STRUCTURING AND APPLYING PRODUCTION PERFORMANCE INDICATORS

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ABSTRACT

This study presents a methodology for structuring Production Performance Indicators (PPIs) and their application to different production levels. A number of relevant characteristics, such as hierarchical levels and relative stakeholders are proposed and the indicators can be structurally defined through the use of a PPIs' template. Two main types of indicators that involve near to real time metrics and the calculation of future best practices, for various aspects of a manufacturing system, are investigated, while at application level, the study focuses on PPIs related to the automotive industry. The successful definition and application of these indicators improves the transparency and awareness of the current status of different production steps, while the proposed PPI structure, provides a meaningful comparison of the different manufacturing processes, within a manufacturing firm and across company borders.

KEYWORDS

Manufacturing, Production Indicator, KPI, Template, Energy Efficiency

1. DEFINITION OF PRODUCTION PERFORMANCE INDICATORS (PPIS)

Measuring the performance of production systems is essential to every manufacturing enterprise since in order for an activity to be controlled, its efficiency should be measured and although the accuracy of mechanistic or physical measurements has advanced over the last years, measuring manufacturing performance is still a complex matter due to its multi-dimensional nature.

The key performance indicator (KPI), is a number or value, which can be compared against an internal target, or an external ''benchmark'' to give an indication of performance (Ahmad and Dharf, 2002). Performance indicators for the assessment of production performance are an essential requirement. Some of these measures are specific and are related to particular properties of particular production processes (Ahmad and Dharf, 2002).

In general, there are four classes of manufacturing attributes to be measured when a manufacturing system is being monitored: cost, time, quality and flexibility. These depend on the particular problems' specific objectives, the goals, and the criteria. An objective is an attribute to be minimized or maximized. A goal is a target value or range of values for an attribute, and a criterion is an attribute that is evaluated during the process of making a decision (Chryssolouris, 2006).

Although monitoring manufacturing attributes was the main issue in the previous decades, recently special attention has been drawn to Energy Efficiency. The manufacturing industry is one of the main consumers of energy with 31% of the primary energy use and 36% of carbon dioxide (CO2) emissions (International Energy Agency, 2007). The European Commission (2006) had estimated that the energy saving potential for the manufacturing sector was 25% and it had set target objectives for the annual consumption of the primary energy to be reduced by 20% by 2020.

One of the definitions of energy efficiency is: that the goal of efforts reduce the amount of energy, required to provide products and services. Another one is; that the same quality and level of some 'end use' of energy be achieved with a lower level of energy input (Ang, 2007). Of course, every definition also depends on the type or category of energy that is measured. For example, in the Embodied Product Energy framework, the energy consumed by various activities, in a manufacturing system, is categorised into two groups: The Direct and the Indirect Energy. Direct Energy is that used by various processes, required for the manufacturing of a product, whereas Indirect Energy is that consumed by activities (e.g. lighting, heating, ventilation) required for maintaining a standard environment in the plant (Rahimifard et al, 2010).

Three main motivating factors have been identified for the integration of an energy efficiency monitoring and controlling system into manufacturing companies (Bunse et al, 2010):

1. Rising energy prices: Soaring prices of oil and gas as well as ofother fossil fuels, such as coal due to scarcity of the specific resources.
2. New environmental regulations with their associated costs for CO2 emissions.
3. The purchasing behaviour of customers, who prefer more “Green” and energy efficient products and services.

It is evident that the two main goals, concerning Energy Efficiency, are reduction both in energy consumption and in CO2 emissions. There is however, a question that arises when developing an Energy Efficiency monitoring system: what differentiates these objectives from the minimization of cost (economic efficiency) which already exists and what are the relationships between these objectives.

Energy Efficiency is usually measured thermodynamically and therefore, it is considered objectively and with a constant value under the same conditions. That is true if, for example some energy KPI is calculated with the use of a particular thermodynamic formula, however, it is in contrast to the energy efficiency measures that incorporate economic units, which change as the economic environment changes and hence so do the fuel prices. However, it could be argued that an indicator of purely economic measurements is not really an indicator of energy efficiency. It can mostly be seen as an economic efficiency indicator, since it is “fully enumerated in economic value terms”, and is therefore, dismissed as a measure of energy efficiency (Patterson, 1996).

It is clear that a measurement system for the assessment of a plant’s Energy Efficiency and manufacturing processes, would require quantitative indicators of both energy efficiency and manufacturing performance. Therefore, a new type of indicator should be utilized that could be used for measuring energy consumption, costs etc. as well as production performance at the same time.

In this document, the term PPI (Production Performance Indicator) is introduced, which is *an indicator using historical energy and production related data, near real-time monitoring data and is used for the calculation and prediction of various production related metrics. Some PPIs are used for optimising the production, whilst others for constructing optimisation objectives* (Figure 1).

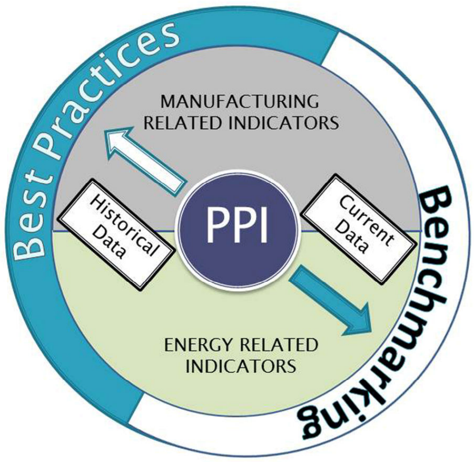

Figure 1-PPI definition

2. DESCRIPTION OF PPIS THROUGH A COMMON TEMPLATE

To ensure that the PPIs can be used for a meaningful comparison of different manufacturing processes within the same manufacturing firm, a common communication vessel must be established. The main characteristics of all the PPIs should be included in their description along with the ways they are interrelated. Furthermore, the template should include all the necessary information so that the PPIs could be used by quantitative tools for analysing complex systems for optimization, simulation etc.

The characteristics chosen for the formation of the template can be seen below:

- Index number: By having index numbers attached to PPIs, it will be easier to describe the interrelationships between them.
- Category: The categories will be Cost, Time, Quality, Flexibility and Reliability. In the case of energy related PPIs, they will be described through cost since most of the industries are concerned with energy only through cost deployment.
- Sector: In the sector column, the production sector that the PPI applies to will be specified (manufacturing, maintenance etc.).
- Name: The name of the PPI as a periphrasis (e.g. Mean Time Between Failure).
- Acronym/Symbol: The acronym or symbol of the PPI (e.g. MTBF).
- Formula: The calculation formula of the indicator with an explanation of the variables and their units, if required.
- Data Source Type: The type of the source that the data will be acquired from (Sensor, MES system etc.).
- Unit: The units of the indicator. In case of percentages the per cent sign (%) should be used.
- Relations: The relevant PPIs in terms of input and output to the described PPI. For the relations the index number of the PPIs should be used (e.g. OUT:3, IN: 4,7 which means that the PPI receives data from PPIs 4 and 7 and gives data to PPI 3).
- Event Type: The type of the event of the PPI regarding the timestamps of the event. The values are periodic and non-periodic. For example in domains such as temperature, where events "happen" between standard time frames, the periodic value is inserted.
- Target: The target value of the PPI. When the target value of a PPI is calculated from other PPIs, the index number of that PPI will be used (e.g. IN: 5, meaning that the number 5 PPI is used for calculating the target value of the current PPI). BEST LOW or BEST HIGH phrases will be used to denoting that the PPI's value should be either as low as possible or as high as possible respectively.
- Level: The hierarchical level that the PPI corresponds to.

3. IDENTIFICATION OF PRODUCTION PERFORMANCE INDICATORS

3.1. MANUFACTURING SYSTEM ANALYSIS METHODS FOR THE IDENTIFICATION OF KPIS

When implementing a Manufacturing Execution System (MES), diagnosing a disorder, concerning material or information flow or when changing a manufacturing process for improving performance, a manufacturing analysis through modelling methods is mandatory in order for decisions to be taken (Vernadat, 2002).

A number of techniques exist to support the manufacturing systems analysis (IDEF, simulation, Petri Nets etc.). In (Hernandez-Matias et al, 2008) a modelling framework was developed, called Production and Quality Activity Model (PQAM) which integrated hierarchy, database and performance indicators. The four components that the framework is comprised of are; the reference information model (a reference for structuring and classifying information), the quantitative and qualitative IDEF0 model (which is used for compiling all the information of the manufacturing system), the manufacturing data-warehouse (storage of all the information required for system diagnosis) and the evaluation methods for the support of decision-making issues. The component most valuable for the identification of KPIs is the reference information model, which uses analytic hierarchical process (AHP) for linking activities. This component is comprised of subsystems, the third of which associates quantitative or qualitative information with the activities. In the subsystem, there are five types of information objects with a specific library of attributes. These are activity data, material input, material output and resource and improvements data. In (Sénéchal and Tahon, 1998) the authors present another modelling method that can be applied to manufacturing systems. This approach is based on modelling a manufacturing system from two points of view, the functional and the physical. Based on the functional view, the system is described through its processes, while when it based on the physical view, it is described on a descending analysis of the resources. The decomposition of the processes of the functional analysis stops when the activities can be associated with the physical elements (Figure 2).

In (Lee et al, 2011) indicators are developed regarding the performance of multiple manufacturing partners on the basis of the Supply Chain Operations Reference (SCOR) model. The

SCOR model provides a reference of supply chain processes and the metrics, whilst through the identification of the processes and their metrics the KPIs can be identified and developed

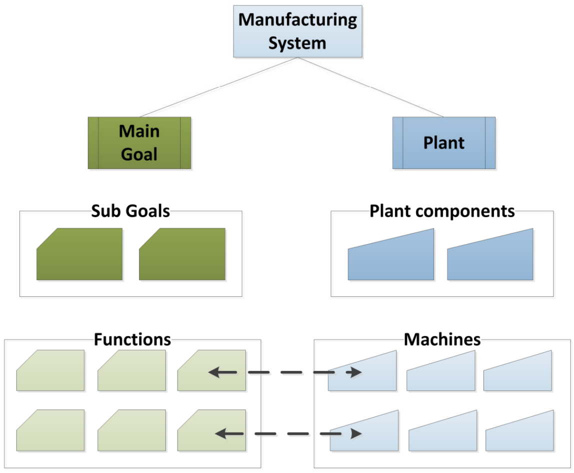

Figure 2 – Physical-Functional decomposition

through a table with the following consecutive columns; the Process of relevant SCOR Level, the relevant metric; the derived KPI; KPI definition; and the equation. Also, in (Cai et al, 2009) the authors stated that given the complexity of supply chains, a process-oriented SCOR model was the top solution for the identification of the basic performance measures and their KPIs. In practice, most of the KPIs, in a supply chain, are correlated and have cause–effect relationships. For that reason, the KPIs that have high correlations with each other have to be identified together with the nature of their relationship. The relationships among the KPIs are classified by the authors into three categories: parallel, sequential and coupled.

3.2 PROPOSED METHOD FOR THE IDENTIFICATION OF KPIS

It has become obvious that for a thorough analysis of a manufacturing system and the identification of the necessary indicators a combined methodology should be utilised. The identification of the necessary components of the methodology can be made through the fulfilment of certain requirements, regarding the analysis, namely:

- Association of manufacturing goals with KPIs.
- Link of KPIs to monitored system's components.
- Identification of relations between the KPIs.
- KPIs association with the system's hierarchy levels.

A kind of comparison among the different methodologies can be seen in the table below:

Table 1- Modeling methods Vs. Requirements

Requirem. / Methods	Manuf. goals to KPIs	KPIs to system links	KPIs' relations	Hierarchy Levels
PQAM (reference information model)	√	√	X	√
Physical-functional analysis	X	X	X	√
SCOR applied to a production system	√	X	√	√

As seen in Table 1, none of the modelling methods fulfils all the requirements, which means that none of them can be used as is. Beyond the requirements' fulfilment, the modelling methods have advantages and disadvantages or a kind of adjustability not described in the table. For example, although the physical-functional analysis only satisfies one requirement, if the functions are replaced by KPIs, derived from the goals, it will come closer to the PQAM and meet the first two. Furthermore, the KPI's relations of the SCOR models can be integrated into the combined method so as to have a clear view of their relations.

The proposed method, regarding the analysis of manufacturing systems, for the identification of PPIs, should combine all the advantages of the methods, described in the previous section. The method has four steps, which use different components to accomplish a system's thorough and precise analysis, to identify PPIs and define them. The steps are described below:

1. Analysis of the physical elements (in respect to the hierarchical levels of the system) and description of the respective activities (Figure 3).

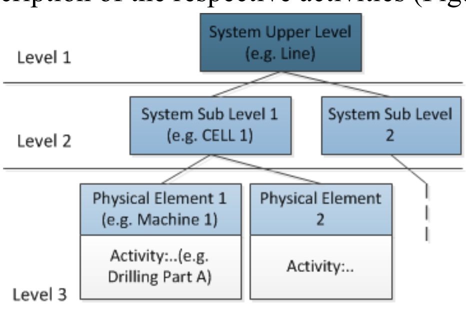

Figure 3 – Physical elements analysis

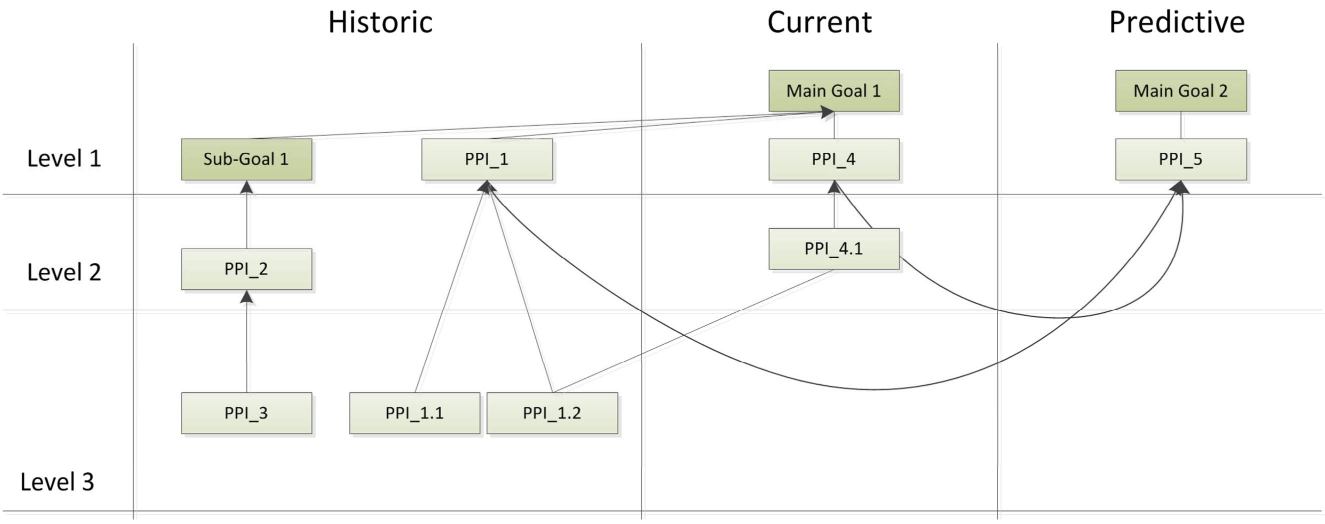

Figure 4 – Goals to PPIs expansion and PPIs' relations

The description of the respective activities can help with the definition of the low level PPIs.

2. Goals placement and expansion to desired PPIs. The goals are vertically placed with respect to the corresponding level and horizontally with respect to the time frame they refer to (Historical, Current and Predictive/ Future information). This way it becomes easier to perceive which PPI refers to which element or activity.
3. Identification of the PPIs' correlations and visual representation as shown in Figure 4. The connections of the PPIs will also reveal any causal relationships. Arrows are used (e.g. PPI_1.2 to PPI_1) to representing computational relationships, while plain lines represent causal relationships, which do not correspond to the quantity associations between them.
4. Organization of PPIs in a PPIs template.

The process described does not necessarily have a straightforward progression. Since every step describes the analysis of a system from a different point of view, gaps that could not be perceived from a previous step can become apparent at any time. Therefore, the process becomes iterative until all PPIs are properly described through the PPIs template and all three steps have been completed for the system.

4. CASE STUDY

To demonstrate the new developments in the method of analysis and the use of the PPIs template, a case study was carried out with requirements, provided by a European automotive company.

4.1 REQUIREMENTS GATHERING AND INTERPRETATION INTO PPIS

The requirements concern a machining line, which comprises four main stations of machining tools connected through gantries. The machines are also connected to a number of necessary support systems, including those of cutting fluid, compressed air, etc. and a central HVAC system. The energy use is 50% for process equipment and 50% for support systems. The main requirement is the low level monitoring of energy consumption of the main equipment and the support systems and the every-day assessment against best practices. The energy consumption should be deployed to cost in order to provide a full assessment of the factory's energy efficiency.

Through the first step, described in section 3.2, the physical elements of the line were positioned at three hierarchical levels accordingly (Production Line, Station and Machine) with the HVAC being on the top level, the Stations in the middle level and the machines and gantries together with their activities at the bottom level.

Following steps 2 and 3, the requirements were placed on the top level and expanded to the required PPIs and metrics (Figure 5). The PPIs highlighted in green are the ones that require "real time" data acquisition (i.e. sensors) and can be spotted since they are (a) in the "Current" time frame and (b) at the bottom of the PPIs connections (don't receive input from other PPIs). All the other PPIs are calculated or originate from them. The three main types of PPIs that were defined are:

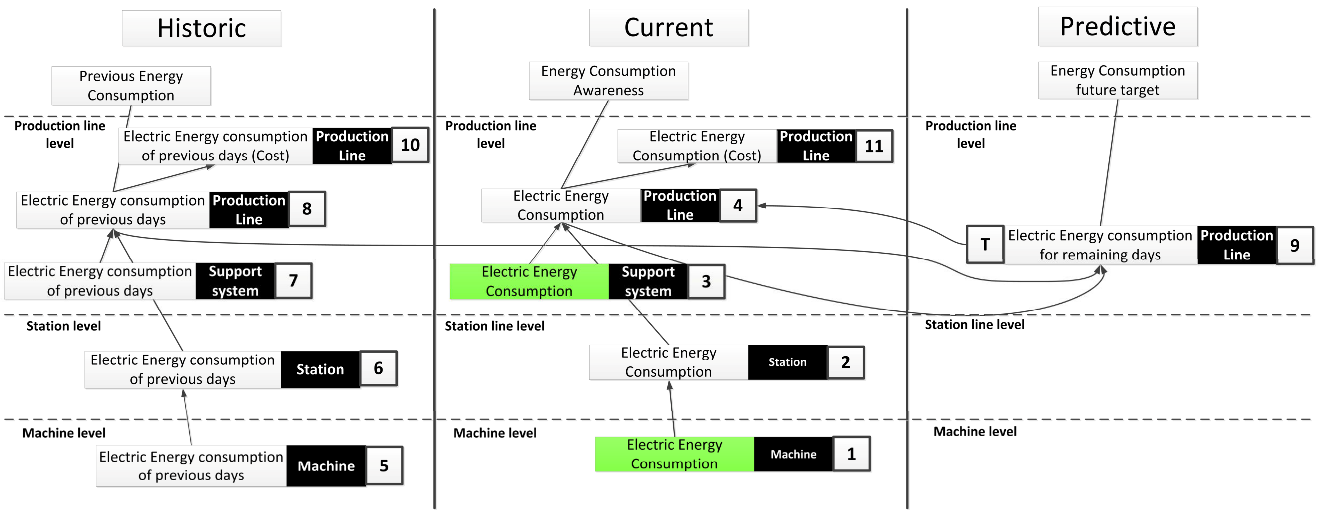

Figure 5: Case study's goals to PPIs expansion and PPIs' relations

Electric Energy Consumption of previous days: This PPI is placed in the historic time frame and is used to extracting the necessary knowledge, regarding the energy consumption of the previous days.

Electric Energy Consumption: This PPI is used to monitoring the energy consumption on a daily basis.

$$EE_C = \frac{\sum_{i=1}^{k} W_i T_C}{n}(KWh) \qquad (1)$$

Where

i Number of instance when power measurements are taken

k Number of measurements

W_i Power measurement at i instance

T_C Constant time interval of measurements in hours

n Number of products produced that day

Electric Energy consumption for the remaining days: the average energy consumption for the remaining days of the year. It can be used in order to benchmark the electric energy consumption that the line should have for the remaining days of a year by using data from the Electric Energy Consumption of the previous days and the goal of energy consumption for that year.

$$E_d = \frac{E_y - \sum_{i=1}^{k} EE_{Ci}}{k_T - k}(KWh) \qquad (2)$$

Where

i Number of day

k_T Total number of days that production is scheduled for the current year

k Number of the days passed in the current year

E_y Energy consumption goal for the current year

EE_{Ci} Energy consumption of day number i

In Figure 5, all the relations between the PPIs can be set up and get transferred to the Relations column of the template. The PPIs of the same name that have different hierarchy stamps (machine, station etc.) are calculated through the sum of all the other ones below them. For example, PPI 2 is calculated through the sum of PPI 1 for all the machines and PPI 4 is calculated through the sum of all the PPI 2 values of all stations, plus PPI 3 which is for the support systems. As an example of the way the indicators are organized in the template, two of them are presented in Table 2.

5. CONCLUSIONS

In this paper, a methodology for identifying and structuring performance indicators for manufacturing systems was presented. The methodology was based on existing methods, which were connected and expanded sequentially. At the

Table 2 – Example of PPIs' organization into the PPIs template

No.	Cate-gory	Sector	Name	Acronym/ Symbol	Formula	Data source type	Unit	Rela-tions	Event Type	Target	Level
1	Cost	Manuf.	Electric Energy Consump. per Unit (machine)	EE_C	$EE_C = \frac{\sum_{i=1}^{k} W_i T_C}{n}$	Sensor	KWh/ unit	OUT:2	periodic	IN:9 (BEST LOW)	Machine
9	Cost	Manuf.	Average Energy Consump. for remaining days	EE_P	$E_d = \frac{E_y - \sum_{i=1}^{k} EE_{Ci}}{k_T - k}$	Central data repository	KWh/ unit	IN:4,8 OUT:1 (target)	periodic	-	Line

end of the described process, all the PPIs are stored into a PPIs template, which is useful for conveying them into event processing and general monitoring systems. The methodology was applied to an automotive industrial use case through the acquisition of industrial requirements, which concern most of the firms in the manufacturing domain.

The effort made for the work prepared and presented in this paper was in order to establish a common knowledge model, concerning the description of production indicators. Further work will be carried out and will be culminated with a more descriptive model of knowledge indicators that will be presented in future papers and a possible integration with an indicator's framework.

6. ACKNOWLEDGMENTS

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