Performance measurement integrated information framework in e-Manufacturing

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The implementation of Internet technologies has led to e-Manufacturing technologies becoming more widely used and to the development of tools for compiling, transforming and synchronising manufacturing data through the Web. In this context, a potential area for development is the extension of virtual manufacturing to performance measurement (PM) processes, a critical area for decision making and implementing improvement actions in manufacturing. This paper proposes a PM information framework to integrate decision support systems in e-Manufacturing. Specifically, the proposed framework offers a homogeneous PM information exchange model that can be applied through decision support in e-Manufacturing environment. Its application improves the necessary interoperability in decision-making data processing tasks. It comprises three sub-systems: a data model, a PM information platform and PM-Web services architecture. A practical example of data exchange for measurement processes in the area of equipment maintenance is shown to demonstrate the utility of the model.

Keywords: performance measurement (PM); e-Manufacturing; B2MML; key performance indicator (KPI); Web services

1. Introduction

e-Manufacturing is a concept that has come to the fore in recent years. It combines Web technologies with the new manufacturing management strategies. e-Manufacturing uses various collaboration tools to facilitate production, manufacturing and assembly process (Xu *et al.* 2012).

e-Manufacturing operates as an information transformation system that maximises the performance of manufacturing operations by using the Web to synchronise manufacturing systems and business systems. Figure 1 shows a current e-Manufacturing environment where the different data flows are integrated. The integration comprises the organisational and operational levels, both at an internal and external level of the company.

In this environment, e-Manufacturing allows monitoring the plant floor assets by using the Internet to schedule production maintenance and order supplies in real time via the Web. This allows integrating manufacturing execution systems (MES) with upper-level enterprise resource planning (ERP) systems. It also provides

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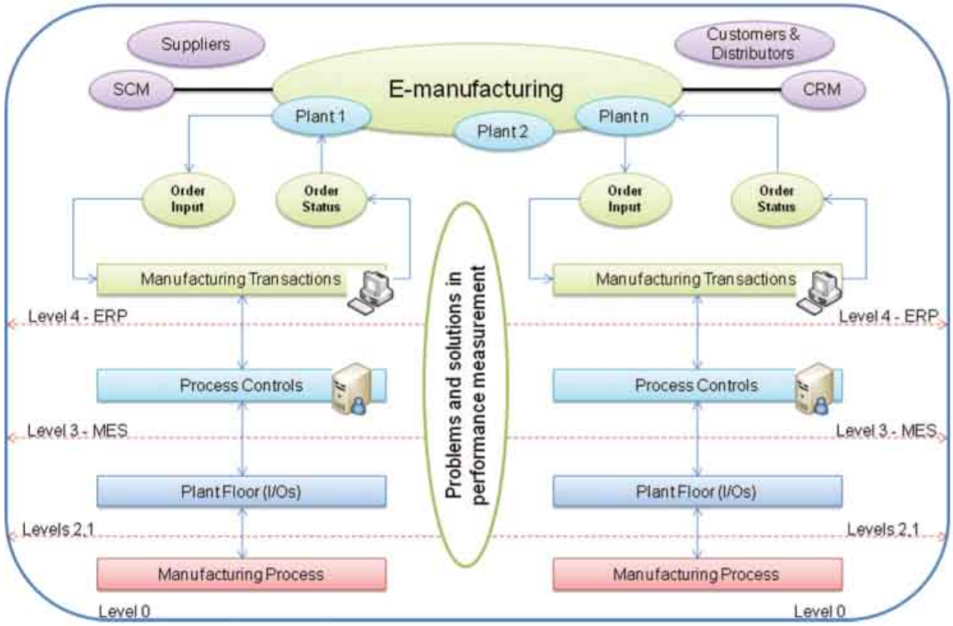

Figure 1. Integration using e-Manufacturing.

efficient configurable information exchanges among manufacturing and customer relationship management (CRM) systems and supply chain management (SCM) systems. Collaborative supply chains seek to coordinate its members to produce and distribute products along the chain for minimum overall costs to satisfy customer demand (Sepehri 2012). This function involves multiple sources and information flows such as data generated by basic devices at a machine or cell level, information from process control computer systems and data of business applications. A higher degree of reliability in the collaborative network can increase the competitiveness and performance of an entire supply chain (Lam and Ip 2012). An appropriate information architecture helps make supply chains more integrated, effective and responsive in the face of complex and fast-changing market conditions (Li and Warfield 2011).

The development of ERP systems, which are the core of all management systems, is the subject of wide research (Scholten 2007). The advances achieved have enabled all business resources and processes to be centrally coordinated. Their limitations, when attempting to deal with a plant management environment with the same flexibility as in an administrative environment, are being solved with MES applications. The MES like reconfigurable manufacturing execution systems (RMES) are used to filling the gap between enterprise resource planning and resource layer for pipe-cutting production with mass customisation and rapid adaptation to dynamic market. Planning and scheduling layer and executive control layer is a key process to achieve this coordination (Yin and Xie 2011).

Development strategies stress the use of Internet technologies, and the current priority is to develop e-Manufacturing tools in the performance measurement (PM). Such integration will allow critical manufacturing resources to be optimised and enhance the decision-making process in manufacturing environments (Braam and Nijssen 2004).

In this e-Manufacturing context, PM serves two purposes. The first is to improve the availability and use of data via the Web, in order to optimise decision making in manufacturing plants. This objective is reached by fully monitoring all the business elements, such as suppliers, manufacturing units (internal and external) and customer service networks. The second purpose is to develop the capacity to control plant assets and predict the variation and loss of performance. By doing so, production and maintenance operations can be dynamically programmed. Also the improvement actions can be synchronised to achieve a total integration between the manufacturing systems and upper-level applications of different businesses. The advances in industrial information integration methods have spurred tremendous growth in the use of enterprise systems. In this process, a variety of techniques have been used for probing enterprise systems (Valerdi and Zhou 2012). Industrial Information Integration Engineering (IIIE) comprises methods for solving complex problems when developing IT infrastructure for industrial sectors, especially in the aspect of information integration (Xu 2011). Developments in e-Manufacturing to achieve information integration have been oriented to the development of tools (Lee 2003, Li and Liu 2012, Ren *et al.* 2012, Tao *et al.* 2012, Wang and Xu 2012, Yin *et al.* 2012):

- Smart software for the continuous, real-time, remote, distributed monitoring and analysis of the manufacturing devices, machines and systems. It enables machine performance to be measured and the application of preventive maintenance.
- Remote, distributed, quality control Web systems and their integration into smart predictive software. This allows identifying variations in quality and their causes in real time.
- Scalable, flexible information platforms to transform and synchronise shop floor data with top level systems, such as resource planning, maintenance, inventory control and SCM.
- The development of virtual design software for collaborative design among suppliers, design engineers and customers. Validation and decision-making processes could be speeded up. Multidisciplinary design optimisation (MDO) involves multiple disciplines, multiple coupled relationships and multiple processes, which is implemented by different specialists dispersed geographically on heterogeneous platforms with different analysis and optimisation tools.
- Reconfigurable manufacturing systems (RMSs) to provide a cost-effective solution to mass customisation and personalisation.
- Collaborative environments or distributed interoperable manufacturing platform to facilitate data exchange among heterogeneous CAD/CAM/CNC systems.
- Manufacturing grid (MGrid) systems to address the resource service optimal-selection (RSOS) and composition problem providing high-quality service to users.
- High performance simulation (HPS) platforms to multidisciplinary design of complex products leads. Between their proposals is how to achieve high efficient utilisation of large-scale simulation resources in distributed and heterogeneous environments.

All these tools, platforms and systems need a new structural basis for information integration enabling them to work more smoothly and efficiently. This paper proposes a PM information framework to integrate decision support systems in e-Manufacturing. The proposed framework aims to ensure an optimised, homogeneous exchange of PM information via the Web making easier to apply virtual manufacturing strategies.

2. e-Manufacturing and PM

Figure 2 shows an example of a classical e-Manufacturing PM architecture applied to a current collaborative industrial context. In general, it would comprise three sub-systems that handle data and convert them into information: acquisition, measurement-analysis and synchronisation. These sub-systems use an enterprise information model with different structures depending on product configurations and ERP system databases (Kimura 1993, Hernandez-Matias *et al.* 2008). Using these sub-systems, the data are registered and transformed into information and knowledge that can be more useful. Acquisition and transformation tools are necessary to correlate data in different formats and transform the data using Web information systems. Measurement-analysis tools can calculate and display PM by taking a wide range of factors, parameters and variables using KPIs (key performance indicator). Finally, the synchronisation tools allow the requested integration and feedback between the plant systems and the e-business systems, including CRM, SCM and B2B. In order to carry out all these functions, current PM

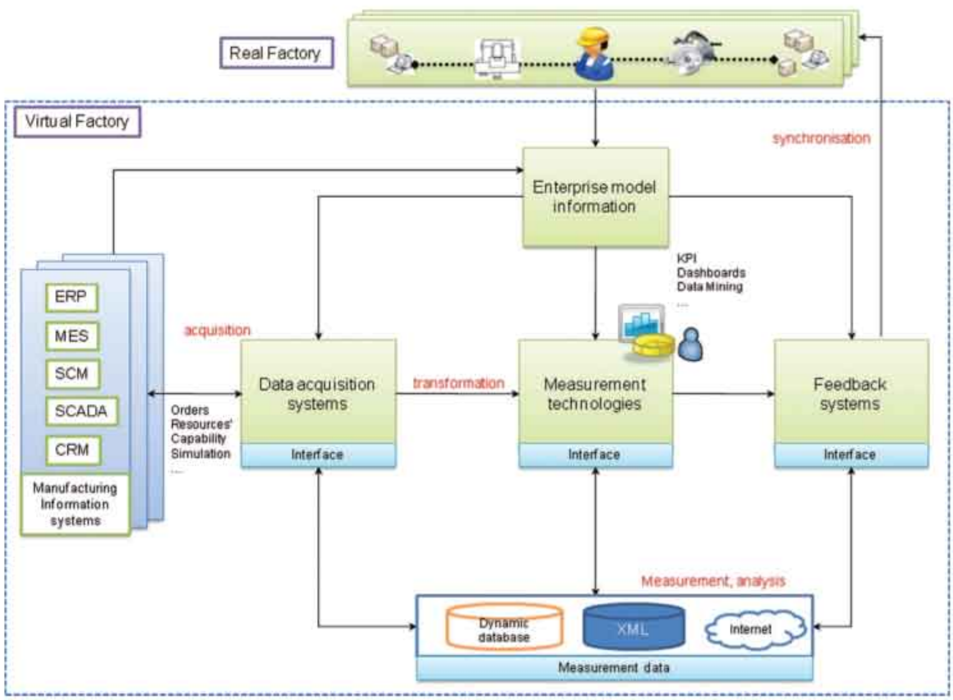

Figure 2. Classical e-Manufacturing architecture.

systems use various technology platforms, such as XML, OLAP, data mining or multi-agent systems.

The use of Web technology has generated a greater data transmission flow between different systems. A homogeneous data exchange is particularly necessary when two or more organisations merge or co-operate with one another. In these cases, the non-proprietary XML data format has enabled interoperability in heterogeneous Web environments. The enormous growth of XML applications for data representation and exchange in different environments is the guarantee of the success of XML (El-Gayar and Tandekar 2007). This use of XML has been supplemented with the development of Web service architectures that guarantee consistent data manipulation and outcomes of business processes running across multiple loosely coupled organisations (Cubera *et al.* 2001, Seunglak *et al.* 2008).

As an extension of XML, it is important to underline the special relevance of B2MML (Business To Manufacturing Markup Language) and the ISA-95 standard. B2MML is an XML schema model that was created by the WBF (world batch forum) to unify the information that is exchanged in manufacturing processes. B2MML uses XML format as the standard for e-business information exchange. Standard ISA-95 has been designed to provide an information interface that is independent from commercial applications and designed to exchange data between business applications and manufacturing control. At present, software management development companies are adopting B2MML in their new projects (Scholten 2007).

In this context of action, companies have to determine the volume of data to be collected by focusing only on the KPIs that directly influence the organisational performance in terms of productivity and competitiveness. In these sense, there are many theoretical models that provide a great value in defining the process of transformation of data into high value-added information. It is essential to take into account such initiatives as the Balanced Scorecard BSC (Kaplan and Norton 1992), new formulations for KPIs (Gunasekaran and Kobu 2007) and contributions from international associations such as ISA-95 (ISA 2003) or the SCOR model (SCC 2003). These tools help companies to adopting quality standards such as ISO 9000 series so that they can develop and maintain supply chain processes that meet certain performances metrics (Li *et al.* 2011).

The Balanced Scorecard is a tool for monitoring of realisation, strategy and analysis of the enterprise operations during a long period of time using a set of measures grouped in four perspectives: financial, customer, internal processes and development. ISA-95 has become an accepted standard in industry as it identifies and deploys all the information related to manufacturing functions that are used by management systems. The four main areas used for the standard to develop the models are manufacturing, inventory, quality and maintenance. The SCOR model is an industrial standard that models the management data of the new SCM models. It lets a business identify the improvement targets of its processes clearly and quickly and objectively measure its performance, enables it to integrate into other businesses and have an influence on the development of future SCM software packages. Until now, the functions of integration and process measurement are developed for the following decision areas: plan, source, make and deliver.

All these initiatives and standards help to unify concepts and criteria so that they can serve as a basis for developing new manufacturing decision systems to represent KPIs on metric dashboards. In order to get the right data into the metric dashboard, the first step will be to identify which systems the data lives in. These will often be different for each department and in many organisations will live in different physical servers and software platforms. The dashboard must be able to tap into these various systems to be effective. Normally, the data warehouse created by OLAP techniques is the best way to enable the dashboard. OLAP tools and data mining are the most widely used techniques in data transformation and measurement processes (Lau *et al.* 2001). The purpose of these tools is to generate automatic or semi-automatic processes to transform data from the operational processes into added-value information for decision making such us dashboards. In this way, new knowledge can be extracted from big and remote databases. The processes include data integration from numerous databases, data management and the induction of models by using learning algorithms. Data mining offers advanced multi-level statistics for approaching the optimisation of decision making. Neural networks, linear regression, decision trees, statistical models and data grouping methods are the essential complements to data mining (Olafsson *et al.* 2008).

3. Current issues

According to literature, PM is lacking in the models and tools. The PM needs new information architecture and technological solutions for defining, storing, processing and analysing performance information within collaborative enterprises (Alfaro *et al.* 2010). The state-of-the-art review produced by Arzu and Erman (2010) concludes that 'PM is still a fruitful research area and very distinctive supportive statements have been traced for the need of further research'.

The technical solutions to implement practical PM solutions are related to the use of standard connections or standard formats for creating specific manufacturing databases, and the use of models based on indicators and the application of business intelligence techniques (EIS, OLAP and Data Mining). The contribution of models such us ISA-95, SCOR and BSC is unquestionable, but these developments offer few references for the practical application of metrics and do not develop the specific information flows that are generated by PM processes (Hernandez-Matias *et al.* 2006).

The current problems arise because organisations use metrics that measure only a portion of the real productivity. This is because many areas of the plant are not measurable in the form of KPIs. The existence of factory areas outside the control of PM makes most companies tend to organise measurement systems based on common accounting principles, which can differ greatly from the performance indicators that are really required (Ahmad and Dharf 2002). These problems are a somewhat disappointing reality because a significant amount of research on PM and the writings on the design of systems and frameworks of PM have been shallow (Neely *et al.* 1996). In the last decade, a number of firms realised the potentials of SCM in day-to-day operations management. However, they often lack the insight for the development of effective performance measures and metrics needed to achieve a fully integrated SCM due to lack of a balanced approach and lack of clear distinction between metrics at strategic, tactical and operational levels (Bhagwat and Sharma 2007).

Although enormous progress has been made in e-Manufacturing tool development, PM requires further research. The e-Manufacturing function must provide an automated information exchange process that is fluid and transparent and favours uniform information management. This function is not being effectively met.

The function is complex to implement due to the large amount of data distributed in industrial plants, coming from multiple sources, such as CRM, SCM, ERP, MES, SCADA, GMAO systems (Madria *et al.* 2008). The reasons behind this lack of integration are given below:

- *Heterogeneity*. A major part of applications function in industries with distributed environments, each one with different technological characteristics. They are industrial environments that suffer from great heterogeneity since their applications have been defined and constructed by different people, in different places, at different times, for different purposes and with different vocabularies. As a result, in a significant number of industrial enterprises, manufacturing information is wrongly handled (ISA 2003).
- *Synchronisation with real data*. The ERP systems are neither sufficiently dynamic nor sufficiently synchronised for managing manufacturing plant conditions in real time, such as unpredictable production stoppages, machine use or supplier unreliability. The limitations shown by ERP for managing a plant environment with the same flexibility as administrative environments has revealed the importance of MES developments. The MES allows a high level view of production, but these systems have been too inflexible to operate efficiently (Cheng 1999). As a result, the link between MES and ERP systems has been hampered by the lack of integrated information with the plant control systems.
- *Performance monitoring*. There are manufacturing areas outside the control of PM, which tends to cause companies to organise measurement systems based on common accounting principles. These can differ widely from the KPIs that are actually demanded. As a result, many companies are incapable of monitoring their functions and the achievement of their goals (Ahmad and Dharf 2002). The information required comes from many sources, but in practice comes from business and is dispersed and badly organised or is simply not compiled. This leads to a major gap when it comes to knowing what the true manufacturing results are (Verstraete *et al.* 2008).
- *Measurement data exchange*. There is a lack of standardisation in information formats to be exchanged via XML. Each organisation or automated application creates its own document structure according to the specific requirements. There are still gaps in the manufacturing data feedback area for validating ERP systems to analyse manufacturing plant performance. The applicability of any system presents difficulties when it comes to standardising methods for companies from different sectors with different manufacturing systems. Documents and data may need restructuring so that they can efficiently share their content with other applications. This is why the use of XML documents for manufacturing data transmission must be strengthened. SAP has announced the adoption of ANSI/ISA-95 standard for its manufacturing module, which opens up a new horizon in the use of modelling and common terminology in the context of manufacturing. Like SAP, other software providers also work with B2MML support and on integration projects. However, ISA-95 and BMML2 do not solve all the problems of integrating information in manufacturing, above all, because they do not approach PM information.
- *Cost*. Analysts define performance systems that the company considers to be the most appropriate for reflecting performance. It is intended that the process of obtaining the results from these performance indicators will be adequate in

terms of costs. However, at this point in time, all the invested effort is neither totally repaid nor well used by the management in the right way (Alfaro *et al.* 2009).

This situation makes it necessary to seek new e-Manufacturing solutions for information exchange that are specifically oriented to decision support systems dealing with PM. Such solutions must be feasible in terms of useful results at a reasonable cost.

4. PM integrated information framework in e-Manufacturing

A new reference framework is proposed (Figure 3) aiming to help in solving the problems previously mentioned. This information exchange framework provides a homogeneous link to harmonise information exchange among the different formats and data existing in the context of e-Manufacturing. It comprises three sub-systems: conceptual data model, PM information platform and PM-Web service architecture (PM-WS). The conceptual data model is necessary to unify information among the data acquisition systems, the production management systems and the upper-level business systems. The model is based on developing all the information needed to define and obtain the different KPIs required by the PM processes. The PM information platform uses XML and B2MML technologies to structure a new set of PM exchange message schemas (PM-XML). This information platform is complemented by a PM-Web service architecture that uses these schemas to integrate the coding, decoding, translation and assessment processes of the KPIs. These services perform all the transactions required to transform the source data into

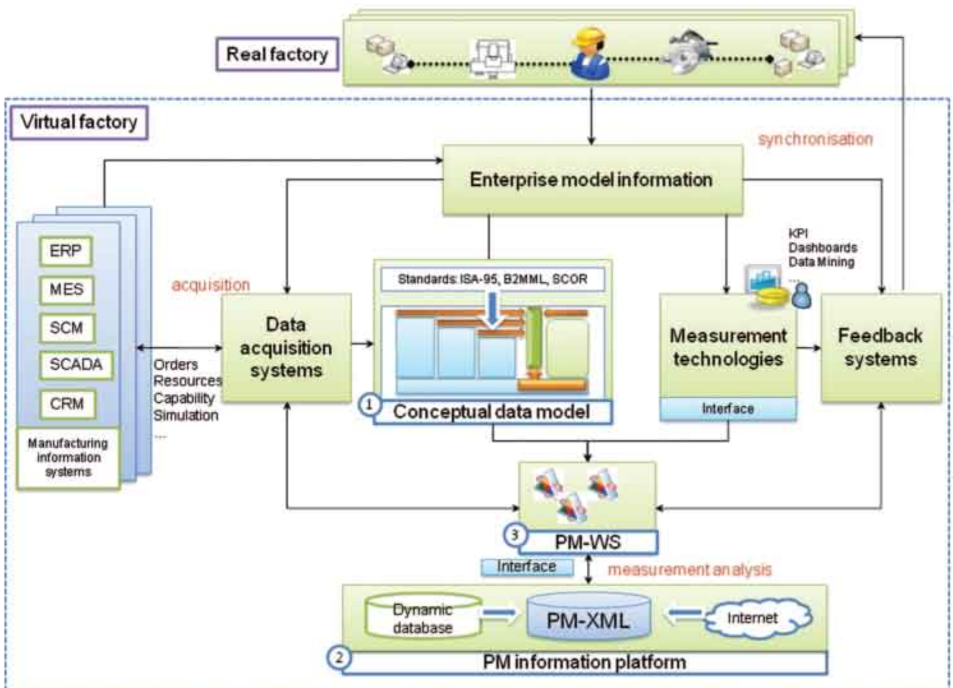

Figure 3. PM e-Manufacturing architecture.

smart information that can be used in the decision-making processes. In this way, the proposed framework offers a homogeneous PM information sharing model that can be applied in a wide range of technological applications.

This framework proposes a new performance information management that will serve as a reference for integrating, standardising and simplifying measurement data. Its use can efficiently manage SCM decision making, in particular in e-commerce and Virtual Enterprise environments.

5. Conceptual data model

In e-Manufacturing business, it is important to select the range of appropriate performance measures and link them to the global strategic intentions or goals to help the business fit in the competitive environment where it operates. The indicators assess the efficiency of manufacturing processes. Due to the importance of the KPI for PM management, the 'Key Performance Indicator' concept is at the core of the measurement information conceptual model. The KPIs are financial or non-financial metrics used to quantify the goals that reflect an organisation's performance. They are generally contained in the company's strategic or operational plan. These indicators form the basis of the PM techniques as a way of getting to know the as-is situation of a process and design continuous improvement actions. They therefore measure the performance level of a process. By doing so, it is possible to be focused on 'how' the set goal can be achieved.

Starting out from this core, made up of the company's set of indicators, a model was developed (Figure 4). The model structures and deploys all those theoretical elements that will enable all the aspects of PM in e-Manufacturing through KPIs.

The theoretical elements have been distributed throughout five data areas:

1. *Definition*: Information for a full definition of the means of measuring the indicator.
2. *Location*: Position inside the production system's hierarchical structure that will allow identifying the data source to get the KPIs.
3. *Programming*: Information related to knowing when and how it will be measured.
4. *Visualisation*: The area balances the different concepts involved in the proposal in a final form that allow viewing and managing the indicators proposed through a model adapted from BSC, ISA-95 and SCOR model.
5. *Results*: KPI values resulting from the measurement process.

The *Definition* area is composed by three elements:

- *Measure*: Numeric value that represents a piece of management data, in this case in e-Manufacturing environment.
- *Measurement approach*: Logical sequence of operations, generally described, used to quantify the value of a base measure.
- *Measurement entity*: Values of KPIs, derived measure or base measure related to the measurement requests.
- The *Location* area is composed by the following elements:
- *Inter-organisational equipment hierarchy*: The equipment model hierarchy. Item types include work unit (lowest level), work centre, area, site, enterprise and

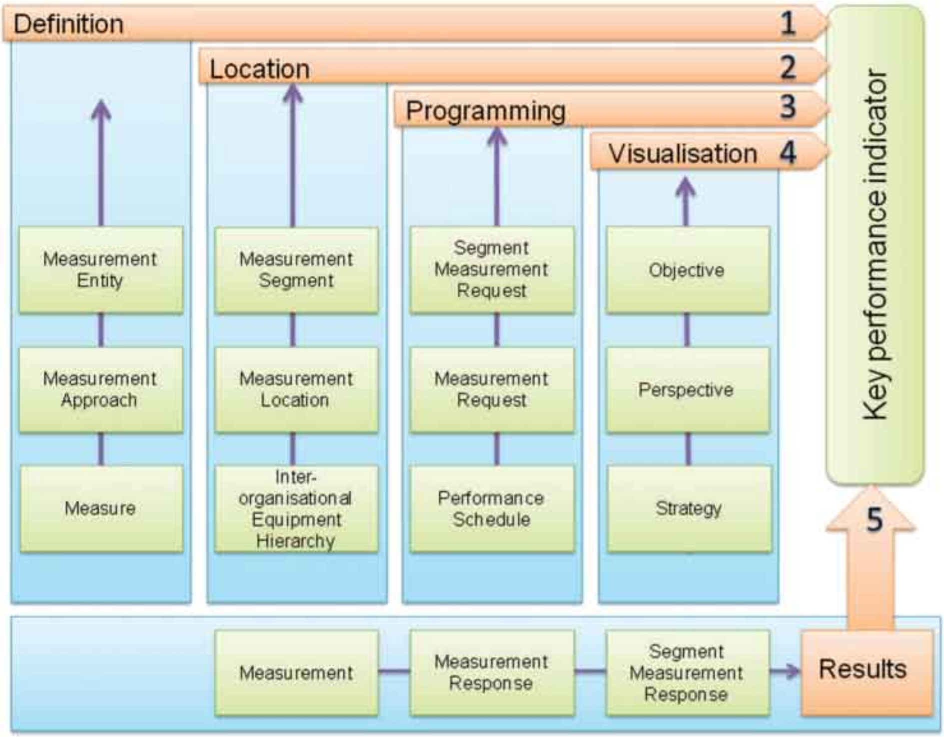

Figure 4. Conceptual model.

inter-organisation (highest level). A top-level location can be composed out of one or more lower-level locations.

- *Measurement location*: Identification of each element in the equipment model hierarchy. Item types include work unit (lowest level), work centre, area, site, enterprise and inter-organisation (highest level). A top-level location can be composed into one or more lower-level locations.
- *Measurement segment*: Resources such as personnel, equipment or material that can be involved in a measurement process.
- The *Programming* area is composed by the following elements:
- *Performance schedule*: Broken down into one or more measurement requests. Each request describes PM specifications.
- *Measurement request*: Involves measurement location, measurement goal and measurement period. A measurement request can involve one or more segment measurement requests.
- *Segment measurement request*: It specifies goals, resources and time of measurement and the measurement segment involved. Finally, each segment measurement request is associated with the KPI defined.

The *Visualisation* area is composed of the following elements:

- *Strategy*: Set of goals for the improvement of the processes which are the object of measurement. The conceptual model takes the top-level SCOR processes to classify, at a higher level, all possible strategies: plan, source, make and deliver. Return SCOR processes will be considered in a future scope of the proposal.

- *Perspective*: Any dimension that is considered critical in inter-organisational decision making and requires a measurement process. The conceptual model does match the perspectives with the four ISA-95 control areas: manufacturing, quality, maintenance and inventory.
- *Objective*: Specific enterprise objectives to measure and improve. As a starting point, the SCOR performance attributes are taken like common objectives: increase flexibility, reduce cost, productivity, increase reliability and increase asset velocity.

Relations between strategies, perspectives and objectives concepts are showed in Figure 5.

In the model, the SCOR processes are the strategies. For example, MAKE process is a strategy. Each strategy is visualised by perspectives using an adapted BSC model. The ISA-95 control areas are taken like perspectives of MAKE process. Each strategy through perspectives is composed of objectives. Objective matches with the SCOR performance attribute. Finally, a KPI set is used to achieve objectives. Table 1 shows examples of the final hierarchy proposed to manage the KPIs.

The last area is *Results* area. This area is composed of the following elements:

- *Measurement*: Each schedule performance is associated with a measurement that provides measurement results. A measurement can contain one or more measurement responses.

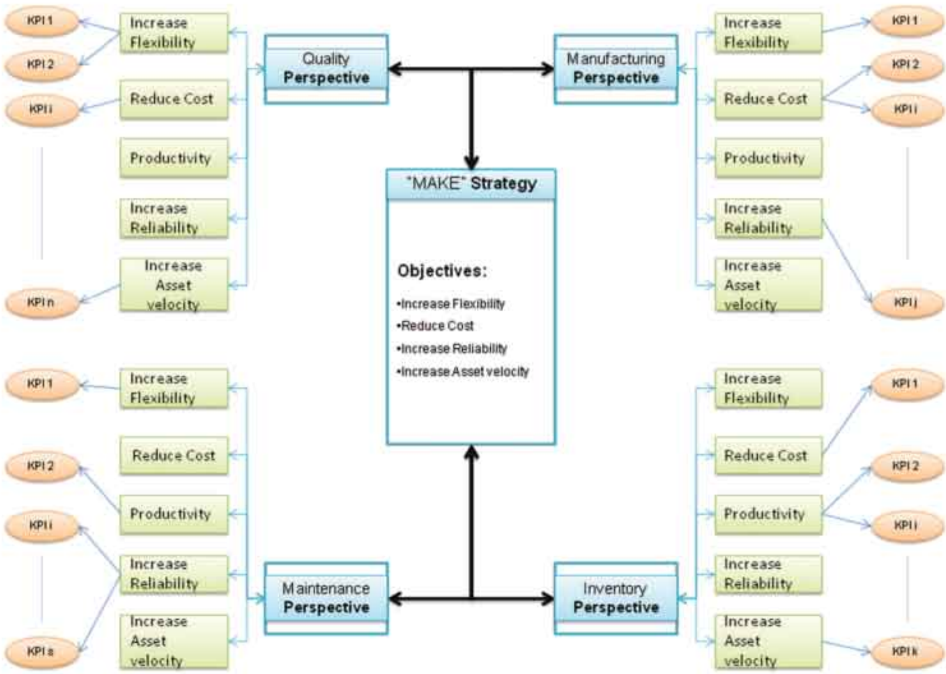

Figure 5. Relations between strategy, perspective and objective.

Table 1. Examples of KPIs and attributes used in the PM conceptual model.

Strategy	Perspective	Objective	KPI
Plan	Planning	Increase reliability	Forecasting accuracy
	Product design	Increase flexibility	Product development time
	Planning	Reduce cost	Order management cost
	Planning	Increase asset velocity	Inventory days supply
Source	Planning	Increase asset velocity	Inventory day-of-supply
	Planning	Reduce cost	Acquisition cost
	Logistics operations	Increase flexibility	Source lead time
Make	Manufacturing	Productivity	Labor efficiency
		Increase flexibility	Lead time manufacturing
		Increase asset velocity	Process cycle time
		Reduce cost	Plant cost per hour
	Inventory	Productivity	Inventory costs
		Increase reliability	Delivery reliability
		Increase asset velocity	WIP days supply
	Maintenance	Increase reliability	MTBF, MTTR, availability
		Productivity	OEE
		Reduce cost	Replacement cost
	Quality	Reduce cost	Warranty cost
		Productivity	Quality rate
Deliver	Transportation management	Reduce cost	Order management cost
	Distribution management	Increase flexibility	Fulfilment cycle time

- *Measurement response*: Measurement response is the result related to a measurement request.
- *Segment Measurement Response*: Segment measurement request can be related to segment measurement response. Its results are the values of KPIs.

All these definitions have allowed developing generic PM information elements that would adjust to international standards such as ISA-95, SCOR or BSC. Such adjustment ensures their applicability and interoperability in heterogeneous environments. The conceptual model for the indicators calculation process proposed in the preceding section has been transformed into specific information elements thought a relational data model (Figure 6).On the basis of these elements, XML templates are created and they form the core of the PM information platform.

6. PM information platform

The proposed PM framework is able to model the required information for decision-making process in performance management. The developed model data allows configuring a central repository for unifying data formats and content to facilitate the transformation, synchronisation and analyses from heterogeneous sources into intelligent information.

For such goal, the construction of the PM information platform based on structuring a set of XML PM schemas called PM-XML Schemas is proposed. These schemas are based on a template to supply all the information and PM rules described in the conceptual model. The schema template allows the construction of XML exchange documents that act as interim documents to transmit the

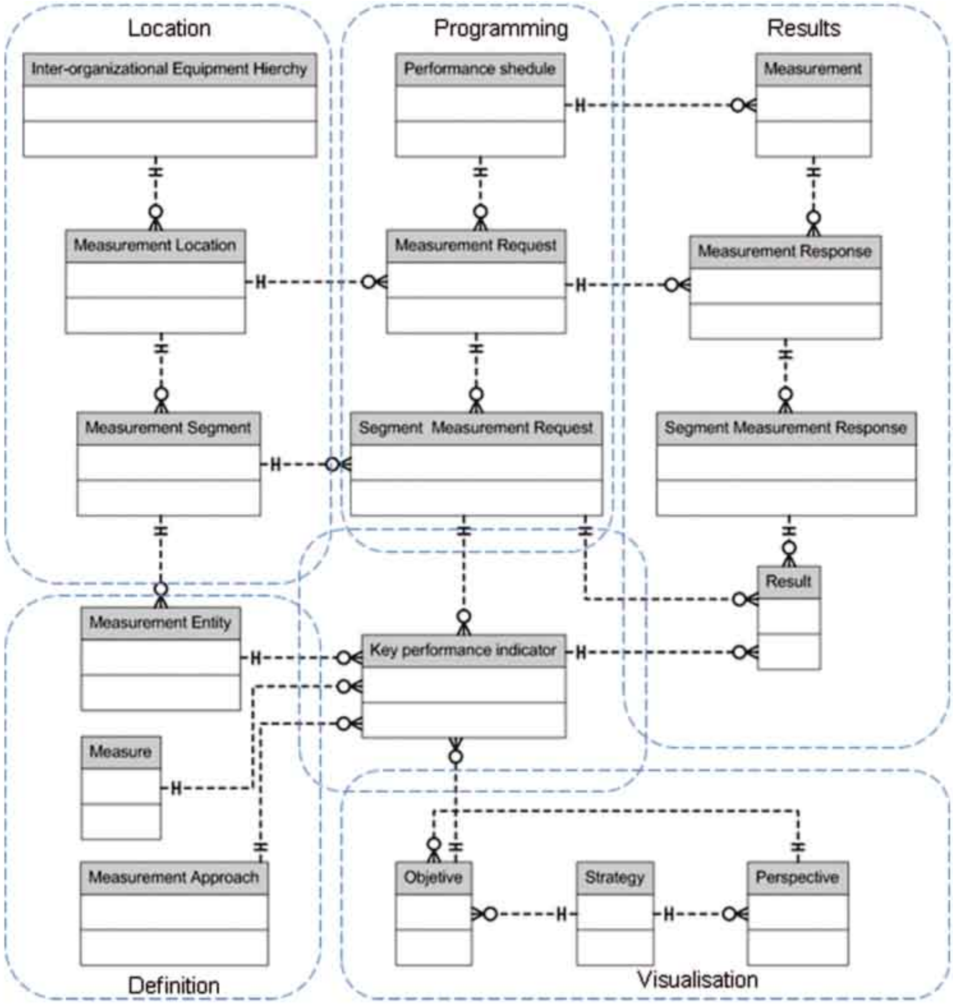

Figure 6. Data model.

information between networked applications. By using XML schemas, the original data remain untouched, but rather the source schemas are combined to construct the messages. A uniform interface is thus created from a multitude of data sources. These schemas have been designed to model PM generic messages as a unified PM information exchange format. The aim is to provide a uniform measurement interface for a multitude of data sources. The PM-XML schemas are constructed in a way that makes them independent from any related applications. The information is exchanged between a transmitter system and another receiver system. In order to hide the heterogeneity, measurement systems can use a unified data format for PM process user applications. This will provide a significant key benefit for a homogeneous information exchange.

For constructing the PM generic message, the structure of the set of PM-XML schemas is based on a template. This template is incorporated into the B2MML schemas as an additional level and is specifically developed for PM. Each PM generic message is a structured information unit that is transported between a transmitter application and one or more receiver applications. An example of PM-XML schema is showed in Figure 7. This example illustrates the rules relating to the message construction for processing measurement schedule proposed in the model. This message is sent from a central measurement system which needs to distribute a measurement schedule to the other applications where this measurement will be executed. As it is explained in the programming area of the conceptual model, the measurement schedule contains the measurement specifications to be performed. The functionality is deployed through two areas: an identification area and a data area. The identification area contains the basic data required by the systems to know from where the message comes and where to send the message response. In this case, the identification area contains the central measurement system information where the measurement schedule has been generated. The data area has two parts: name and verb. The name represents the information of the measurement schedule such as measurement requirement location, start time, end time and key indicator. The verb defines the action to be performed, or the response to a request. In the example, the 'process' verb is related with processing of the measurement schedule.

Due to the creation of the PM-XML schema model, the information formats are transformed into and from the schema template. This is a major advantage, and it provides a solution more efficient than having an undetermined number of combinations of transformation between the different existing data formats.

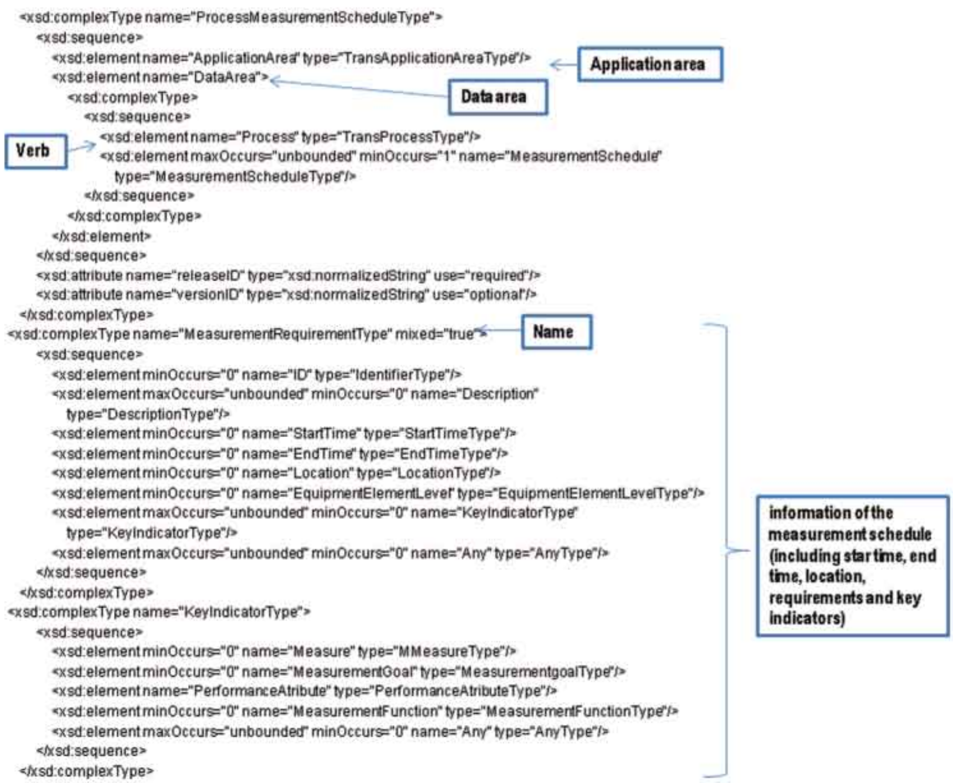

Figure 7. An example of PM-XML schema.

7. PM-Web services architecture

The final sub-system of the framework is an architecture for Web services. These services are converted into an information transmission system for the compilation, conversion, transformation and evaluation of the measurement data, thereby facilitating the conversion from proprietary data to data messages with a unified format.

The Web services architecture lets the information model be applied in PM data acquisition, transformation and data synchronisation systems so that the user will have a unified view of the information. The following requirements were taken into account when designing the Web services architecture:

- *Modularity*: The modules are developed in different parts to reduce development time.
- *Extensibility*: Its application can be extended to construct new control levels.
- *Re-usability*: Use of generic scalable architecture to ensure its use.
- *Independence of hardware and software*: Enables different modules to be distributed in different machines and with different operating systems.
- *Independence of programming language*: Module developers can feel free to choose any programming language with no restrictions.

Figure 8 shows the Web services internal architecture. It comprises four modules that function as Web services: PM decoder, PM coder, PM translator and PM evaluator.

These services function connected to the information source or destination applications or to the message dispatch systems. The services architecture works as a conversion and data communication layer. The mission of these services is to transform a PM source message into a PM generic message and a second phase transforms a PM generic message into a destination PM message.

In the first phase, every PM message coming from any source system passes through a message dispatch system and is received by a PM decoder Web service. This service decodes PM messages and collects the information in order to recognise its structure. To do this, the PM decoder Web service should consider two aspects: the PM content and the action to be performed with this PM content. In the message, the PM content is located in the name area name and action is located in verb area.

The second service to act is the PM translator service. The translator Web service collects the decoded information by the PM decoder Web service and translates the content of the PM source message to the PM generic message by applying the associated message schema rules. The PM translator service depends on the PM evaluator service to apply the calculation functions to acquire the measurement values and check for inconsistencies. Once the PM generic message has been structured, it is sent to the message dispatch system to be transmitted to the destination system.

In the second phase, the PM generic message undergoes a coding process. The PM coder Web service interprets the content of the PM generic message and collects the message schemas associated with the destination system. This information is collected by the PM translator Web service so that the PM generic message can be converted into the required PM destination message. The translator Web service also depends on the PM evaluator Web service to verify that the messages contain all the

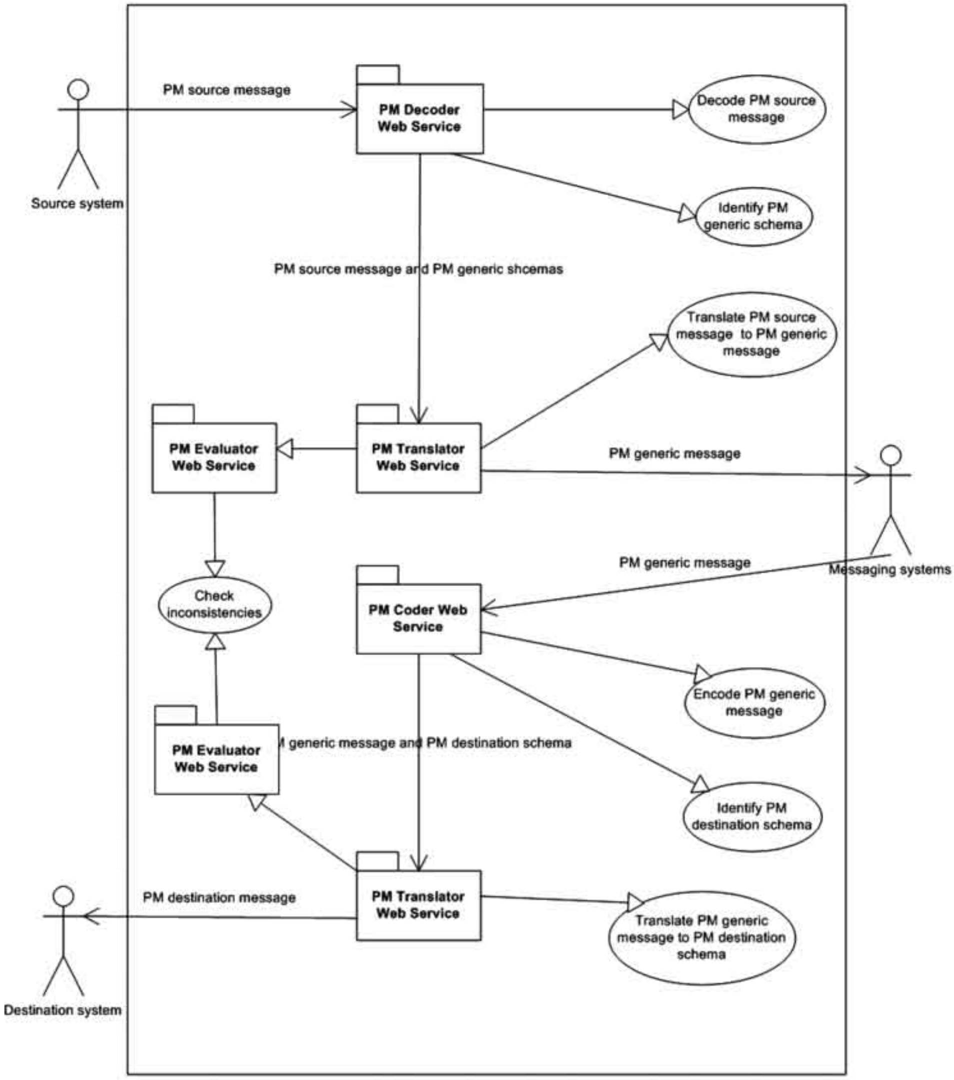

Figure 8. PM-Web services architecture.

information required or if the schemas fail to offer a solution for all the data to be exchanged. If this is the case, any inconsistencies are checked before continuing to handling exceptions.

8. Case study

The feasibility of the proposed framework has been validated by developing a PM data acquisition, consolidation and synchronisation prototype. The processed data correspond to performance loss measurement in production operations. Four phases were executed: preparation, planning, development and test.

- *Preparing*: An e-Manufacturing environment was built including PM data, data source analysis, hierarchical structure and measures selection.

- *Planning*: Models of prototype components were designed.
- *Development*: Development of components was executed on base by models.
- *Testing*: After the prototype was built, tests were executed to valid the information architecture applications.

The result of the preparation, planning and development phases is shown in Figure 9. Data were taken from a set of incident records related to equipment belonging to various production plants. A testing environment was created made up of the following inter-related systems:

- A heterogeneous information environment made up of three data sources. An SQL-Server data register server feed by the PRISMA commercial application service for computer managed maintenance. In second place, the MS-ACCESS data records of a maintenance proprietary application. Finally, an industrial network that equipped the different types of machine and work cell PLC controllers that generated proprietary data in the form of flat log files with the coded records of machine failures.
- A Microsoft Biztalk environment as the motor for exchanging and converting the measurement data.
- The conceptual data model (sub-system 1) as basis to build a unified database called PM-DB.
- The PM information platform (sub-system 2) based on the proposed framework comprising a KPI system and the set of PM-XML schemas used for standardising and normalising data during message construction and conversion.

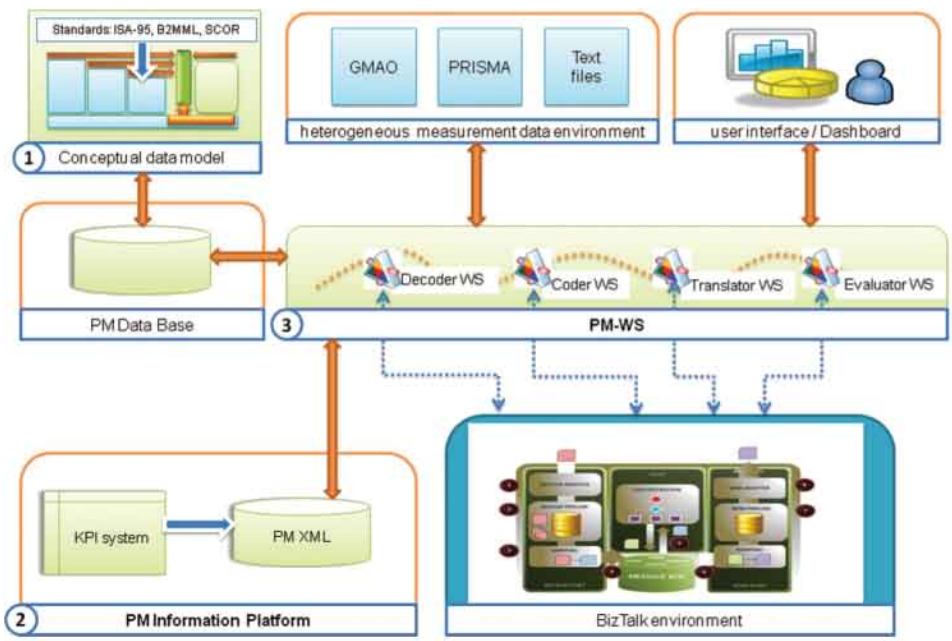

Figure 9. Functional prototype.

- The PM-Web services architecture (sub-system 3) developed in Visual C# used for information exchange and the processes defined in the framework.

The first objective of the prototype was to acquire, transmit and process each piece of maintenance data generated from the three information sources into a common data repository, unifying the terminology according to the proposed PM framework. The second objective was to process the data in the common repository to transform them into information with added value in the form of KPIs that could be used by a dashboard.

Information was transmitted and converted by using the Ms-Biztalk platform supported by the use of the proposed Web services architecture. The PM decoder Web service was chosen to convert the data from the three different formats into messages with a common format. The PM translator Web service worked in conjunction with the Biztalk data conversion environment. The Biztalk environment was also entrusted with transmitting the messages to the PM database. The messages were received by the PM coder Web service which converted the message into data so that it could be recorded in the database. The coder and decoder Web services were dependent on the evaluator Web service, which ensured the compatibility of contents with the defined PM-XML schema set.

Other Web services were programmed for information processing and indicator calculation. In the developed use case, the coded machine incidents were processed to identify the downtimes and to calculate usual maintenance metrics such as MTBF, MTTR or Availability.

Testing phase was executed to valid the prototype functionality and information framework. Three kinds of tests were executed: unit tests, integration tests and validation tests. Unit tests were executed to valid the modules functions. Integration tests were executed to valid the functionality of the prototype. These functionality was controlled through an ASP.NET Web application that is shown in Figure 10.

Using this Web display control, the flow of maintenance information could be managed from data sources to PM-DB. Web controls were designed to manage the following steps:

1. *Source application*: Execution in a Web environment of the source data application.
2. *Source data model*: Reference to entity-relationship model established in the source data application. This is used for the analysis of data formats and types.
3. *Source database*: Revision of tables or queries of specific data in the databases involved.
4. *PM source message*: XML documents generated from the data extraction from source systems so the different formats can be evaluated.
5. *Execute data integration*: Start a data integration cycle.
6. *PM generic message*: XML documents transformed by the Web services using PM-XML schemas.
7. *Inconsistencies*: Possible inconsistencies generated in a data integration cycle.
8. *Unified database*: Central data repository to display data acquisition from the various sources of information.

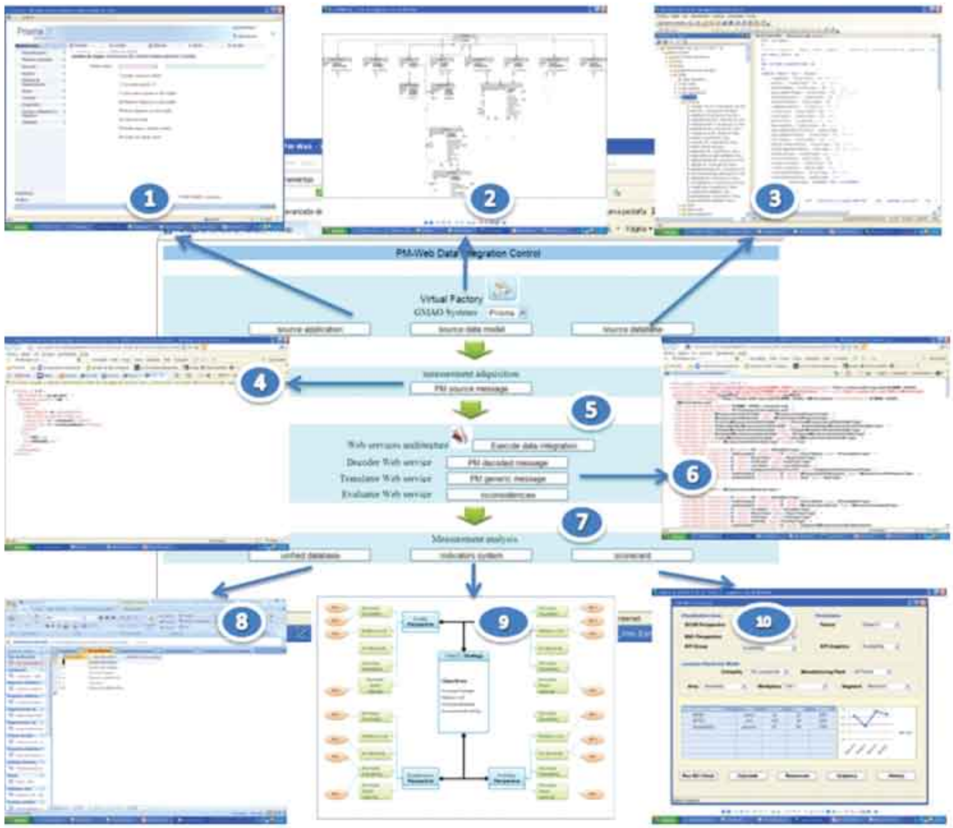

Figure 10. Web display control.

9. *Indicators system*: Access to the group of maintenance indicators used by prototype to analyse their roles and relationships through the maintenance data flow.
10. *Scorecard*: A dashboard generated by the prototype for the processed data (Figure 11).

From the business point of view, the prototype shows its full potential in the developed control panel. The control panel translates, to the real practice, the Visualisation and the Results area proposed by the conceptual model. In this way, the prototype integrates all the performance information in a simple user-interface:

- An area for selecting the set of indicators based on filters. It displays values based on SCOR Strategy (plan, source, make, deliver), Perspective (quality, manufacturing, maintenance, inventory). These values are associated with objectives or KPI Groups and they can be created by the user in a flexible way. In the case developed, the KPIs are related to the maintenance area. The flexible structure of the PM Model can be used to define a database of KPIs tailored to the specifics of each case.

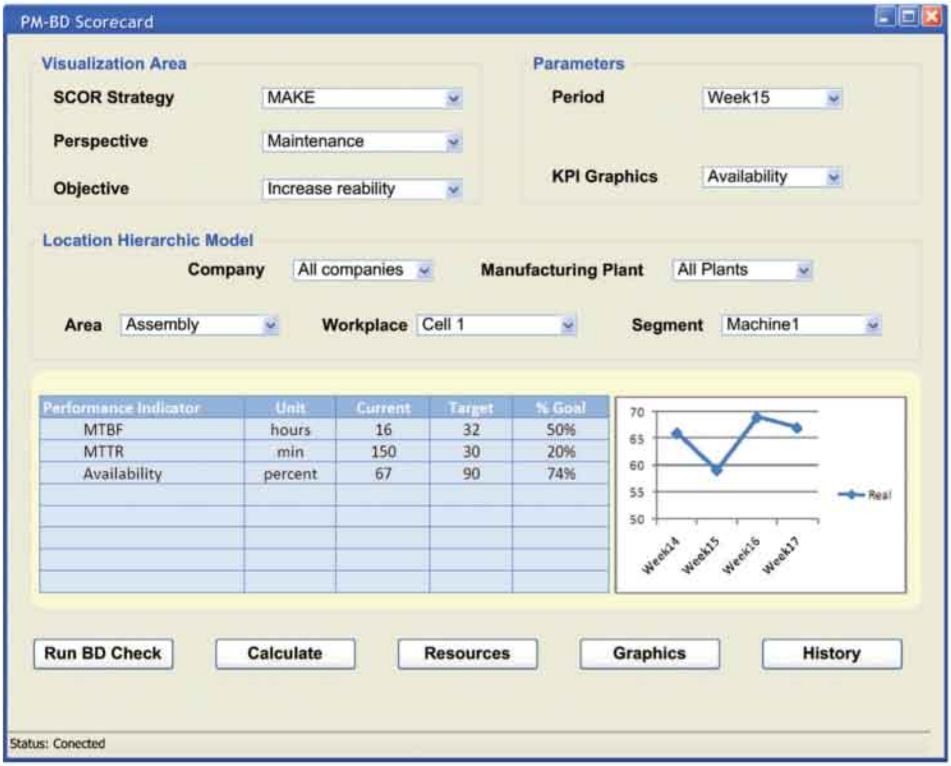

Figure 11. Scorecard panel for performance measurement.

- An area for selecting the physical location of the manufacturing system and where the data are generated. It is based on the attributes of the hierarchical structure of the model PM: company, manufacturing plant, area, work place and segment. The model's flexibility allows configuring any production system, including a collaborative model between companies. In the case developed, all maintenance data sources are processed by the PM-Web Services to create unified information associated with the process segment, defining the rules and formulas that translate row data into metrics.
- A grid of follow up with the list of specific indicators involving the PM Process for the defined strategy-perspective-objectives. For each indicator, it shows the unit of measurement, baseline and target values.
- Graphical tools for tracking process improvement for each KPI.

Validation tests were used to valid the information architecture framework. A testing plan was designed including four testing cycles:

- *Cycle 1*: Sending measurement data from data sources to PM-BD. These data were integrated and registered without any previous calculating processes. This cycle involved a huge sending of data message. Measures values were calculate after the data were integrated.

- *Cycle 2*: Sending base measure values from data sources to PM-BD. Base measures values were calculated before they were sent. This cycle involved less data amount during the message sending than the previous cycle. Key indicators and derivate measures values were calculated after the data were integrated.
- *Cycle 3*: Sending derivate measures values from data sources to PM-BD. Base measures and derivate measures values were calculate before they were sent. This cycle involved less data amount during the message sending than the previous cycle. Only key indicators values were calculated after the data were integrated.
- *Cycle 4*: Sending key indicators values from data source to PM-BD. In this case base measures, derivate measures and key indicators values were calculate before they were sent. This cycle involved the least data amount during the message sending. No values were calculated after the data were integrated.

Testing phase has validated the flexibility of the information framework application. The successful integration of different Web heterogeneous data sources ensures its applicability to other areas of the factory. The greatest potential of the model is the flexible hierarchy of the framework. Such flexibility is allowed by the conceptual model, object model, XML schemas and Web services. The system allows integrating, in the same environment, all the concepts surrounding the management strategies to improve manufacturing systems through KPI. Moreover, the system ensures interoperability with business applications that follow BSC, ISA or SCOR models. All of them are currently being used widely by industry. Under these conditions, the proposed framework becomes an alternative for the development of new generations of systems to manage Web information in real-time to generate KPI systems.

9. Conclusions

The emerging demands of e-Manufacturing environments in the context of inter-organisational manufacturing require new frameworks and tools to approach PM processes in Web environments. In this sense, e-Manufacturing would be able to integrate innovative intelligence into manufacturing systems.

This paper has presented a PM information framework which helps to improve the integration required for decision-making information processing procedures in Web environments. Addressing one of the main issues identified in the literature to support PM processes.

Within the proposed framework, a practical possibility is suggested for unifying data formats and contents to facilitate the transformation, synchronisation and analyses required by PM processes. The proposed data model allows modelling the information required by PM processes, while the Web services architecture performs all the transactions to convert the data collected in the plant or business applications into smart information for decision-making processes. The data model is supported by the use of XML and B2MML data exchange standards to ensure its applicability. The proposed PM-XML template lets homogeneous data messages be constructed. Such messages can be exchanged between the various applications, systems or connected devices. In this way, a reduction in the time needed to process these messages can be achieved, while it also allows the construction of software with a more general functionality that is adaptable to different formats and data types. The practical use of the set of tools was validated through a specific case study of manufacturing equipment performance information measurement.

The results from the case study show that the proposed framework provides an optimised and homogeneous exchange of PM information via the Web to facilitate the application of virtual manufacturing strategies.

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