A Multi-Perspective Performance Approach for Complex Manufacturing Environments

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Abstract. Complexity in manufacturing systems appears under a variety of aspects, namely product, processes and operations and systems. Considering that the manufacturing environment is rapidly and constantly changing, with higher levels of customization and complexity, there is higher demand for flexibility and adaptability from companies. In this context, it seems essential to explore new approaches that can support decision-makers to take better decisions concerning the action plans that they need to launch to achieve the expected strategic and operational performance and alignment goals. Companies should become able to analyse their performance drivers, understand their meaning and the feedback loops that affect them. Therefore, decision makers can look into the future, and act even before these causes affect the transformation systems efficiency and effectiveness. This paper presents an approach oriented to multi-performance measurement in complex manufacturing environments. With this approach it is expected to overcome the gap between the operational and strategic layers of a manufacturing system, in order to reduce time when measuring performance and reacting to unexpected behaviours, as well as reduce errors when taking decisions. Moreover, it is expected to decrease the time necessary to calculate an indicator or to introduce a new one into performance management process, reducing the operational costs.

Keywords. Performance measurement, Complex manufacturing, Proactive behavior, KPI, Key performance indicator, Semantic interoperability, Ontology.

1 Introduction

1.1 Problem Framing

Due to the increasing globalisation process and the current economic situation, the power has shifted from the producer to the costumer, forcing companies to become more aware of the market needs (Wortmann, 1997; de Ron, 1998; Chen, 2008, Hedaa, 2005; Heinonen, 2010). Consequently, aiming to succeed in competitive environments, where all competitors have similar opportunities and surgical improvements can present important competitive advantages, the challenge is to develop solutions capable of supporting companies so that they can continuously improve their core processes in a proactive way, aligning, from the beginning, their behaviour with their goals (Almeida et al., 2012). Only this way can companies become more flexible, manage shorter product life cycles and thus, satisfy their customers by continuously adapting themselves to meet the needs and expectations of the market (Yusuf et al., 2004).

It is recognized that fulfilling the company's strategy implies the capacity of identifying and designing their key business processes, and namely establishing the main multi-perspective objectives for these processes as well as the related key performance indicators (KPIs) and metrics to assess if the objectives are being achieved (Feurer, 1995; Neely et al., 2001; Neely, 2007). It is important to highlight that, the multi-perspective concept in the performance management scope means the capability to assess not only the effectiveness at the end of the process, but also the efficiency and relevance along the entire process execution (Marques et al. 2011; Lauras et al. 2010).

Moreover, in order to become proactive instead of remaining reactive, companies must decrease their reaction time in order to find and solve process bottlenecks in the shortest amount of time possible and thus remain resilient and competitive (Sheffi 2005, Lohman, Fortuin et al. 2002). Hence, companies should explore new solutions that allow them to collect and manipulate data from the shop floor and, consequently, support them so that they can promote a holistic performance monitoring approach capable of measuring performance with high granularity, and identify the causes that are affecting or will have an impact on the system's performance (Gimbert, Bisbe, Mendoza 2010).

However, within complex manufacturing systems, meeting the challenges proposed is not a trivial task due to a number of factors. Firstly, complex systems are by definition environments whose behaviour arises from the interactions (feedbacks) between the different components of the system, and not from the complexity of the components themselves. Therefore, within a complex manufacturing system, there are immense ranges of different feedback processes that interact with each other, as well as different stakeholders with their specific objectives, which may result in paradoxical behaviours. Therefore, it is essential to understand each of the different feedback loops and manage the different strategic objectives in order to assess the dynamics of the global manufacturing systems (Sterman, 2000).

Another difficulty arises from the fact that technology infrastructures make it difficult to obtain the right information to calculate KPIs (Richtermeyer and Webb, 2010). In order to overcome this, companies have sophisticated enterprise systems or extensive legacy systems that can measure operational performance. However, the technology available may make it either too expensive or time-consuming to access the data required for effective performance measurement, and this is due to the complex and sophisticated nature of these systems.

This fact has led to another obstacle, which is the gap between the strategic and operational layers of an organisation. In fact, since decision-makers deeply depend on the performance data extracted from the shop floor and, since they normally are not able to get the data by themselves, it is possible to observe a critical misalignment between strategic and operational layers. In line with this, it is important to explore how to enhance the interoperability between the strategic and operational layers of a manufacturing system. Interoperability is a property of a system, whose interfaces are completely understood, to interact with other systems without any unexpected restricted access or implementation effort. Thus, interoperability should be seen as a key driver for an effective performance management, once it will facilitate the data flow between legacy systems and, consequently, its transformation into information.

Currently, this gap is a critical bottleneck for the reaction time of the company and consequently it prevents companies from acting in a more proactive way.

1.2 Research Objectives

This research aims at improving knowledge and insights on the performance measurement and management area, mainly as part of complex manufacturing environments. In line with this, one of our objectives is to formalize a performance measurement and management reference data model addressing the requirements of complex manufacturing environments and addressing the interoperability issues between the strategic and operational dimensions layers.

Moreover, contemporary decision-makers require a small number of key variables capable of representing a large quantity of information, in a synthesised way, in order to visualise the global system behaviour, identify the causes and take the important decisions in a proactive way. Therefore, it is essential to promote a platform capable of building and maintaining rich and powerful KPIs, in a collaborative way, making it possible not only to assess, but also to drill down a performance disturbance with high resolution. Similarly to the image resolution concept, in our context, high resolution means the ability to increase the level of detail of a manufacturing system's performance picture.

The questions leading this research are the following:

> *Q1 - How should the reference data model be for a proactive performance measurement approach?*

This research question aims at exploring a reference data model for performance measurement that allow companies not only to store performance data, and assessing it taking as reference the strategic goals of the company, but also to share this information with other legacy systems, and make it comprehensible both for machines and humans.

Hence, since issues related to strategic performance data interoperability are still an open subject, this research question aims at exploring an innovative solution based on a semantics approach capable not only of storing information in a structured and formalised way, but also of collecting, combining and inferring knowledge.

> *Q2 – How should the structure of a KPI be and what should be the level of detail of a performance measurement system?*

This research question intends to explore a new approach that supports decision-makers decreasing the number of indicators but maintaining the ability to assess the performance of their manufacturing systems from different perspectives, due to the capability of formalizing aggregated KPIs. With these metrics it should be possible to combine different types of leading factors, from different feedback loops, that can be easily analysed and understood in order to extract the most meaningful information from the performance data, and thus detect critical bottlenecks even before the respective core objectives are affected.

> *Q3 - How should the production system's raw data be fused and related in order to achieve a high-resolution performance measurement in complex manufacturing systems?*

The aim of this research question is to investigate how the architecture of a dynamic performance measurement system should be, capable of integrating not only the raw data existing in the different data sources, but also combining this with the production system's tactical data and information related with the organization strategy. The idea is to present a solution capable of providing performance measurements with high levels of granularity, that can be adjusted for the different stakeholders belonging to different hierarchical layers of the organisation.

The article is organised as follows: the next section presents the literature review and research development that supports this research work. Next, the reference data model for an innovative and integrated strategic performance management approach will be presented. This section is very important since at this stage it will be explored how strategic, tactical and operational data should be structured in order to become comprehensible and reusable by different tools and people. The fourth section will explain the developed platform architecture and its main technical details. Here, a special sub-section is presented dedicated to knowledge database querying and updating process. In order to explain the importance of this performance measurement and management approach in the industry, the implementation efforts performed within a real test case will be documented in the Experiments and Results section. We conclude with a discussion of results achieved, limitations and the conclusions.

2 Literature Review and Research Development

This section provides a review of the literature on performance information, as a key driver for innovation, improvements, and the impact of the performance management systems for the total quality management era. Moreover, since this is an issue that has been broadly explored as a result of the continuously necessity to align the performance management discipline with the organisation's strategy, during this section it will be detailed both the concepts and functionalities explored and defined in the literature that are suitable for proper strategic performance management systems.

2.1 Information Feedback as Key Driver

In 1958 Forrester, founder of the System Dynamics approach for complex and dynamic systems, stated that management was on the verge of a major breakthrough in understanding how industrial company success depends on the interaction between the flows of information, materials, money, manpower, and capital equipment (Forrester, 1958).

Within a complex manufacturing system this is neither a simple nor a straightforward task to be accomplished. In fact, due to the increased intricate relationships and interrelations among the system's elements, characteristic from complex manufacturing systems, along with the stochastic and non-linear nature of the system, characterized by unpredictability, make the system management more and more complex. In line with this, its management critically dependents on the decision makers capability to model the system behaviour, extract the correct information from the real system and, from the merging between model and data, to build his own mind-set about present and future behaviours (McCarthy, Rakotobe-Joel, & Frizelle, 2000). Moreover, this should be seen as a continuous activity, with which decision-makers are capable to maintain their knowledge on the manufacturing system, even when the system's behaviour continually changes.

It is becoming clear that, in order to setup the right measures and the correct analysing methods, aiming to study the manufacturing complexity, it is no longer feasible to simply rely only on the existing traditional approaches (Efthymiou, Pagoropoulos, Papakostas, Mourtzis, & Chryssolouris, 2012). In fact, as systems become more and more sophisticated, in terms of information processing, also the capability to link one form of feedback with future events will be enhanced. From this advantage, it is possible to accumulate experience about every kind of feedback. In fact, this type of information, if well structured and formalized, can be seen as the main pillars of a complex manufacturing model capable to support decision makers to foresee and anticipate decisions in a proactive way. In the scope of these approaches, the information continuously obtained through feedback loops from the system, represents a critical advantage, being seen as a key driver for the complexity analysis of a manufacturing system.

2.2 Strategic Objectives and Operational Performance Alignment

A Performance Measurement System (PMS) aims to support decision-makers by gathering, processing and analysing quantified information on performance and presenting it in a succinct format (Neely, Gregory, & Platts, 2005) (Garengo, Biazzo, & Bititci, 2005). By definition, all performance measurement systems consist of a number of individual performance measures, which can be categorized in different ways, ranging from Kaplan and Norton's (1992) balanced scorecard, Bititci's Integrated Performance Measurement Systems (Bitici et al., 1997) and Lynch's Performance Pyramid Systems (Neely et al., 2000).

Each of these PMS models can be categorized as vertical, balanced and horizontal (De Toni & Tonchia, 2001). Vertical architectures are defined as models that are strictly hierarchical (or strictly vertical), characterized by cost and non-cost performances on different levels of aggregation, until they ultimately become economic-financial. On the other hand, balanced architectures are models where several separate perspectives (financial, internal business processes, customers, learning/growth) are considered independently. Finally, horizontal architectures, also known as by process, are models strictly focused on the value chain and on the internal relationship of customer/supplier.

However, despite the differences between the PMS models previously described, the rationale behind a performance measurement system implementation is that performance measures used need to be aligned with the strategic vision of the organization, as they define the metric used to quantify the efficiency and/or effectiveness of an action. On the other hand, performance measurement may be seen as the standardized process of quantification by which it is expected to stimulate actions and influence people behaviour. Indeed, as pointed out by Mintzberg (1978), it is only through consistency of action that strategies are realized. Finally, a performance measurement system should be seen as the set of metrics used to quantify, in a multi-perspective way, the efficiency and effectiveness of performance of actions.

In line with this vision, Meyer (Meyer, 2002) proposed that performance measures could have seven different purposes. In terms of the time dimension, a measure could either look back (lagging indicator) or look forward (leading indicator). From the organisational perspective, a measure could be summed from the bottom to the top of the company to allow a clear visible linkage between the unit performance and the organisational performance. Likewise, it could cascade down from the centre to individual operating units. It could also be used for performance comparisons among horizontal operating units across the company to facilitate performance comparison. Finally, from the human perspective, a measure could be used for motivational and compensation needs. In the context of manufacturing systems, all seven purposes are required from the operational and control point of view.

In sum, a successful and effective performance measurement system implementation may lead to more than query and reporting capabilities. On the other hand, the purpose of performance management is not just managing but improving performance.

Based on these perspectives, it is important to highlight that when one is specifying a PMS to certain manufacturing system, the rationale behind the methodology applied must be composed by three main stages, as depicted in figure 1 (Neely et al., 2005):

- Analysis of the relationship between the performance measurement system and the environment within which it will operate;
- Specification of the set of performance measures and their relationships – the performance measurement system as an entity;
- And finally the specification of individual performance measures.

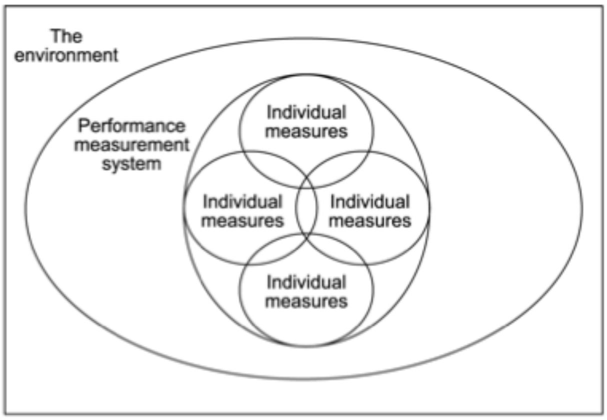

Fig. 1. A Framework for Performance Measurement System Design (Neely et al., 2005)

2.3 Multi-Perspective Performance Measurement

The most significant criticism of the traditional PMSs is the fact that they strictly focus on financial measures. However, as already explained, balanced models (also called multidimensional or multi perspective models) should be explored in order to enhance performance measurement systems with different perspectives of analysis, aiming to manage them in a coordinated way (Chenhall & Langfield-Smith, 2007; Garengo et al., 2005; Lauras, Marques, & Gourc, 2010).

Actually, the innovations in information technology and systems have made it easier to gather and elaborate large amounts of data at a lower cost. Since the dissemination of new managerial concepts and paradigms such as JIT, TQM and others, the role of short-term financial measures within current performance measurement systems is critically impaired. Indeed, the decreased reliance on direct labour, increased capital intensity and increased contribution made by intellectual capital and other intangible resources made it invalid to rely on traditional methods of matching revenue to costs (profit analysis) as a measure of performance. Therefore, it is proposed that a selection of non-financial indicators should be employed in contemporary performance measurement systems, based on the organization's strategy, as well as including measures of manufacturing, marketing and research and also growth and development (Parmenter, 2009).

Dossi and Patelli (2010) underline that against pure financial indicators, non-financial indicators are more forward-looking, better able to predict future performance and more adequate to measure intangible assets. Moreover, in this paper authors studied the importance of non-financial indicators in the creation of strategic alignment within international organisations. According to these authors, when performance measurement systems are empowered with non-financial indicators, these become powerful strategy tools, mainly because they contribute towards the achievement of all strategic objectives defined, through three mechanisms: (i) a better understanding of the linkages between various strategic priorities; (ii) more effective communication of the association between objectives and actions; and (iii) more efficient allocation of resources and tasks.

As previously explained, the 1980s were strongly marked for the rise in the popularity of the "quality gurus", resulting in a resurgence of interest in the measurement of operations performance, especially in terms of the three main clusters: efficiency, effectiveness and relevance. As depicted in the performance triptych (figure 2), the effectiveness assesses whether the output of the process meets the goals for which it was created. Efficiency expresses whether the resources have been used properly to attain the results. Lastly, relevance assess if the means suit the objectives (Marques, Gourc, & Lauras, 2011). This way, it is possible to define a series of indicator types to assess performance from different perspectives, aiming to achieve an optimum balance in the quality, dependability, speed, cost and flexibility dimensions. By taking a number of variables from each of the five dimensions and attributing a weight to each of them it is possible to create a new global and aggregated KPI capable of evaluating the production system according to the expected behaviour, trade-offs and priorities related with the decision-maker's strategy.

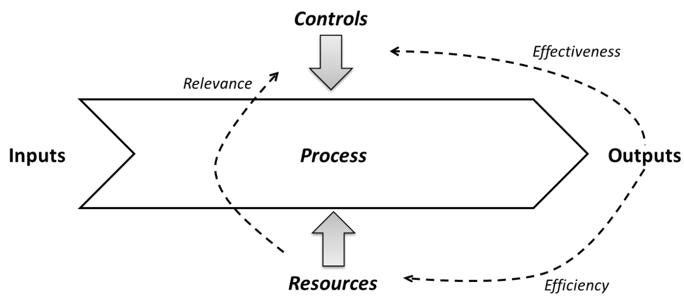

Fig. 2. Performance Triptych (Lauras et al., 2010)

2.4 Dynamic Adaptability

A performance measurement system should include systems for reviewing measures and objectives that make it possible both to adapt the PMS quickly to the changes in the internal and external contexts, and systematically to assess a company's strategy in order to support continuous improvement. Many scholars have studied and defined the dynamic approach (Bititci, Turner, & Begemann, 2000).

2.5 Process Oriented

Performance measurement systems have been explored for a long time. Initially, the most popular measurement system was the so-called DuPont scheme, introduced in 1919 by the DuPont company. However, during the following years the situation changed significantly. In fact, since then it has been observed a considerable evolution concerning performance management approaches, once these are becoming more process-oriented, involving not only decision makers but also process actors (Tupa, 2010).

In general, a process oriented performance measurement system can be seen as an information system that supports organizations so that they can visualize and continuously improve processes performance, controlling its execution by comparing process models with data collected (Kueng & Krahn, 1999).

Due to the fact that more and more process performance management tools and methodologies are considered as being essential for enterprises continuous improvement, new approaches have been developed such as: self-assessments, quality awards, benchmarking, activity-based costing, capability maturity model, balanced scorecard and workflow-based monitoring (Kueng & Krahn, 1999; Melchert & Winter, 2004).

2.6 Causal Relationship

Many scholars have written about the causal relationship between results and their determinants in performance measurement. Kaplan and Norton (1996) underline that identifying a causal relationship between performance indicators and objectives supports the strategy review and learning. Since performance measurement is supposed to support planning and control, a PMS should measure not only the results, but also their determinants and quantify the 'causal relationship' between results and determinants in order to help monitor past actions and the improvement process (Bititci et al., 2000; Neely et al., 2000).

Suwignjo et al. (2000) have analysed different techniques to analyse the relationship between results and determinants, such as cognitive maps, cause and effect diagrams, tree diagrams and analytic hierarchy processes. All these methods can introduce critical advantages when managing and controlling performance.

3 Multi-Perspective Performance Measurement Approach

3.1 Linking Performance Management to Strategy Vision

There is general consensus that, only linking strategic and operational performance, it is possible to improve the overall organizational performance. Despite the fact that strategy and operations are two different and sometimes not associated perspectives, when they are properly aligned the plant is more likely to achieve specific performance goals. Both strategic and operational levels of a manufacturing organization can be defined in terms of the customer-product-process-resource (CPPR) approach (Martinez-Olvera, 2010). In the scope of this model, the strategic perspective of a manufacturing enterprise corresponds to the customer level while the operational perspective corresponds to the process level.

However, in order to approximate both perspectives, a strategic performance management system, covering the entire system's life cycle, should be explored, aiming to link the plant's strategy for the market and operations floor. As inspiration, a strategy management cycle depicted in figure 3 and developed by Morita et al. (Morita, Ochiai, & Flynn, 2011) was used. This model proposes that, initially organizations must clearly define their business opportunity as well as establish their vision about the goals to be achieved. Following, the strategy should be designed, capable to support the organization to achieve the goals defined before. Defined the goals and the strategy, initiatives and operational processes must be designed, in order to materialize and implement the strategy defined. Finally, it is necessary to use a feedback closed-loop approach, capable to measure if the operational layer is satisfying the organizational vision. Indeed, for a performance measure to be considered as a Key Performance Indicator (KPI), it has to be linked to one or more of the organizational critical success factors, more than one balanced scorecard perspective and more than one organization's strategic objectives.

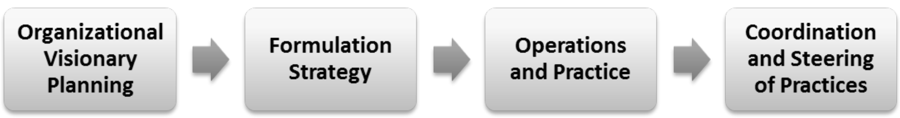

Fig. 3. Strategic Performance Management Cycle

Currently, one of the important paradigms explored within the industrial management scope is strictly related with the idea that a factory is simply a very complex type of product (Jovane, Westkämper, & Williams, 2009), called "Factory as a Product". This innovative way of seeing a factory defines that a factory should be compared with a very complex product, with its own structured and complex life cycle. This means that, similarly to the product development process, factories have to be permanently adapted for changing products, markets and technologies in order to fulfil economic, social and ecologic requirements (Constantinescu & Westkämper, 2010). However, this new kind of product itself is responsible for the manufacturing of other products with a shorter lifetime under the constraint of an ongoing operational, tactical and strategically change and the required adaption to it. Within such an approach is referred as Unified and Sustainable Life Cycles Management and envisions an orchestration or harmonization of the specific life phases of products, production systems and corresponding design methodologies.

Consequently, aiming to explore this paradigm, as well as guarantee the alignment between product and factory life cycles, a functional modelling approach from product design was adapted (Almeida et al., 2012; Jufer et al., 2012; Politze et al., 2010) aiming to model the strategic goals of a factory, called Function Oriented Product Descriptions (FOPD). The FOPD constitutes an approach that combines a requirements model and a functional model. In general, the modelling includes three main steps:

1. Firstly, a functional requirement has to be defined and formulated. By strictly following the rule that it has to be derived from higher goals, a specific stakeholder vision and/or the mission of the company, the rationale behind each functional requirement is captured and may be used later to justify each of the company goals.
2. In a second step, one or several selected KPI that are seen as suitable to assess the intention that stands behind a functional requirement are mapped to them.
3. Finally, a target or reference value has to be provided by the management. This value indicates the intended grade of target achievement and assures its measurability. Moreover, dynamic adjustments may be scheduled which have a direct impact on the target values and allows a dynamic adaptation of the factory goals.

In line with the FOPD paradigm, strategic plans should involve the vision, the mission, the guiding principles and the goals for the business. Therefore, when specifying a manufacturing system, at the strategic level, it is important to define not only the functional requirements, defining the specific behaviours or functions, but also the KPIs that will evaluate these objectives. On the other hand, a tactical plan focuses on methods and processes that support organizations to achieve their strategic goals. Then, at the tactical layer, it is necessary to define the non-functional requirements that specify the criteria that can be used to judge the operation of a system. Finally, the technical layer establishes the connection between the tactical and operational layer in order to define the most granular and detailed production planning.

3.2 Real-Time Performance Measurement and Assessment

As stated by several authors, traditional performance measurement and management approaches are considered unsuccessful, since they mainly use performance data that are extracted after a long feedback period (Figure 4), and only after this time frame – Tf – can the data be analysed in order to promote improvement actions for the next period (Braz, Scavarda, & Martins, 2011; Lohman, Fortuin, & Wouters, 2002). This means that, according to the current approaches, the reaction time is conditioned and increased by feedback and improvement periods. Because of this reason, this approach is no longer suitable. In fact, since the reaction time available is decreasing significantly, if organizations make decisions based on facts that happened on a previous Tf, they are not only losing opportunities during the time in which the problem really occurs until it is identified and solved, but they are also propagating the problem during a Tf, which can definitely compromise the achievement of strategic goals because the time available to achieve the operational excellence is limited (Chen, 2008).

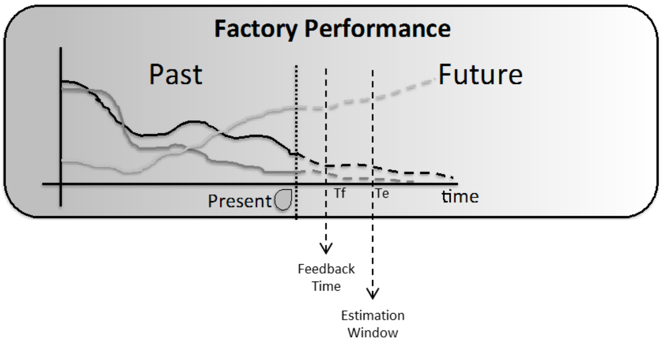

Fig. 4. Performance Management - Time Analysis

Since it is not possible to manage a system if its performance cannot be measured continuously during its entire life cycle, it is necessary to explore a flexible and agile performance measurement and management systems capable to overcome the gaps identified before (Bititci et al., 2000; Braz et al., 2011). Designing a performance measurement model involves a series of important decisions and considerations that should be taken into account since the design stage of the performance measurement system architecture. This means that issues such as the meaning of the measurement, the domain of the calculation and its multi-scale structure, the frequency of the measurement and the source of the data should be considered (Braz et al., 2011).

Based on this premise, Figure 5 presents the main steps of our methodology for a successful performance measurement system implementation, from production network to its locations and sites. Initially, the domain of calculation should be well defined. This means that the boundaries of the system to be managed should be well defined as well as the components of the system that will be controlled and measured individually. Defined the domain of calculation, following, the static assumptions characteristics from this domain should be enumerated and specified. For instance, the effective capacity can be seen as an example of a static assumption. By definition, "effective capacity" is the maximum amount of work that an organization is capable of completing in a given period due to constraints such as quality problems, delays, material handling, etc.

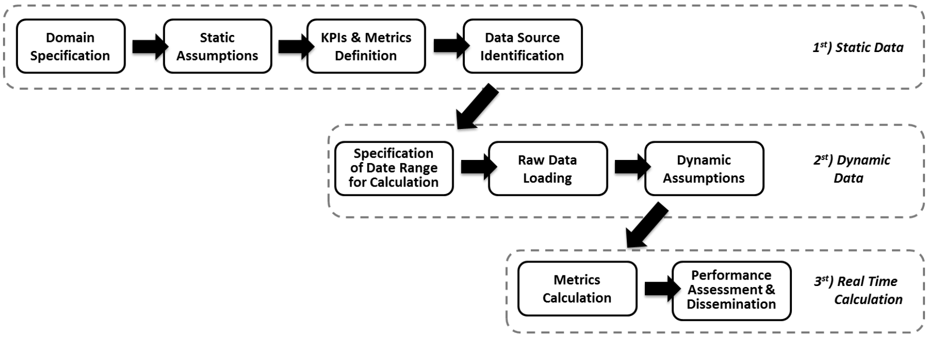

Fig. 5. Performance Measurement System Requirements

The metrics specification is maybe one of the most important steps of this methodology, developed within this proactive performance management concept. Actually, this stage can be performed following two main perspectives: a process-driven or goal-driven perspective. Concerning the process-driven perspective, the system performance manager should start by identifying the core-processes of the system under analysis and, based on the purpose for which each process was designed, select the correct indicators that will evaluate their efficiency, effectiveness and relevance. Contrarily, in the case that a goal-driven strategy is defined, then it is critical to initially define the stakeholders of the system as well as their visions and objectives. Following, the KPIs that will make it possible to evaluate if these objectives are being achieved or not, should be designed. In fact, this is a critical step since it is expected to combine the information desired at the strategic level with the raw data available at the operational level. Consequently, for this proactive performance management concept it is proposed a hierarchical metric definition that support system's performance managers to continuously mould the available raw data scattered throughout the different legacy systems, aiming to respond to the requirements imposed at the strategic level.

At this stage it is already available not only all static and dynamic data necessary to the KPIs calculation but also the mathematical formula, defining how these indicators should be calculated. However, this information is not enough since it will not make it possible to calculate each indicator with the desired level of granularity. Consequently, and taken into account that almost all manufacturing systems produce more than one family of products, that can share or not resources and information, when calculating these indicators it is essential to introduce these variables within the calculation formula in order to calculate each indicator with the higher level of detail as possible. Only this way it is possible to calculate a KPI for each manufacturing system section/department and products perspectives.

Finally, having calculated each of the KPIs defined for the performance measurement system in question, it is essential to compare the obtained values with the target values as well as disseminate this information throughout the entire manufacturing system. From this statement it is important to underline that both dissemination and targeting processes should be competent and efficient. For instance, when broadcasting the performance information it is important to guarantee that an appealing interface is used in order to provide decision makers with a clear, simple and rich visual experience. On the other hand, it is important to respect the fact that each actor involved in the manufacturing system should have access to a personal dashboard where only the KPIs that will support him improving their competences should be available. Actually, this is an important innovation compared with the approaches normally used within current industrial organizations. Indeed, nowadays the performance information is customized according to the necessities and requirements of a limited number of actors, being after that imposed to the entire organization. However, due to the hierarchical construction of the KPIs and its metrics it becomes possible to easily mould the information available aiming to answer to necessities of all the actors involved in the production system.

4 Framework Proposal

If it is true that, in one hand, a PMS should be able to increase the level of accuracy and reliability of the performance information calculated, focusing at the same time on the level of granularity of each key indicator measure, on the other hand the performance measurement component should be flexible enough to gather, whenever necessary, information from multi-data sources, aiming to fuse raw data generated by different functional modules.

Nevertheless, the process related with the combination of raw data should not be performed in an ad-hoc way. This means that both the rules for raw data handling and the KPIs metrics definition should be extended from the strategic objectives defined at the management levels of an industrial organization. Since this research project is not focused on the strategy definition, the performance management framework should be scalable and holistic enough to allow 3rd party modules, strictly related with organization's strategy formalization (e.g. strategy maps, balance scorecard (BSC), and others), to feed this framework with the functional requirements defined as well as the KPIs, metrics and targets that should be assessed.

Due to the levels of complexity characteristic from current manufacturing systems, reading and analysing the performance information is neither a straightforward nor a trivial issue, mainly due to the high number of factors that can hinder the normal behaviour of the system, as well as the trade-offs that can be observed from the synergies between these variables. Therefore, after guaranteeing that performance information is calculated with high levels of reliability and detail possible, it becomes critical to explore new approaches that support decision makers to formulate their mental models about the system, to validate with the different stakeholders, to reuse knowledge for continuous improvement purposes and finally to broadcast this conception about the system behaviour through the organization, aiming to achieve higher effectiveness and homogeneity on the decision making process.

Aiming to fulfil the requirements and gaps previously identified, in figure 6 it is depicted an overview of the multi-perspective performance management approach developed within the scope of this research project, as well as the data flows between the different components. Indeed, one of the key drivers responsible for the flexibility requirements described before is the data model, responsible for the data interoperability not only between the different components of this framework but also with other modules, external to the proactive performance management framework, which can also be interested in absorbing the knowledge developed related with the manufacturing system performance behaviour (Chituc, Azevedo, & Toscano, 2009).

Moreover, it is important to underline that a flexible performance measurement and management system should be capable to read information not only from databases available in the manufacturing system, but also from other functional models applied by decision makers during their planning activities. For instance, if a performance management system is capable to collect the information related with a simulation performed in a specific 3D simulation tool, then it becomes possible to compare if the real system is performing as planned within the virtual world. In the same line, if a performance management system is capable to collect data concerning the layout of a plant, then this information can be used to build a more dynamic and rich domain of calculation, continuously aligned with the reality of the shop floor.

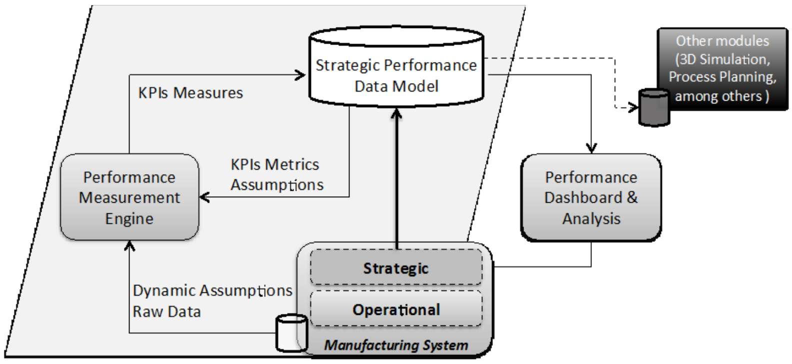

Fig. 6. Proactive Performance Measurement Architecture

Aiming to implement this vision, as showed in the previous figure, the strategic performance data model is the heart of this framework. This is the element responsible by defining which information should be generated as well as the relational model that rule data and knowledge management. Moreover, this reference model defines how data should be stored in order to guarantee that modules, seeking for performance information and with the correct permissions, can gather or even change information (read/write).

Similarly to the data model previously described, the Performance Measurement Engine (PME) is a functional module, developed under the umbrella of a European project called Virtual Factory Framework (VFF), strictly focused on manufacturing system's performance measurement and management. As it is possible to see in Figure 6 the PME mainly relates three types of information:

i. Firstly, due to the continuous necessity to streamline the strategic performance assessment, the PME updates its internal information concerning new/updated KPIs specification, as well as the internal and external static variables that characterize the system in analysis. This kind of information is normally generated at the highest levels of the hierarchical structure of an industrial organization, where do not exist any kind of knowledge or even consciousness about the raw data available at the legacy systems of the organization capable to provide with the raw data necessary to the KPI calculation. Thus, KPIs are usually formulated without specific knowledge about the raw data available to feed them.

ii. Consequently, the second PME perspective is strictly related with the necessity to establish tunnels of communication, from where it will be collected, fused and filtered the correct raw data and dynamic assumptions from the shop floor. This is one of the main functionalities of the overall framework responsible by agile and enhance the linkage between the strategic and operational layers of an organization since it allows decision makers to easily define KPIs metrics, choose the suitable raw data available for its calculation as well as identify the databases where this information is available.

iii. The third most important perspective of this engine is mainly related with the KPIs calculation and information broadcast. In fact, collected all the information related with KPIs metrics, static and dynamics assumptions, domain of calculation as well as raw data location, then it is feasible to calculate with high level of reliability each performance indicator defined at the strategic level. Finally, all the performance information generated through this functional module should be stored at the strategic performance reference model, aiming to make this data available to internal but external modules seeking for this type of information.

Following, it will be provided more detailed information concerning the strategic performance data model and the PME.

4.1 Strategic Performance Data Model

The SPM ontology was developed as part of a European research project (Sacco, 2010) which focused on the need to streamline the introduction of new products within the production system, decreasing the ramp-up, increasing the production system's capability and efficiency. In order to achieve these goals, the "Factory as a Product" paradigm was explored aiming at supporting the implementation of simultaneous/concurrent engineering between products, processes and resources life cycles.

The heart of this European project was the Virtual Factory Data Model (VFDM), mainly responsible by guaranteeing the data interoperability between different functional modules used during the different stages of a factory life cycle. In other words, the development of the VFDM is critical because it not only defines how the data should be exchanged between the different modules involved in the planning and operational stages of a factory, but also clarifies how data should be generated and used.

The VFDM has been decomposed into a series of macro areas, creating a hierarchical structure of ontologies that decompose the problem and reduces its complexity, keeping a holistic approach. As final result, the VFDM is available as a network of ontologies, implemented as OWL files, where each ontology can relate its data with attributes available on others ontologies of the network. This way, the VFDM defines only the so-called Metadata (i.e. the classes, properties and restrictions), whereas the actual instances (i.e. the individuals) will be stored in a Data Repository. However, not all ontologies of the VFDM have been developed from scratch. Therefore, in order to assure reliability and confidence on the reference data model developed, it was taken into account different technical standards available in the state-of-the-art of different domains. For instance, it was taken into consideration the Industry Foundation Classes, STEP-NC (International Organization for Standardization), and ISA-95 (International Society of Automation) (Scholten, 2007).

Nevertheless, in the scope of this research work, the emphasis will be both the strategy and performance management areas of the VFDM. As previously mentioned during the enhanced strategic performance management concept, to make maximum use of the information extracted from the performance measurement system adopted by an industrial company, it is essential to bring together both the strategic and operational perspectives of an organisation's structure, concerning the performance management strategy to be implemented. In fact, while at the strategic layer people define what to measure and the targets to be achieved, at the operational side people are focused on calculating the metrics defined as well as locating the data sources where the suitable information for a reliable KPI calculation is. Therefore, it is critical to define the data model that bridges the gap between the strategic and operational layers of an industrial organization, by formalizing the performance management concept at both the hierarchical layers.

In line with this, a holistic and generalized data model was developed using the semantic concept as pillar. In Figure 7 it is depicted the Ontograf of the SPM ontology. This is a technology developed by the Protégé consortium that allows to, interactively, explore and navigate throughout the relationships of a specific OWL ontology.

It is important to highlight that the SPM ontology here presented results from the merged between the VffStrategy and VffPerformanceManagement ontologies. Thus, when clearly defined the boundaries between these two universes, three concepts gain a higher dimension: measurements, metrics and performance indicators. Despite the similarity between these three concepts, it is important to clarify the main differences between them. A measurement is a number that is quantified at a certain point in time. However, in the performance measurement sphere this value only represents an add-value if it contains a certain meaning associated, which makes it a metric. On the other hand, in the performance management scope a metric only becomes useful if it has a target associated which makes it possible to evaluate these metrics.

In sum, while a KPI is responsible by representing a certain non-functional requirement by a measurable concept, capable to evaluate quantitatively a certain object in a specific scope, a metric is a characteristic of a KPI responsible by formulating it into a mathematical way, with a well-defined objective function.

In line with this, the strategy part of the SPM ontology was developed aiming at modelling the data related to the company strategy, envisioning the alignment between the manufacturing system performance and the market needs. In other words, with this ontology it is expected that the goals envisioned by the stakeholders of the system can be formalised; the KPIs can be mapped with the requirements defined for the manufacturing system and; the information related to the target objectives can be modelled (Dekkers, 2003).

But, how it is possible to map this vision using the semantics and ontologies as pillars? The main premise of the strategy ontology is based on the idea that a manufacturing system (since a supply chain until a micro-factory) is a very complex system, composed by a series of entities (since industrial partners until factory departments, respectively). Each of these entities has a specific reality that can be modelled with the VffScenarioDetail class (Figure 7). Moreover, each of these entities should have a well-defined strategy. Therefore, each manufacturing entity should define its own strategy map, aligned with the entire vision of the manufacturing system.

Consequently, each strategic map is composed by a series of functional requirements. By strictly following the rule that each functional requirement has to be derived from a specific stakeholder's goals, which, consequently, should be aligned with the organization vision, the rationale behind each functional requirement should be captured in order to justify and compose each of the company's goals. Therefore, each of the functional requirements, which should be modelled by the FunctionalRequirement class, may be linked with a criteria (Non-FunctionalRequirement class) and a certain solution (SolutionProperty class)(see Figure 7).

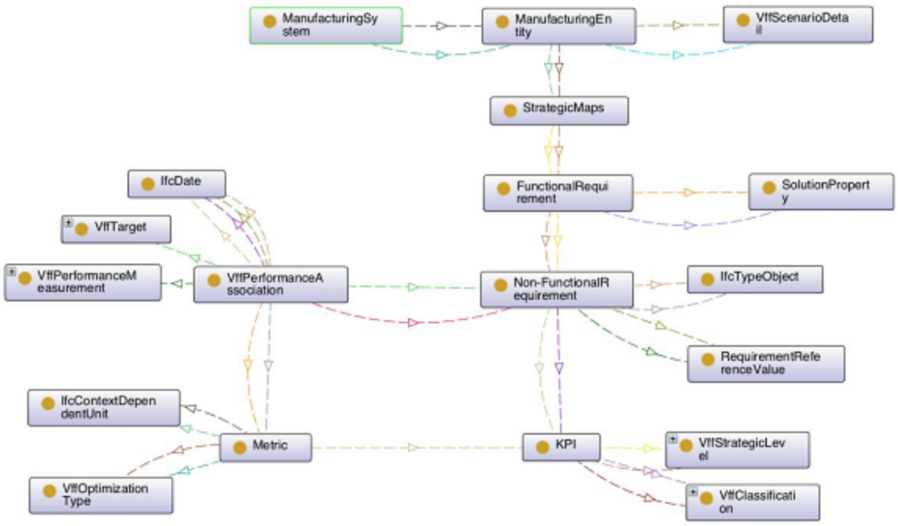

Fig. 7. Strategic Performance Management Ontograf

In a second layer of the ontology, one or several selected KPI/PI, which are seen as suitable to assess the intention that stands behind a functional requirement, should be mapped. The KPI class focuses on storing the main characteristics and specifications of an indicator in order to provide meaning to the measurements obtained. Each KPI must be catalogued according to its classification and strategic level. In the strategic level, the controller must specify if the KPI/PI under analysis is used to evaluate a planning or operational process. In the classification level, it is specified in which terms a KPI/PI evaluates a specific object in the production system: Cost, Quality, Time, Flexibility or Reliability.

On the other hand, the Performance Management part of the SPM ontology aims at modelling the data related to the behaviour of the production system, assessing its performance against the expected targets values. However, the performance measurement should be explored as a dynamic process that alters according to the specific environment that characterises the manufacturing system under analysis. In line with this, the VffPerformanceAssociation class was designed to link a performance target with the performance measurement, calculated with a specific metric, designed to mathematically formulate a certain KPI, for a certain time window.

4.2 Performance Measurement Engine

By definition, a suitable performance measurement and management (PMM) system aims to support decision-makers by gathering, processing and analysing quantified information on performance and presenting it in a succinct format. Strategic performance measurement systems (SPMSs) are a subset of PMM systems. They support the production system stakeholders through a series of distinctive features, such as: integrating long-term strategies and operational goals, providing performance measurements in the area of multiple perspectives, providing a sequence of goals/metrics/targets/action plans for each perspective and presenting explicit causal relationships between goals and/or between performance measurements (Gimbert, Bisbe, Mendoza, 2010).

When designing a SPMs for complex manufacturing systems, there are issues that need to be taken into consideration as this involves gathering multi-disciplinary themes. For instance, it is expectable to find a number of difficulties related to data collection from multi data sources (Jain, Triantis, Liu, 2011). Consequently, during this stage it is important to solve the conflicts that can occur between different performance measurement sources, guaranteeing an appropriate balance between internal and external measures, as well as cataloguing and providing meaning to the data for further use. However, as it is possible to see in Figure 8, issues related with data handling are just the bottom of the pyramid of requirements for a suitable SPMS implementation within complex manufacturing environments. In line with this, since this type of systems presents dynamical behaviours, it is necessary to guarantee the flexible link between tactical manufacturing planning and the different strategy perspectives, which should be formalized by KPI’s metrics and respective measurements.

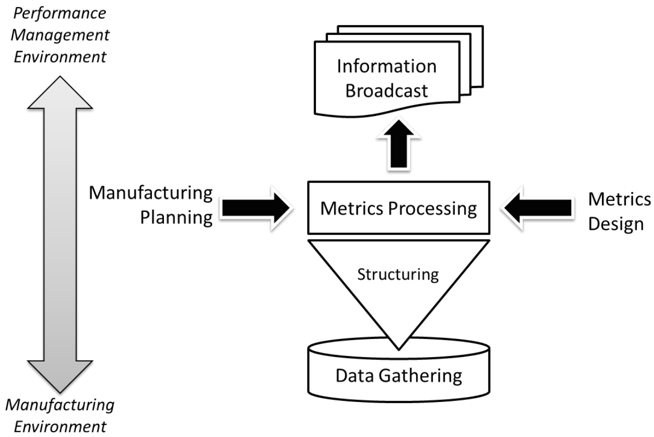

Fig. 8. Requirements Pyramid for Complex Manufacturing Systems

The PME was designed and developed aiming to overcome and simplify all the small details that characterises a dedicated performance measurement solution. Indeed, the main objective was to create a software solution easy to install, setup and maintain but, capable to provide powerful information to stakeholders, shareholders and decision makers. Thus, the biggest contribution of this research work is based on the set of concepts, and respective technological implementations, developed to streamline and boost the performance measurement and management strategy to be implemented in a specific organization. In order to show the main differences between the PME and the solutions currently available into the market, the core features enumerated before for performance management software's will be used as plumb line.

Data Collection: Within complex manufacturing systems, it can be a challenge when the technology infrastructure makes it difficult to obtain or extract the right information to calculate the suitable KPIs in a reliable way. In order to overcome this, there are sophisticated enterprise systems or extensive legacy systems that can help or hinder progress with improving strategic performance measurement. However, the technology in place may make it either too expensive or too time-consuming to access the pieces of data needed for effective performance measurement due to the complex and sophisticated nature of this systems.

Therefore, the PME was developed with the aim of supporting users, during the process of data gathering from the different data sources available in the factory facility. With this in mind, the gathering of data for the calculations was defined in a way that it is possible to combine data from multiple sources, and establish relations between them, so that, more relevant information can be extracted. With this possibility the manufacturing system manager can have more meaningful information without having the hard work of dealing with the data, everything is made through the PME and it is only necessary to define rules and relations using a simple graphical user interface.

Key Performance Indicators: it is critical that an organization defines a number of KPIs capable of measuring its core processes or activities. However, in order to better interpret this important information, sometimes it is necessary to go deeper and study the reason of bad performances behaviours. In line with this, the PME follows an innovative and distinctive approach that defines a KPI according to a hierarchical tree, which enables companies to perform a series of performance management actions and retrieve more information capable to support decision makers.

Moreover, the PME allows production system managers to adapt the performance measurement approach to complex manufacturing environments. In order to simplify the KPIs definition, the PME solution allows the manufacturing system manager to build and store the different KPIs using Drag & Drop functionality. However, it is also possible to define new KPIs to be calculated using other functional modules. To do that, the PME solution has a synchronizing functionality that read formulas stored by other modules in specific data repositories and then presents it to the user so that he can define the data sources for the new KPI. Therefore it is possible to integrate information generated by different functional modules aiming to bridge the gap between the strategic, tactical and operational layers of a manufacturing company.

Generating Information: According to the KPI's metric, the PME solution allows the manufacturing system manager to visualize and analyse the current status of a specific KPI in an interactive way. Using a hierarchical KPI metric definition, where a KPI can be seen as a combination of different indicators, decision makers cannot only assess the KPI value but also all the variables used for its calculation, due to the continuous capability of the measurement engine to power different charts and tables with real performance values. This information can be used not only to better understand the system behaviour, but also to detect bottlenecks.

However, the hierarchical KPI metric definition is not the only concept developed to enhance the quality of performance information generated. If it is true that start analysing a KPI as a function and not as a variable allow decision makers to have a wider view of the system, it is also true that there should be, at the same time, a greater concern in providing a more detailed information about the performance of a complex manufacturing system.

This perception about current necessities of stakeholders of large and complex manufacturing systems led us to another concept called High-Resolution (HR). The HR concept defines that, similarly to the resolution concept of a picture, in the scope of this research, high resolution means the ability to increase the level of detail of a manufacturing system's performance picture. The idea is to present a solution capable of providing performance measurements with high levels of granularity that can be adjusted for the different stakeholders belonging to different hierarchical layers of the organisation. In the application case section an example of both hierarchical KPI metric definition and High-Resolution concepts and its advantage for industrial companies will be presented.

Response to Data Analysis: Following a defined schedule, the PME solution is able to generate performance reports that can be broadcasted through the factory using email services features. The Key Performance Indicators values can be easily consulted, inside and outside the factory, through a web-based application. Permissions were also implemented. Depending on the user logged in, different actions can be performed. Thus, some users might have all the permissions to create and calculate KPIs, while others can only see the calculation results.

Since the PME allows the user to analyse the KPI in a more detailed way, with this performance management system becomes possible to anticipate and prevent low performance behaviours (according the PME approach, the different components of the KPI calculation can be used as leading factors). Therefore, with the PME solution it becomes very simple and quickly to perform "what-if" scenarios activities, understand the reason of low performance rates and predict future performances according to leading factors.

Hierarchical KPI Definition. Aiming to guarantee that operational, tactical and strategic information could be fused within a single but rich aggregated performance indicator, aiming to related different perspectives, a hierarchical KPI definition was explored. Three levels of indicators have been defined for the performance indicator structure: Raw Data, Performance Indicators (KPI0) and Key Performance Indicators (KPI1+).

The Raw Data level gathers the information available on the production system, providing meaning to the measurements obtained from the different sensors available. Therefore, the measurements available in external sources, such as, xls, xlm, csv documents and database tables can be located and modelled to be reused every time this kind of information is required in order to calculate indicators affected by them. Examples of these kinds of data are the data source locations of the following information: order logs and process event logs.

The Performance Indicator level can be seen as a combination of Raw Data to build linear and simple indicators. Indeed, added value information is not expected from these metrics but they do represent critical data that allow key performance indicators to be calculated and analysed swiftly. Examples of this kind of indicators are: elapsed time for the completion of each order type (CET), the number of orders received (NOR), the working duration of each activity in the process (TPA) and the percentage of an order type (POT).

In order to obtain significant and meaningful indicators capable of retrieving a clear and reliable picture of the system's behaviour, it is important to define Key Performance Indicators (KPI). These indicators can be seen as a combination of performance indicators, from different perspectives, and manufacturing system assumptions. In fact, the manufacturing system assumptions are another important variable used by KPIs that should represent the limitations and characteristics of the system.

Architecture. The PME was developed in order to materialise the concept explored by the reference data model as well as provide the right answers to the requirements mentioned before for SPMS. Next, the main layers that compose the PME are presented, from the data extraction and reference models to the KPI calculation and performance management functions.

In order to perform the functionalities already described, the PME solution was designed according to a layered architecture approach (Figure 9). This kind of approach was selected as it makes it possible to share the concerns on the application into stacked groups and, therefore, there is a higher level of flexibility to capture and handle data from different sources and afterwards to calculate the right metrics in order to evaluate the performance of the current strategy. The main components, and respective benefits, of this layered architectural are:

PME WebService: The WebServices connector is at the foundation of the PME structure. This module is responsible for managing all the communications with the semantic repository. Therefore, when it is necessary to read or write any kind of data from the repository, this module selects the suitable SPARQL query template, completes with the missing data and invokes it, using the Suds gateway. The Suds web services client is a lightweight soap-based client for Python that is public available.

Extract Transform Language Layer (ETL): This is a module responsible for collecting data from various sources, transforming the data according to business rules/needs and loading the data into a destination database. Therefore, due to the implementation of this layer it is possible to read data not only from external databases such as Oracle, Mysql, Postgres, SqlServer, but also from diverse file formats (excel, csv, xml and email). An open source technology called CloverETL was used in order to implement this ETL layer.

Raw Data Fusion: For a reliable dynamic KPI calculation it is necessary to gather three kinds of performance data: real-time shop floor data, production system constraints data, and finally strategic data. In line with this, the Raw Data Fusion module is responsible for identifying the data source, selecting the data fields desired, applying filters capable of increasing the performance calculation reliability and expressing the correlation between data available from different sources. After this information is determined, the Raw Data Fusion module retrieves this information to the ETL layer in order to extract the right information with the highest quality possible.

Production System Emulator: After the performance data required to calculate the KPI metric are defined and archived, it is necessary to extract the variables (assumptions/constraints, as well as production system outputs and resources) from the production system. These variables must be taken into account during the calculation process of the indicators since they can influence the detail and reliability of the measurements. In line with this, the production system emulator has the responsibility of characterising each manufacturing agent (collaborative network partner, departments or production sections), organising for each of them the static variables, the main strategic objectives, mapping them with the different manufacturing objects (machines, human resources or products) and respective KPI instances.

KPI Manager: This module intends to manage generic KPIs. In other words, this module is responsible for creating the KPI hierarchical structure and connecting each entity of this structure to the respective Raw Data. However, when dealing with KPIs it is important to integrate in the calculation not only Raw Data but also other indicators. This fact makes this management process more complex, but on the other hand it provides interesting add-value to the production system managers as it simplifies performance assessment.

KPI Calculator: This module is responsible for compiling all the data retrieved from the KPI Manager, Production System Emulator and Raw Data Fusion components, and for calculating the indicators according to the manufacturing system manager specifications.

KPI Analyser and Event Manager: Finally, after the strategic, tactical and operational data are identified, the PME calculates the indicators when necessary (user orders or event triggers), confirms whether the object analysed performs as desired by the different stakeholders, and sends reports (alarms) with charts and possible reasons for low performance rates using KPI Tree analyses.

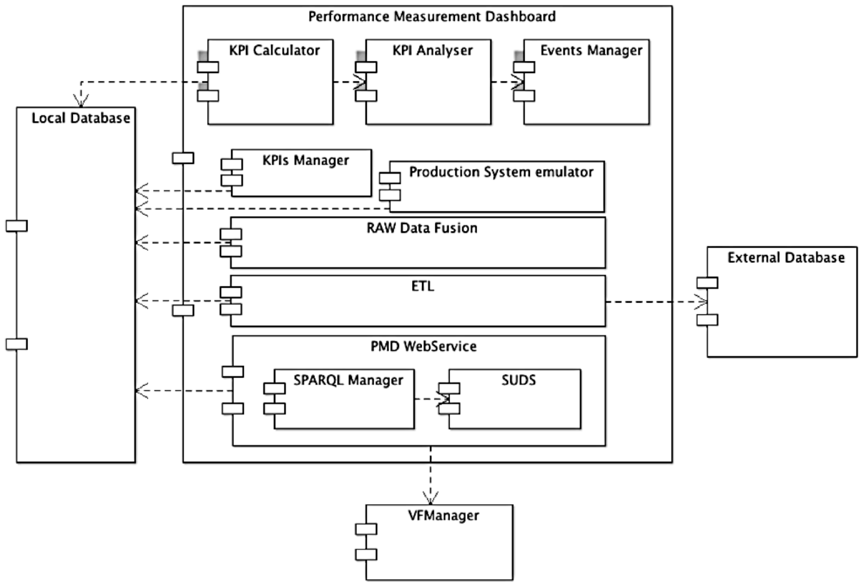

Fig. 9. Performance Measurement Engine Architecture

5 Experiments and Results

5.1 Scope

Aiming to test and validate the PME developed, an industrial partner belonging to the automotive sector was selected to be used as use case. Indeed, the scenario handled at this industrial partner can be classified as a complex system since despite the fact it is composed of a single production line, the truth is that along this production line different families of cars are produced, with different characteristics and requirements (sportive and family cars), sharing processes and resources. Moreover, this production line is divided into the following parts: stamping, painting, body, assembly and quality. Therefore, it is also necessary to calculate each indicator, not only for each product but also according to the structural division of the production system. While some resources are shared between all of the cars, others are shared by a subgroup of families of cars and others are specific to each product. Due to the complexity and time consumption required to perform the KPI calculations and its respective assessment, this presents a very interesting opportunity to evaluate the PME solution.

As illustrated in Figure 10, the PME is located between the strategic and operational levels, aiming to compile raw data according to the KPIs specifications and planning constraints and assumptions retrieved from the strategic level.

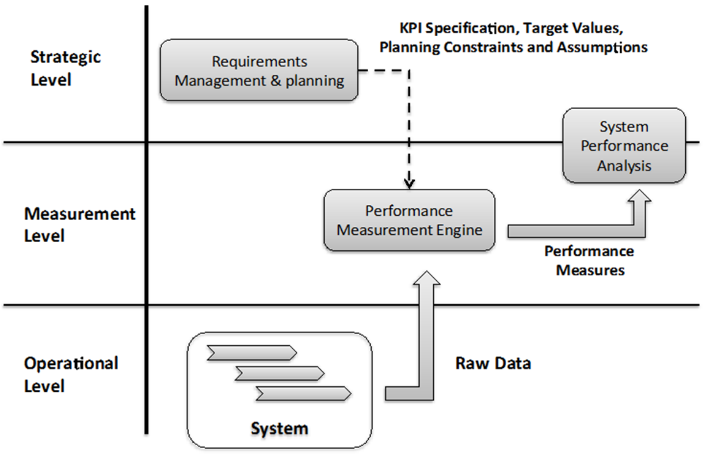

Fig. 10. Integrated Strategic Performance Management

Requirements Management Planning (RMP) tool, at strategic level, supports the design of strategic maps modelling and the necessary alignment with organizations policies and visions. In this pilot case, the Harbour Report was selected as the conceptual pillar supporting the validation of this strategic performance management system. The Harbour Reports, from Harbour Consulting, are relatively standard for empirical research in the automotive industry. Indeed, is one of the most important benchmarking reports aimed not only to ranking automotive plants in terms of efficient but also support organizations involved within this comparison exercise enhancing their manufacturing systems and the entire supply chain.

A relevant KPI related with the manufacturing system productivity, called Hours per Vehicle (HPV), was selected to be included in this pilot case. The KPI HPV takes into account all of the hours worked by the direct plant personnel divided by the number of units produced, with the expected levels of quality, in the time interval defined. This is an aggregated KPI that belongs to the efficiency perspective and is composed of simple indicators from different dimensions, for instance time and quality.

However, the calculation of the variable Manpower is not a straightforward calculation. Thus, in order to calculate this performance indicator it is necessary to know the list of people that directly interact with the production line, the list of people in absenteeism or in training and the list of people that moved from an organizational area to another.

Since the industrial partner's plant produces more than one type of vehicle and the line has five distinctive areas (stamping, body, paint, trim & assembly and quality), the calculation must be performed per car, taking into account the entire line, but also splitting up the production line stages. In other words, the domain/universe of calculation is the production line divided by the five areas and its output, represented by the volume of cars per type. Following a high-resolution paradigm, the more detailed is the calculation of a certain KPI, more information is possible to extract in terms of management issues. Therefore, aiming to automate and increase the level of information extracted from the HPV measure, the PME was used as the engine of calculation of the KPI HPV.

Therefore, the following stage of the pilot case was divided into two main steps: KPIs metrics parameterization and KPIs calculation. While the first stage is mainly responsible by the definition and specification of a certain KPI as an object, during the KPI calculation the main objective is to instantiate the object created in order to answer to the requirements imposed by performance management strategy, such as domain/universe of calculation, static and dynamic assumptions as well as percent of resources allocation per product type.

5.2 KPIs Metrics Parameterization

As previously described, at a first stage of this pilot case, the KPI HPV was specified using the data fusion and metrics formalization capabilities of the PME. Thus, the first task performed was to identify the raw data sources (databases or flat files) available, in order to create the tunnels for data communication. In line with this, initially, all tables containing information about the necessary raw data for the HPV calculation were identified, such as: list of Cost Centres, the payroll table, list of absenteeism, list of people in training and list of people transferred temporarily from one organizational area to another.

Identified the data sources, where the raw data will be available, the following step was strictly related with the KPI0 specification. As previously explained, this type of indicators is mainly responsible by the structuring of raw data through a data fusion approach. For instance, it is possible to merge the list of cost centres with the payroll list in order to obtain the number of persons working in each cost centre. This step is critical, since it is expected to calculate the KPI HPV per organizational areas, which are composed by cost centres. Due to the drag and drop functionality, the user is not required to have any knowledge of SQL language, being only necessary to link the similar attributes from the selected tables.

Identified the data sources as well as specified the KPI0 it is now possible to specify the mathematical formulas for each of the key performance indicators (KPI1+) identified before: Manpower and HPV. In this specific pilot case, the PME was capable to download from a knowledge-based server, where the strategic and performance measurement and management ontology was deployed, the information created by the RMP software concerning KPIs formulas and respective target values. However, if the PME was being used as a standalone solution, then, similarly to the previous step, the formula could be built using the drag and drop functionalities of the PME tool.

It is important to underline that, due to the innovative hierarchical approach explored within this performance measurement engine, it is possible to define KPIs that are composed not only by KPI0 and assumptions but also by others KPI1+. For instance, the KPI HPV is composed by one KPI1+ (Manpower), which, consequently is composed by a set of four PI of level zero (payroll, absenteeism, training and transfers). This hierarchical approach, built according to the metric of each KPI, can be seen in figure 16.

5.3 KPI's Metric Calculation

Specified the metrics of the desired KPIs, the following step of the pilot case is strictly related with the metric calculation. In fact, this is a second process that allows approximating as much as possible the KPI calculation from the real characteristics of the complex manufacturing system.

Therefore, aiming to calculate the KPI HPV, initially the static and dynamic assumptions were defined. Since at the moment that this pilot case was performed it was not possible to establish a direct connection with the data sources where it would be possible to extract the real volume of cars produced, and then this information was manually introduced into the system. At this moment, it is possible to parameterize the day for which it is expected to perform the calculation and, if necessary, update the value of the static assumption "EffectiveTime".

In fact, one of the main advantages of this approach is the capability to calculate a certain KPI with a higher level of detail but with lower effort. Therefore, during the description of the pilot case it was stated that it would be important to calculate the KPI HPV not only per product but also per cost centre. Therefore, the following steps are related with the specification of the performance measurement domain and the percentage of effort allocated for each car family. This means that it is possible to specify for each cost centre selected to make part of the performance management strategy clusters the effort allocated for each car family. In line with this, for each cost centre it is possible to indicate which car family used the resources available and the percentage of usage (in this case human resources). The calculation of this percentage can be done automatically by the PME, through the planned volume of production, or introduced manually by the system's performance manager.

Finally, reports can have different formats: KPI hierarchical trees (Figure 11), charts, tables or pre-defined emails. For instance, the KPI trees represent an innovative approach to analysing and assessing a performance indicator measurement. With this approach, it is not only possible to visualise the entire structure of a KPI (raw data and performance indicators used) but also detect the reasons for low performance rates. Therefore, it is feasible to detect watermelon situations and anticipate possible production system malfunctions. This means that, by using different colour tones from light green/red to dark green/red managers can instantly understand if KPIs are far (darker) from or close (light) to the target. In order to provide managers with more detailed information about the performance behaviour of the system, the possibility of clicking on each of the indicators that compose the KPI in analysis was implemented, so that they could see the real values compared to targets, by domain, and thus providing an even more detailed view of the KPI status.

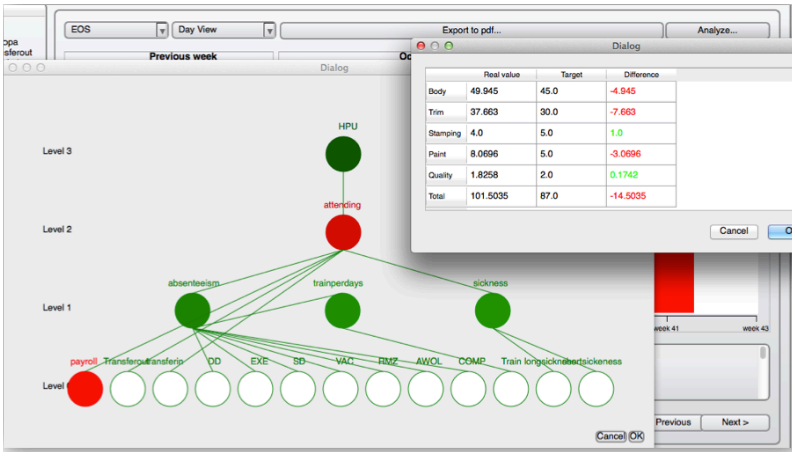

Fig. 11. Root causes analysis through innovative PME drill-down approach

6 Results Analysis and Conclusions

From a literature review, it is possible to confirm that a considerable change has occurred in the managerial culture and rationalisation of the manufacturing systems, which required small and large manufacturing systems to become more and more complex. However, it has been observed that inappropriate research has been conducted in the scope of performance measurement systems in the search for the continuous evolution of manufacturing systems.

For instance, if is true that companies are improving their technical and technological capabilities to meet the market needs, on the other hand this work has had a low impact on the formalisation of holistic and robust performance management models, adopted to deal with this increasing complexity (Garengo, Biazzo and Bititci, 2005).

This research project was developed on the premise that aiming to support decision makers to become more proactive, in terms of performance management strategies, it is necessary to enhance the way in which organizations execute their performance measurement activities, as well as improve the reliability, confidence and granularity on their KPIs metrics and measures.

Due to the simplicity and effectiveness of the technology developed, it was possible to break with the stigma linked to the performance management discipline, where the effort required to obtain interesting performance information neither complies with the added-values obtained nor reinforce the organizational core business processes.

Furthermore, it was demonstrated that based on this approach it is possible to extract more powerful information, envisioning knowledge creation. In other words, providing decision makers with the capability to build multi-perspective and aggregated KPIs, it is possible to decrease, significantly, the number of KPIs necessary to make decisions but keeping, at the same time, a multi-perspective vision of the manufacturing system.

Thus, with the implementation of this application case, it was demonstrated that it is possible to innovate and enhance the way how decision makers interpret this important information, drilling down a problem and study the reason behind a poor performance, in a high resolution way. In this specific case, it was proved that with low effort, it was possible to calculate the KPI HPV for each cost centre, clustered in well-defined organizational units, as well as assess the strategy deployed, and materialized by the manufacturing system performance, per product family. Moreover, by following an innovative approach that structures KPIs in a hierarchical tree, combining multi-perspectives indicators, the PME allowed not only decision makers to analyse the impact of a specific indicator within the KPI structure but also integrate both tactical and operational information, and thus achieving a powerful "what-if" analysis.

In sum, it was possible to evaluate the proposed approach considering three perspectives:

- Time constraints: the time required to calculate each indicator and to broadcast a performance report by the different stakeholders (time constraints) was measured using both the PME method and a traditional method.
- Effort: the number of resources required in both processes was also measured (required effort) taking into account the performance assessment and bottlenecks identification error obtained.
- Learning curve: the time required to train a new performance measurement technician (learning curve). In addition, the time necessary to introduce a new goal and respective KPI(s) was also assessed.

Our study has limitations. The developed approach was tested in the automotive industry, which presents the characteristics stated previously concerning a complex manufacturing system. However, the approach has not been evaluated in other manufacturing environments. Thus, future work should explore the application of proposed approach in multiple industries addressing different operational and markets environments.

7 Acknowledgements

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