intensity (RI) = TR/TH
- Output Intensity (OI) = VO/TH

The flows considered and the proposed high level indicators are multidimensional quantities and can be represented through vectors*: each position in the vector expresses in an appropriate metric the quantitative flow of a particular physical substance, with reference to the specified time horizon. For instance, total resources TR can be considered all the different resources types needed by a specific manufacturing system to produce finished goods, such as raw materials, energy, manpower, time, etc.

Each flow is represented in its relevant specific units. At each flow can also be attributed a financial value "F", calculated through unit costs and/or prices or cost functions F(r). At each flow it can also be attributed, when pertinent, an environmental value "E", calculated according to appropriate environmental standards (i.e. Ecoindicator 99 [20])

We show in Figure 2 how the proposed KPI framework allows a complete and integrated coverage of the performances necessary for the assessment of an Eco-Factory: traditional production performance, economic and environmental performance with a specific focus on energy and resources efficiency. We note that we do not address here

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*All the flows considered (such as resources: TR, VR, NVR), output (VO, NVO) and environmental impacts, EI) can be considered tuples, that is ordered list of elements. E.g. Total Resources is the tuple TR = (r_1, r_2 .., r_n) in which each r_i relates to a specific type of resource. UO is the nested pair tuple UO = (NVO, EI).

in detail all the traditional production performance indicators that are widely addressed in literature.

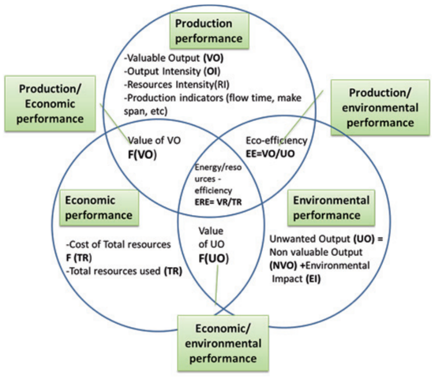

Figure 2 Holistic KPI framework and eco-factory performance

4. First analysis and preliminary findings

An initial analysis of the proposed KPI framework has been deployed targeting a small sample of industry experts and researchers in the field of the sustainability and especially energy efficiency. The experts belong to seven manufacturing companies and technology providers, whereas academia is represented by eight university and research institutions. The results of the energy efficiency KPI (from now on, eeKPI) survey are available in Appendix A.

The eeKPI survey presented includes the multi-faceted view point of different stakeholders from academia/research and from industry and reflects a multitude of experiences and research based theoretical and business PMSs and most likely on the various problems addressed. The KPIs collected come both from literature and practice. Therefore the survey cannot be taken as a basis of a complete PMS that fits all, while we can exploit it to show how: i) the collected KPIs fit in the proposed KPI framework and how ii) the collected KPIs can be seen as a schema of a possible potential PMS for energy efficient factories.

4.1. Holistic KPI framework coverage of the eeKPI survey

Some (7) of the 54 indicators collected focus on “traditional” production indicators, such as flow time, lead time, Overall Equipment Efficiency (OEE) and its components (availability, performance, quality, effectiveness) and we do not go in detail about them, as there is a rich literature on this topic. The main body of the KPIs addresses the manufacturing performance from the point of view of the energy and resource efficiency.

More in details, if we exclude the seven production performance KPIS we have 47 KPIs that can be all classified related at least to one of the five types in our KPI framework (see Table 2), specifically:

- 22 indicators can be classified as resource productivity (RP) indicators (that is, are related to ratio of total resources used per output unit);
- 1 (PI29) is built up upon yearly carbon footprint of a factory and therefore is related to an eco-efficiency (EE) indicator as per our proposal;
- 8 are energy/resource efficiency (ERE) indicators (that is they are related to the percentage of resources used for “valuable” activities to the total resource used);
- 15 are intensity indicators of physical flows (energy /resources);
- 1 (PI18), production volume, is of course an output intensity (OI) indicator.

Furthermore, some of the above mentioned indicators (such as PI25, PI27, PI29, PI32, PI33, PI46) can be derived from one of the other indicators evaluated along the economic dimension (including operating costs or even Total Cost of Ownership –TCO) as described in our proposal.

The survey performed therefore is a first step in the validation of the proposed Holistic KPI framework that stands as a model for the assessment of the future eco-factories.

Table 2: ee KPIs , framework coverage and hierarchical levels

	KPI framework				
	OI	RI	RP	ERE	EE
Manufacturing process/component			PI01, PI02, PI03, PI04, PI05, PI06, PI07, PI08, PI09, PI49, PI50	PI11	
Machine /part		PI12, P20	PI10, PI24		
Machine / batch				PI59, PI60, PI61, PI62	
Process chain segment/building		P21, P22, PI57, Pi58	PI44, PI45, PI46	PI56, PI43	
Process chain / product			PI25, PI35		
Factory/plant	PI18	PI15, PI16, PI26, PI31, PI32, PI54, PI55, PI36, PI37	PI30, PI33, PI28	PI34	
Enterprise			PI27		PI29

4.2. A first idea of an energy and resource efficient PMS

If we analyze the 47 KPIs related to energy efficiency, we may note that 43 of them support a decision process which, focusing on one physical intervention area (machine or line) are interleaved with the aggregation of the information of the usage of resources from the single machine/components to the process chain segment to the process chain producing a single product up to the whole factory, including TBS and building. This reflects how data on physical systems and flows can be aggregated in a bottom-up approach in order to provide feedback to management towards reaching strategic goals (see previous Table 2).

Finally, the remaining four indicators, PI11, PI43, PI54 PI55, although derived from the previous indicators, introduce some interesting concepts, as per following paragraphs.

As the previous KPIs are apt for evaluating different alternatives during design or redesign or compare different improvement plans (that is, for one-time decision making) indicator PI54 depicts some cases during Operations in which planned energy/resource consumption is computed ex-ante (possibly with the above mentioned top down and bottom up approaches) and then is compared with the actual consumption): this can be easily applied while monitoring a single manufacturing element (machine, component, TBS) in order to spot unexpected behaviours, failures originating waste and the like. Another KPI interesting for Operations, or even when evaluating Continuous improvement plan progress, is PI55 "Target energy consumption for the rest of the period", which identifies the energy consumption target flow until the rest of the decision horizon subtracting to the total energy consumption of the time horizon the actual cumulate energy consumption so far. This indicator can be useful at higher level of the factory for energy management. Finally, PI11 and PI43 can be used for supporting continuous improvement analysis and interventions.

5. Conclusions and future work

This paper has presented a framework for key performance indicators to assist eco-factories' stake-holders in setting and pursuing economic and environmental objectives; in monitoring their achievements; in steering decision making and adoption of corrective actions. The proposed framework is built up on only a few main types of indicators that allow capturing the whole eco-factory performance, from the economic and financial perspective, the environmental perspective and in connection with production performance. The framework has had a first validation by means of a survey performed involving industry experts and academia researchers.

The paper has given a first idea of a possible PMS that enables a systematic and thorough assessment of the behavior of manufacturing systems from a holistic perspective, an assessment from different viewpoints, such as production, economic, environmental, furthermore paving the way to root cause analysis of the system's performances and further improvement opportunities.

The next research steps involve measuring the coverage of the proposed framework with reference to existing indicators' sets, to better evaluate its scope and limitations. In the prosecution of the work, to fully exploit the potential of the framework, allowing benchmarking among different factories, plants, processes etc., additional effort is needed to investigate how the production systems with their valuable output, as well as resources and emissions could be referenced to shared taxonomies and standards in order to set up target values and proper benchmarking approaches.

Further work might research about the opportunity to integrate the input-output schema proposed in this paper with additional elements reflecting internal recovery and/or recycling of energy, resources in general, waste and emissions, and, as well, about the extension of the schema to integrate classes of events that may be set into a cause-effect relationship with the performance of the future sustainable factories.

Acknowledgements

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KPI-repository

2 = KPI can be used properly for this "Factory level"/"Field of Action"/"Objective" of the factory
1 = KPI can be partially used for this "Factory level"/"Field of Action"/"Objective" of the factory (e.g. may be case dependant or also i
0 = KPI can not be used
O = Output flows R= resource flows VR= Valuable resources flows (no wastes)
E = economic / financial flow functions

Reference units	
units	number of processed units (product)
kg	kg of processed materials (product)
m³	m³ of processes materials (product)
€	revenue, TCO or value of processed parts
m²	m² of area (e.g.shopfloor)
h	productive hours, processing hours
m	length of joint
N	strength of joint
a	year/annual

(K)PI-Title		Physical Dimension	What superior objectives are evaluated? KPI framework: Production performance	OI Output Intensity	RI Resource Intensity	RP Resource Productivity	ERE Energy and Res. Efficie	EE Eco-efficiency	Technology specific?	Object of evaluation
Cutting specific energy	PI01	[J/mm³]				1			yes (cutting)	General milling roughing operations
Energy consumption with N2 and MQL as coolant	PI02	[kWh/mm3]				1			yes (cutting)	Machining of the Belly Fairing
energy input of process chain per unit length for joining	PI03	[kWh/m]				1			yes (joining)	considering the process chain and parts of building
energy input of process chain per joining strenght	PI04	[kWh/N]				1			yes (joining)	considering the process chain and parts of building
energy input of process per unit length	PI05	[kWh/m]				1			yes (joining)	joining processes including parts of building
energy input of process per joining strenght	PI06	[kWh/N]				1			yes (joining)	joining process and parts of building
total energy for generative manufacturing	PI07	[kWh/kg]				1			yes (generative)	considering the process chain and parts of building (appl
total energy for generative manufacturing	PI08	[kWh/m³]				1			yes (generative)	considering the process chain and parts of building (appl
Cycle Energy Consumption	PI09	[kWh/cycle]				1			no	Component in a machine (component level)
Energy consumption per part produced	PI10	[kWh/part]				2			no	Component in a machine (component level)
Improvement Potential	PI11	[kWhnew/kWhold]					1		no	Component (component up to building level)
Energy Consumption per machine	PI12	[kWh/Machine]			2	1			no	Machine Level
(Planned) Material transport	PI13	[m] or [#]	1						no	Factory level
(Planned) Setup times	PI14	[h]	1						no	Factory level
(Planned) Overall energy consumption	PI15	[kWh]			2				no	Factory level
Factory Power peak load	PI16	kW			1				no	Factory level
Average Lead time	PI17	[s]. [days]	2						no	Assembly or production lines, job shops etc.
Production volume	PI18	parts/year or kg/year	2	1					no	Assembly or production lines, job shops etc.
Compressed Air/machine	PI20	[m^3/year]			2				no	Assembly or production lines, job shops etc.
HVAC consumption	PI21	[kWh]			2				no	Building
Lighting consumption	PI22	[kWh]			2				no	Building
Energy input per weight	PI24	[kWh/kg]				1			no	process chain
Energy input per revenue	PI25	[kWh/€]				1E			no	process chain
Energy input of factory	PI26	[kWh/m2*a]			1				no	factory
Energy input per revenue	PI27	[kWh/€ * a]				1E			no	factory, line, machine
Energy input of productive hours	PI28	[kWh/ h * a]				1	1		no	factory, line, machine
ECO efficiency	PI29	[kgCO2eq./€TCO * a]						1E	no	value chain, factory
Specific Energy Consumption	PI30	[kWh or MJ /part or kg]				2			no	Factory/Building Level
Overall yearly energy consumption	PI31	[kWh or MJ/year]			2				no	Factory/Building Level
Total cost of Ownership	PI32	[€]			2E				no	Factory/Building Level
Specific Energy Cost	PI33	[€ /part or kg]				2E			no	Factory/Building Level
Energy (or resource) efficiency	PI34	[%]					2		no	Factory/Building Level
Energy input for primary production processes per manufactured unit	PI35	[kWh/manufactured unit]				2			no	production processes (applicable on all factory levels)
Energy input for secondary processes per productive hour	PI36	[kWh/h]			1		1		no	secondary processes, TBS ((applicable on all factory leve
normated total energy costs per year and productive hours	PI37	[€/a*h]			2		1		no	factory, areas, lines
Availability	PI38	[]	2						no	lines, machines
Performance	PI39	[]	2						no	lines, machines, control algorithms, machine cycles
Quality	PI40	[]	2						no	lines, machines, control algorithms, machine cycles
Effectiveness	PI41	[]	2						no	lines, machines
Potential energy saving per part produced	PI43	[kWh/pp]					1		no	lines, machines, non defective part
Coolant consumption per part produced	PI44	[l/pp]				2			no	lines, machines, non defective part
Compressed air consumption per part produced	PI45	[Nm3/pp]				2			no	lines, machines, non defective part
Energy cost per part produced	PI46	[€/pp]				2E			no	factory, areas, lines
Volume of Shielding Gas per Welding Length	PI49	[m³/m]				1			yes (joining)	joining process
Energy for Exhaust per Welding Length	PI50	[kWh/m]				1		1	yes (joining)	joining process
Actual Energy consumption / Planned energy consumption	PI54	[%]			2				no	factory , area, lines, machine
Target energy consumption for the rest of the period	PI55	kWh /month			2				no	factory , area, lines, machine
Avg. Air flow in non-productive times (i.e. leaking)	PI56	[m³/h] or [kW]					1		no	Building, CA distribution system
Pneumatic Energy consumption	PI57	[l/min], [kWh/cycle]			2				no	area, line machine
Variance of Temperature	PI58	[°C]							no	Building, building area
Direct energy allocation to a process/machine per batch during value adding times of a machine	PI59	[Wh/batch/machine]				2	2		no	factory, areas, lines, machines
Direct energy allocation to a process/machine per batch during non value adding times of a machine	PI60	[Wh/batch/machine]				2	2		no	factory, areas, lines, machines
Indirect energy allocation refered to a batch produced on a machine during value adding times	PI61	[Wh/batch/machine]				2	2		no	factory, areas, lines, machines, only TBS and building
Indirect energy allocation refered to a batch produced on a machine during non value adding times	PI62	[Wh/batch/machine]				2	2		no	factory, areas, lines, machines, only TBS and building

Appendix A. KPI survey results