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Knowledge-based assessment of manufacturing process performance: integration of product lifecycle management and value-chain simulation approaches

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Regarding the market globalisation, manufacturers have to improve the performance and efficiency of their production plants. To fulfill this goal, managers need methods and tools to assess their product development and their production engineering processes by assessing the performance and the value of the specified technical solutions. This article presents a new approach to support this assessment of manufacturing enterprise processes in terms of performance and value indicators based on knowledge management (KM) integration. Based on the principles of value chain, in one hand, and on methods of KM, on the other hand, the aim of the proposal is to help experts to make relevant decisions on product development and/or production process planning. The approach originality is to use of product lifecycle management (PLM) capabilities to achieve semi-automated capitalisation of heterogeneous knowledge from various enterprise information systems. Capitalised knowledge is then used as an input of the assessment module. This module implements a set of simulation algorithms for the assessment and evaluation of different alternatives of value chains according to required performance criteria.

Keywords: knowledge management; product lifecycle management; value-chain simulation

1. Introduction

In the current context of globalised market, companies are faced to a hard competition and always need to develop new sources of value. In parallel, manufacturing enterprises try to save money by using numerous means such as relocation or concentration on core industrial activity and business process.

In such a context, the evaluation of the business performance and enterprise assessment is already an important challenge for any kind of industry, which intends to preserve its competitive advantage regarding globalised market. According to Kaplan and Norton (1992), such an approach allows managers to answer four fundamental questions:

- How do we look to our shareholders (financial perspective)?
- What must we excel at (internal business perspective)?
- How do our customers see us (customer perspective)?
- How can we continue to improve and create value (innovation perspective)?

Due to such important questions, several research works are led in product lifecycle management (PLM) field to define enterprise strategies and performance management system and to develop tools and technologies to support these purposes (Peñaranda et al. 2010).

In an operational view, the aim of performance assessment approaches is to evaluate and compare different technological or manufacturing activity choices (based on product and process development alternatives) on the manufacturing performance activity of the enterprise (Bosch-Mauchand et al. 2010). To perform such evaluation and comparison, value-chain concept is applied to define performance indicators that provide means of comparison between several alternatives of value chain. The result should help both the manufacturing expert to assess the process performance, and the designer to choose the best technical solutions.

However, one of the major challenges of such approaches is the need of different knowledge categories covering, on the one hand, product and process characteristics and, on the other hand, the expert viewpoint and all links between product-process properties and performance indicators.

Knowledge management (KM) becomes a necessary stage for the success of the performance assessment. In the case of explicit knowledge, the information system (IS) encapsulates knowledge’s modelling. An efficient way to capture knowledge is

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to use communication and information functionalities provided by information technology (IT). Indeed, the new generation of information and communication technology (ICT) systems might foster better consideration of these aspects by supporting the management and the traceability of relevant data and information. Thus, it might facilitate stakeholders’ collaboration among the whole product lifecycle in a context of virtual organisation.

Because of its distributed and multi-IS connection properties (Abramovici and Sieg 2002), PLM offers significant advantages to support the knowledge capture stage. The use of PLM approach might improve the capture of the product and process knowledge from numerous applications. This approach might be also used to generate, organise, share and reuse the relevant knowledge according to the projects’ goals.

The aim of the proposal is to describe a new knowledge-based approach taking advantage of PLM systems for captioning product and process knowledge from different IT systems. This knowledge is used as an input of a performance assessment module based on a chain value concept.

The following section presents a literature survey focusing on the problem statement of manufacturing enterprise performance assessment. It is also introduced a discussion on the concepts of value chain and analytical hierarchy process (AHP) with the aim to use them in the performance assessment process. The problem statement is detailed in Section 3 with an overview of the capabilities of ISs to support KM in order to cope with the lack of knowledge integration in an oldest approach. In Section 4, the field of PLM and KM is depicted to underline the enrichment that can be obtained by a KM approach. Section 5 details the set of performance indicators used to assess enterprise performance based on the value-chain concept and AHP method presented in Section 2. Finally, Section 6 describes an innovative PLM–KM-based framework integrating knowledge capture module associated to a performance assessment module that aims to generate performance indicators. The conclusion discusses the advantages and limits of the proposal.

2. Manufacturing process performance assessment

The specification of performance measurement systems fitting the organisation and management of modern companies is a topic of increasing concern for both academics and practitioners (Neely et al. 2000). This section presents an overview of the research works dealing with enterprise performance assessment. After a short literature survey, an analysis of the value-chain approach is developed in order to identify and define its main characteristics. This analysis should point out the needs to integrate various experts’ knowledge in order to improve result robustness.

2.1. A literature survey

The performance assessment of manufacturing processes is generally performed by using models developed from a particular point of view (temporal, financial, etc.). For manufacturing companies, a classification of the most useful performance criteria has been established in order to determine what criteria must be evaluated to give a measure of the product value and also the value provided by the value chain. Abdel-Maksoud et al. (2005) distinguish six broadly separate categories of measures: product quality, customer satisfaction, on-time delivery, employee morale, efficiency and utilisation, and product development. Each category owns financial and non-financial indicators.

Furthermore, cost indicator takes a huge interest because it concerns all product life stages. A benchmark of market cost concepts gives a checklist of cost functions: activity-based costing (ABC), direct materials costing, process costing, cost-centre analysis, cost element analysis, cost planning, cost variance analysis, etc. (Moalla et al. 2009).

Some research works try to find a methodology for performance assessment of enterprise processes. In this aim, Ghalayini et al. (1997) review the historical evolution and modern developments of manufacturing performance measurement within a systems framework based on five metrics and five levels from single workstation to the entire enterprise network (Hon 2005). The five levels cover: machine, cell, line, factory and network. In parallel, five major metrics are used for performance measurement, i.e. time, cost, quality, flexibility and productivity.

Based on industrial experience, Ahmad and Dhafr (2002) set out the basis to establish key performance indicators (KPIs) in manufacturing companies within a measurement methodology for the implementation of such indicators in industrial case. The KPI system is divided into six sections: safety and environment, flexibility, innovation, performance, quality and dependability (or reliability). It focuses on dependability in which the key indicators are customer complaints, on-time-in-full delivery to customers, on-time-in-full delivery from suppliers and overall equipment effectiveness.

In more recent work, Tan et al. (2007) propose a methodology for dynamic performance assessment of enterprise processes based on seven criteria: time, quality, service, cost, speed, efficiency and importance. The evaluation models are based on ABC and
Activity-Based Management. Other specific evaluation approaches are proposed in the literature in context of extended enterprise and supply chain management (Beamon 1998, Folan and Browne 2005) and for customer-satisfaction orientation (Ahmad and Dhafr 2002, Chen 2008), etc.

Another interesting way for the assessment of the enterprise performance is to focus on all benefiting entities, which contribute to the creation of added value for a specific project. Previous works on this topic have argued the advantages of AHP and value-chain approaches (Mauchand et al. 2007). The following sections describe these approaches in a detail way.

2.2. Interest of AHP and value-chain approaches for manufacturing process performance assessment

In the context of new organisations of manufacturing enterprises, the concept of value becomes a relevant indicator for the definition and the implementation of a performance measurement system (Cunha et al. 2008, Rodriguez et al. 2009). The value nets approach proposed by Elhamdi et al. (2003) gives good example of such applications. In this work, value nets are used to model the enterprise dynamic regarding material and information flow. It tries to estimate the performance regarding the efficiency and the effectiveness of the manufacturing system.

Regarding value engineering subject, AFNOR X50-151 standard gives the definition of the term ‘value’ as: ‘The value is the judgment related to the product on the basis of the user’s expectations and motivations, expressed by a ratio which increases when, all other things being equal, the satisfaction of the user’s need increases and/or the expenditure related to the product decreases’. Other definitions pointed out the property of multi-point of views and multi-criteria of the value concept (Elhamdi et al. 2003). The definition adopted in this work is based on the proposal of (Lonchampt 2004): ‘Value reflects the judgments related to the product on the basis of the user’s expectations and motivations, expressed by a ratio which increases when, all other things being equal, the satisfaction of the user’s need increases and/or the consumption of resources required by all the life cycle phases decreases’.

The value of an enterprise object is linked to the benefiting entities (for instance, the shareholders). The benefiting entities can benefit or act on this value. They can be external and/or internal actors of the enterprise. Their appreciation of the product and enterprise performances needs to be modelled in order to give a value indication. The assessment of value is the result of a combination of several performance indicators such as cost, quality and time (Chen and Huang 2006). These criteria could be mixed with more subjective indicators such as customer perception, associated services and environmental impact.

To be realistic, the assessment approach must not just be an analytical evaluation. A way to be more relevant is to use simulation such as it is done for product performance simulation (structural analysis, kinematics simulation, etc.). Furthermore, the integration of qualitative and measurable criteria should improve the result robustness. The integration of such criteria requires the use of a robust multi-criteria decision-making approach such as AHP (Ayag 2007), Multiple Attribute Utility Theory (Keeney and Raiffa 1993) and Out-ranking Methods (Roy and Vanderpooten 1996).

The AHP method consists of three main principles, including hierarchy framework, priority analysis and consistency check. Formulating the decision problem in the form of the hierarchy framework is the first step of AHP, with the top level representing overall objectives or goal, the middle levels representing criteria and sub-criteria, and the decision alternatives at the lowest level. Once a hierarchy framework is constructed, users are requested to set up a pair-wise comparison matrix at each hierarchy and compare each other by using a scale pair-wise comparison as shown in Table 1 (Saaty 1980). Finally, each comparison matrix is then solved by an eigenvector method to determine the criteria importance and alternative performance.

Based on the AHP and value concepts, the process of enterprise performance assessment is proposed to evaluate and compare the performance of different alternatives of value chain for a same product in the

Table 1. Scale for pair-wise comparisons in AHP process.

<table>
<thead>
<tr>
<th>Relative intensity</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal value</td>
<td>The two elements have equal value.</td>
</tr>
<tr>
<td>3</td>
<td>Slightly more value</td>
<td>Element A is slightly important compared with element B.</td>
</tr>
<tr>
<td>5</td>
<td>Strong value</td>
<td>Element A is strongly important compared with element B.</td>
</tr>
<tr>
<td>7</td>
<td>Very strong value</td>
<td>Element A has demonstrated importance compared with element B.</td>
</tr>
<tr>
<td>9</td>
<td>Extreme value</td>
<td>Element A is extremely important compared with element B.</td>
</tr>
<tr>
<td>...</td>
<td>Other values</td>
<td>Intermediate values when compromise is needed.</td>
</tr>
</tbody>
</table>
first steps of its development. That is why this assessment process is divided into three main stages aiming at forecast the performances (Figure 1):

- The value-chain modelling is the first stage of this approach. It aims to identify all required inputs and expected outputs for the approach.
- The value-chain simulation provides the performance results of the expected process chain that are considered for the manufacturing of the product.
- The value-chain analysis uses the AHP process to draw a multi-criteria analysis including the judgement of the benefiting entities.

3. Problem statement: lack of expert knowledge integration

The value-chain modelling gives an appropriate support for performance assessment in the way that this kind of modelling is based on heterogeneous indicators and that the basic principle of activity links (or is linked to) all the modelling elements. Those indicators have to be understood by all the experts. Moreover, the AHP process gives more advantage by taking into account various expert’s views in the decision-making.

The main question to solve is: what is needed to make relevant decision to assess the set of technical solution in terms of performance criteria such cost, quality and time? To fulfill this need of assessment, the first point is to be able to specify the manufacturing resources that must or can be used to produce this set of technical solution. Also, the technical solutions have to be declined in terms of manufacturing and supply activities. How can I produce this? What? Who? Where? When? How? Why? . . . What are the raw materials? What are the manufacturing resources? . . .

This is the main concern of design for manufacturing that requires knowledge and understanding of the relationship between product features and manufacturing process (Elgh and Cederfeldt 2007).

For instance, a link can be established between product and some kinds of performance criteria such as cost and value. To explain this idea, Perrin (2001) describes a product according to two views: a Function/Value view and an Artefact/Criteria view. In the Functions/Value view, the product is described as a set of abstract functions tree representing its utilities. Associated to each function, performances to fulfil are clarified. The value of the product is then estimated according to the real utility of its functions.

In the Artefact/Criteria view, the product is described as a set of technical solutions. The technical solutions represent the physical objects produced to meet the functional requirements. The performance of the product is assessed in this view according to the triptych: cost, quality and time. In order to underline the operational aspect, Mauchand et al. (2007) propose to add a third view, named Value Chain/Performance view. This view will give the concepts to be able to link the technical solution to the corresponding manufacturing activities that contribute to its production.

Regarding the last proposal, the essential and tricky point is to define the link between technical solutions and activities. Only experts that own specific knowledge on the enterprise and on the technical processes are able to define this link. Consequently, the deployment of the value-chain approach requires the contribution of various experts. In parallel, numerous product and process knowledge are used as input for the approach (Figure 2).

To cope with this complexity, this expert knowledge has to be captured and modelled to define expert rules. In a manual way, the expert is in charge of the introducing of all relevant information for the deployment of the method. The KM methods might be used

![Figure 1](image1.png)  
Figure 1. Process of manufacturing process performance assessment.

![Figure 2](image2.png)  
Figure 2. Main factors for the success of the value-chain approach.
in order to ensure the capitalisation of knowledge from manufacturing experts (Studer et al. 1998).

Regarding KM research community, numerous systems and methodologies are developed with the aim to support knowledge modelling, storage and reuse (Liao 2003, Virtanen and Helander 2010). Regarding industry needs, knowledge-based systems can be presented as dedicated databases, documents, reports, etc. The integration of a knowledge-based module with the value-chain approach might enhance the results robustness and decrease the need of manual contribution of experts in the aim of an automated assessment process.

However, new generation of IS should offer large capabilities to manage information representing the explicit part of expert knowledge. One of the most judicious solutions is to use these capabilities for the building of the knowledge-based module. Due to their integration properties, PLM systems should give several advantages for the implementation of such a solution. The following section presents a literature survey on the existing expert knowledge in the enterprise and how this knowledge can be structured in IS. The main conclusion is to validate the capabilities of PLM systems to support KM process.

4. PLM and KM

Unlike data and information, knowledge is more difficult to define since it is associated to cognitive resources and expert activity (Grundstein 2001). Indeed, according to Guerra-Zubiaga and Young (2005), data relate solely to words or numbers, which meaning is dependent of the context where it is used. Information is structured data used to provide a meaning within a given context. Knowledge exists when the user within that specific context recognises useful data relationships, or when the user is able to derive those relationships from raw, but structured information database.

Furthermore, two kinds of knowledge are currently distinguished in the literature: tacit and explicit knowledge (Nonaka 1991). Explicit knowledge is the objective and rational one that is captured in storable document such as texts, tables, formulas, diagrams and product specifications. Tacit knowledge is subjective and cannot be articulated. However, several research works are developed in the literature to deal with the problematic of tacit knowledge representation and capitalisation.

Regarding industry context, two main categories of knowledge are currently distinguished as key knowledge for development process: product engineering knowledge and manufacturing process knowledge. In order to model, structure and share this knowledge, experts use different documents and IS’s components.

The next subsections present a survey about recent development of ICT systems supporting such a kind of knowledge.

4.1. ICT supporting product knowledge

There exist several recent works dealing with models and ontology in order to represent the product knowledge. Product modelling techniques in computer-aided design (CAD) systems currently include parametric design and feature technology, whereas features can contain information regarding geometry and/or semantics (Krause et al. 2005). The product model includes not only the geometry and shape (Liu et al. 2009) but also higher level of product information (e.g. product and manufacturing information, and geometric dimensioning and tolerancing). Within product model, designers/engineers can also integrate information required to support decisions that can be used at later stages of product lifecycle such as manufacturing, maintenance and sales activities (Abinash et al. 2009). However, one of the most usual modelling approaches is the ‘Function–Behaviour–Structure’ (FBS) approach (Gero and Kannengiesser 2004). Various models are developed as an extension of the FBS method to cope with specific needs (Sudarsan et al. 2005).

Product data management (PDM) systems are claimed as capable of speeding up the process of distributing engineering information and knowledge, while centralising management of the overall product development process (Eynard et al. 2004). In a general way, the modelling and the structuring of the product’s functions are currently supported by requirements’ engineering applications. The PDM systems are used to manage the engineering Bill of Material (eBOM) that is composed of components, parts and sub-parts. The corresponding product’s structure for manufacturing view (mBOM) is stored in the enterprise resource planning (ERP) system. More conventional database approaches in the industry are related with configuration management systems in order to integrate others categories of product knowledge.

A number of shortcomings appear in the current commercial systems, such as the lack of: design knowledge sharing, links with ERP systems and a generic standard for PDM system implementation (Gao et al. 2003). A few research prototype tools have been reported, aiming at integrating artificial intelligence into PDM systems such as the distributed open intelligent PDM system (Kim et al. 2001). Other prototype systems using metadata, ontology and mapping relationships have also been developed to manage product data in virtual enterprise (Yoo and Kim 2002). Other specific systems are reported as being able to manage product knowledge. For instance, a
KM database was developed to support the manufacturing assessment of gas turbine engines (Balogun et al. 2004). This is another specific KM tool, which refers to the modelling of complex product specifications, down to component feature details, allowing for the representation of manufacturing operations, process chains and costs. Design Analysis Tool for Unit-cost Modelling project proposes another interesting knowledge-based system that aimed at estimate the cost of an aircraft engine and its subcomponents (Scanlan et al. 2006).

4.2. ICT supporting process knowledge

During the first steps of the production engineering and production planning, numerous expertises are needed to set up the manufacturing activities. Manufacturing knowledge is included in standards and specific documents. It concerns the process scheduling, the resource allocation (human resources, machines, tools and tooling), the product description (part masters, mBOM, etc.), the definition of the manufacturing unit (work centres numerical control (NC)/Robot programs, etc.) and the manufacturing know-how (Fortin and Huet 2007, Guerra-Zubiaga and Young 2008).

The process knowledge definition is based on activity models: activities allow creating the link between products, resources (facilities, workers, etc.) and their characteristics (behaviour, task, properties, etc.). They define and structure the processing of operations. An activity aggregates several kinds of knowledge such as sequences, functions, rules and states (Vliegen and Van Mal 1989).

The knowledge modelling required for specifying production plans is often a huge task in manufacturing field. The knowledge capturing and management are another important challenge in manufacturing (Rentzscn et al. 2005), especially when product definition may change during its lifecycle.

Facing to this complexity, the modelling and management of manufacturing knowledge have long been an important challenge for scientific researchers (Guerra-Zubiaga and Young 2006) and for IT vendors (Chryssolouris et al. 2008). This highlight interest is reflected in the large panel of current systems in manufacturing process planning. Nowadays, ERP, manufacturing process management (MPM) and digital factory systems are largely used to structure, store and manage the process knowledge. The MPM with the mBOM, the resources Bill of Material (rBOM) and process plan definition is the gate to ERP system (Newman and Nassehi 2009).

The ERP systems have been developed to integrate and optimise large range of business processes that are multifunctional and complex. The aim is to reduce process implementation problems (Mabert et al. 2001, Botta-Genoulaz and Millet 2005, Hermosillo et al. 2005). The MPM systems have been developed with the goal of aiding production engineers in the specification and planning of manufacturing process (Denkena et al. 2007). In Verein (2008), MPM is defined as ‘a comprehensive network of digital models, methods and tools – including simulation and 3D visualisation – integrated by a continuous data management system. Its aim is the holistic planning, evaluation and ongoing improvement of all the main structures, processes and resources of the real factory in conjunction with the product’.

Other specific manufacturing knowledge-based systems are proposed in the literature such as ‘Pro-Planner’ system developed in Pham and Gölloğlu (2001) and Gölloğlu (2004) for integrating a series of computer-based applications using multiple knowledge and reasoning models for representing process limits and machining capabilities in existing shop-floor facilities.

Based on manufacturing facility information and knowledge model (MFIKM), Guerra-Zubiaga and Young (2006) have proposed a knowledge-based system to support process planning decisions such as process selection according to a set of knowledge element describing the manufacturing context. The MFIKM model is based on knowledge, process and resource (KPR) concepts forming the knowledge structure for manufacturing. Guerra-Zubiaga et al. (2006) illustrate the global architecture of the KPR model applied to assembly process design. The knowledge structure distinguished three major parts: facility knowledge which is classified in process knowledge and in resource knowledge. In parallel, the classification of the three types of knowledge is introduced for explicit, tacit and implicit knowledge.

Agent-based approaches have also been proposed by Koh and Gunasekaran (2006) in order to simultaneously use tacit and explicit knowledge, within material requirements and manufacturing resource planning systems, for the management of uncertainty in manufacturing field.

4.3. PLM system as enabler for KM

One of the moment questions for industrial companies is how to define an IS that is the most suitable tool for knowledge capitalisation/management. In a lot of companies, the IS consists of heterogeneous components covering all sectors of the company. Each element covers a particular function (ERP, PLM, supply chain management and customer relationship management). The idea to exploit ICT as support for KM has been explored by several authors. For example, Bissay et al. (2009) propose methodological approach for the integration of the classic knowledge capitalisation cycle
within PLM system. In the same perspective, Mahdjoub et al. (2010) propose a new knowledge engineering system that is embedded in a PLM environment in order to capture knowledge generated during collaborative design activities. This knowledge is used to guide the designer inside a virtual reality environment to improve the product or workplace usability.

The PLM is defined as a systematic concept for the integrated management of all product-related information and processes through the entire lifecycle, from the initial idea to end-of-life (Saaksvuori and Immonen 2006, Terzi et al. 2010). In Jun et al. (2007), PLM is considered as a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination and use of product information across the extended enterprise. The PLM ensures the integration, the storage and the management of numerous data that is created by specific application in different stages of the product lifecycle. The aim is to improve the information and data sharing between partners, customers and suppliers (Merlo et al. 2005, Belkadi et al. 2010). The ICT support for PLM results from the integration between heterogeneous systems such as ERP, PDM, CAD and computer-aided manufacturing (Schuh et al. 2008).

Because of highlight interactions between design and manufacturing department, MPM systems are rapidly becoming an integral part of new PLM solutions derived from engineering tools. But they also offer viable and systematic links for integration with ERP systems (Galeta et al. 2008).

According to Ameri and Dutta (2005), lifecycle knowledge is the knowledge generated or consumed by various processes throughout the product’s life cycle. Associated with each lifecycle process is one or more human or non-human agents which interact with the PLM knowledge base (KB) in the course of delivering their service. In such applications, PLM KB is not necessarily a physically centralised knowledge repository but it should be presented as an interconnected network of distributed knowledge repertoires which are virtually unified using ICT (Guerra-Zubiaga et al. 2006). For instance, four PLM applications are identified by these authors as support for information and knowledge sharing in assembly process according to the KPR concepts. It concerns: product design analysis, layout planning analysis, ergonomic analysis and factory flow simulation.

4.4. Synthesis

The literature survey shows the important interest given to the development of ISs that support the expert activities and that aims to handle information sharing and storage in the databases. Some of these tools intend to capture knowledge expert such as expert rules and procedures. Both implicit and explicit knowledge are considered in these systems.

In coherence with Grundstein (2001) and Tsuchiya (1993), our position is that both explicit and tacit knowledge are incorporated in cognitive resources of individual and only information and data are observed and shared in the real world. Documents, databases and other supports manipulate a set of data and information. A part of this information is a representation of knowledge. The transformation process from information to knowledge is based on interpretative framework. When information is sense-read through the interpretative framework, it becomes knowledge.

Based on this postulate, an effective manner to capitalise expert knowledge is to focus on their representative information stored in daily used IT systems. However, regarding to the complexity of tacit dimension, the scope of this article is limited to the use of representative information describing explicit knowledge.

Otherwise, the role of the proposed IT systems in the literature is to support one of more of the following tasks: knowledge capturing, knowledge sharing and knowledge maintenance. However, these ISs are not really considered as a source of expert knowledge and knowledge caption mechanisms from these systems for industrial application is less developed.

In this topic, the aim of the proposed approach is to use PLM capabilities for supporting a knowledge capture and management module. This module is integrated on performance assessment system in order to automate the evaluation process of performance indicators. The computing process of this system is based on a value-chain approach which is detailed in the following section.

5. The value-chain framework for enterprise performance assessment

As said before, the value-chain evaluation process is divided in three steps: modelling, simulation and analysis (Figure 1). During the modelling, expert knowledge is essential to determinate value chain and performance. For instance, the initial link between product functions and the set of activities is managed by one or more experts. The knowledge related to this ‘link’ was not captured and managed. The aim of PLM system should be the support of these activities.

In step 1, named value-chain modelling (Figure 3(a)), there are specific activities:

1. Product modelling: this step is fulfilled by designers to define the product/project reference, the design team members, etc.;
(2) Function clarification: the designers clarify the technical functions and give a classification of them;
(3) Technical solution specification: the designers specify the technical solutions and detail them. The delivered elements are the principle solution, the Bill of Material, etc.;
(4) Activity definition: this step is the crucial one because all the evaluation is based on it. The definition of the set of activities needed to manufacture the product will be the basis for the simulation process.
(5) Value-chain definition: several scenarios can be established based on the previous identified activities. The expert has the responsibility of the definition of these scenarios.

All these steps allow building the value-chain database that provides the relevant information for simulation purposes.
In step 2, named value-chain simulation (Figure 3(b)), there are specific activities:

- Entities modelling: in this step, a part of the simulation model is generated based on the database value-chain elements.
- Expert value-chain activity: the expert in value chain must complete the simulation model in order to structure and check the value chain.
- Simulation run: the first part is the configuration of the simulation (duration, etc.) and the configuration of the export. After that, the expert runs the simulation.
- Simulation report export: the report exportation is automated and the results are displayed and registered in a specific Excel file.

In order to compare different value chains, the simulation is run several times with different configurations of input parameters.

In step 3, named value-chain analysis (Figure 3(c)), there are specific activities:

- Analysis report creation: the results of the simulation run are ordered in an Excel file so as to enable their use.
- Comparison table creation: the expert builds the analysis tree by defining the performance indicators hierarchy.
- Judgement of benefitting entities: the benefitting entities define the weighting factor of the performance indicators.
- Analysis processing: the AHP is done regarding the benefitting entities judgement on the value indicator construction.
- Value report: a report gives comparison elements based on value indicators for each value chain and each benefitting entities.

Regarding the value-chain framework, a final indicator is defined to give an assessment of the product value relative to a set of performance criteria such as cost, risk, product conformity, time and function satisfaction (Mauchand et al. 2007). These performance criteria are integrated in a set of evaluation models.

The assessment function of performance indicator defines the relation between the objective (o) and the measure (m; Porter 1985). Porter addresses the declaration of the objective, its representation and its measure for performance analysis.

In this work, the comparison is relative. The objective is the value of the best criterion and then the evaluation function is based on the AHP scale.

For this analysis, an activity-based approach is proposed. The goal is to report financial and non-financial information such as those put forward by Gunasekaran et al. (1999). In this work, ABC provides the structuring support (the activity) to keep non-financial information such as defect rates (quality), throughput rates (effectiveness of the industrial process) and delivery time (delay/effectiveness).

5.1. Cost model

One of the main elements of the modelling is the one that enables the application of the ABC method. It is based on the principle that activities consume resources that drive costs.

Consequently, a value chain has to support the modelling of resources, activities, cost objects (product and process) and three kinds of drivers, and to model the relation between them.

A cost driver is defined for each activity, and thus the activity cost is expressed as the product of the consumption of this cost driver by the associated rate. The correlation method is used to determine the relevant cost driver of an activity.

The principles of resource consumption and cost drivers come from the ABC method and the cost entity approach. Product cost drivers are captured and analysed by screening the value drivers of each activity. In order to obtain performance indicators, manufacturing activities are defined by decision criteria.

Mévellec (2005) advocates the use of non-conventional cost models for industrial contexts based on the activity principle ABC:

\[
PC_i = MP_i + MOD_i + \sum_{j=1}^{n} (NbCD_{ij} \times CD_j) \quad (1)
\]

- \(PC_i\): cost of the product \(i\)
- \(MP_i\): cost of the material and components incorporated in the product \(i\)
- \(MOD_i\): cost of the direct labour consumed by the product \(i\)
- \(CD_j\): cost of the driver of the analysis unit \(j\) (activity \(j\))
- \(NbCD_{ij}\): consumption of the cost driver \(j\) by the product \(i\)
- \(n\): number of activities needed to produce the product \(i\).

5.2. Function fulfilment

This criterion is relevant to the designer that establishes its assessment for each function and each solution. It reflects the definition of the solution to fulfil a specific functional requirement.
5.3. Time model

The time evaluation is based on historical data since the calculation is time-rate based. For each activity, the process time to transform one entity that passes through the activity is estimated. Also, the time to process one entity is known immediately.

The time cycle is calculated by the simulation tool. It gives an average time cycle for each product.

For product value evaluation, the time criterion is defined by two measurements: cycle time per product and lead time.

5.4. Quality evaluation

Quality is defined by the level of global defective rate that is represented by the number of defective products. Statistical defective rates are defined for quality controls.

A quality criterion is thus estimated by the cost of defective products.

5.5. Value evaluation

In the product development process and during value engineering, the expert clarifies on product functions. These required functions are the mediators for the choice of technical solutions and their evaluation is needed to define the final product.

A raw interpretation of the standard of a product value definition is proposed by Yannou (1999) as:

\[
\text{Value of a Product} = \frac{\text{User satisfaction towards the product}}{\text{Product cost}}
\]  

(2)

This definition does not explicitly give the measurement process. For that reason, the author breaks down the value as the sum of the value of each function required by a product. The logical equation used to evaluate a function value is:

\[
\text{Function Value} = \frac{\text{Function contribution to user satisfaction towards the product}}{\text{Cost of the solution to produce the function}}
\]  

(3)

For a function, the formula proposed by Yannou (1999) to define the function value for a specific technical solution is:

\[
\text{Function contribution to user satisfaction} = I_j \times S_{ji}
\]

\[
\text{Value of a Function, for a Solution}_j = \frac{I_j \times S_{ji}}{C_j}
\]  

(4)

with \(I_j\) is the importance of the function, \(S_{ji}\) is the satisfaction of the solution, \(C_j\) is the cost of the solution.

In that case, solution costs are known; one of the goals is to estimate the solution cost to obtain more accurate evaluation results.

The attributes of Value are Cost, Quality, Time and Function Satisfaction. So, Value is measured by a weighted method, the AHP process. Benefiting entities express their viewpoint on the importance of a criterion for the evaluation of the product value.

6. A PLM–KM-based framework for performance assessment

In the proposal, a shared knowledge-based framework is built to assess the product–process engineering adequacy in terms of feasibility and performance. As a result, design checks, cost estimation, optimisation, etc. can be performed on heterogeneous data (different types of data, for instance). This section presents the different modules of the proposed PLM–KM framework to support an automated assessment of enterprise performance.

6.1. Global architecture

The shared knowledge-based framework is obtained from the mapping between product knowledge and process knowledge. This mapping is achieved according to three complementary stages:

- Identifying the product functions,
- Capturing the possible technical solutions and the associated assembly plans from the KB and
- Applying the feasibility and performance assessment method.

Regarding the mapping process, an integrated architecture is proposed in this work to support a manufacturing process assessment. Three main modules are distinguished (Figure 4):

- The knowledge capture module from various ISs.
- The KB structuring of all knowledge captured from IS and expert applications.
- The performance assessment module is based on different assessment algorithms.
6.2. Knowledge capture module

The purpose is to propose a flexible infrastructure which should take advantage of the various ISs and which should capture the necessary data for building the shared knowledge.

One of the advantages of the proposed approach is that it will not disrupt the enterprise IS. Whatever used the software, the way they are interconnected, the data models they are based on, the approach is able to adapt to any configuration. On the opposite of traditional approach, the purpose is not to integrate some data coming from specific software to another based on a different data models, or to try to define a generic data model able to make different software working together.

Figure 5 presents the global architecture of the IS integration for knowledge capture. On the left part, ERP, MPM and PLM servers are used to store the product lifecycle information, created and managed in numerous expert applications. On the right part, different modules covering the building process of shared knowledge.

For each involved IS’s components, the goal is to capture the required data and to store it in the KB. This job is carried out by a specific mechanism called, in this article, IS workers. Each worker is dedicated to an IS module; it takes advantage of the extension’s capabilities of every module in terms of chosen programming language, available application programming interface (API), data model, etc. Sometimes, the data stored in the IS module need to be opened by
specific software. In this case, this specific software can be installed in the worker in order to capture the desired information and to store it in the KB. For instance, in a PDM system, CAD data can be retrieved, read and analysed in order to store the right information in the KB.

In order to not disrupt the setting of modules, the workers have to make their jobs during the periods of idle (for instance, during the night if the system is not used in other countries).

As it is shown in Figure 6, the communication between PLM server, enterprise IS and the KB is ensured by the workers following four steps:

- PLM workflow sends notification to concerned workers;
- Worker asks for data to capture from server using API;
- Server back required data to the worker and
- Worker stores captured data in the KB.

The data retrieved from all the IS modules thanks to the different workers are then stored in the KB. The chosen structure for the heterogeneous information coming from the different systems is dependent of the company way of working and of the 'shared knowledge deployment' goal. The KB can be developed as a unique database or be distributed on several computers, for instance, on the workers.

The PLM workflow mechanisms are used to manage data updating and validation processes. According to the workflow structure, 'update required' notifications are sent regularly to the workers during the development process in order to update the only needed information at the good time.

The use of a rule-based system is proposed as a preprocessing step for the mapping between knowledge coming from different enterprise ISs and expert applications. The rule-based system is a centralised referential that can be manually defined by the knowledge expert to ensure the consistency of the capitalised knowledge for the requested assessment.

6.3. Data model for KB structuring

The KB should integrate all product–process knowledge required or resulted by the stored performance assessment. This knowledge is captured from various ISs or obtained from the expert. Figure 7 illustrates the main classes of the model. The product is manufactured by the use of a value chain that makes the production operate in order to fulfil the expected functions. The value chain is composed by several processes that contribute to the creation of relevant value for the project/product. Estimation of the value chain is based on a set of criteria (quality, time, cost and function satisfaction), which are related to one of more project entities (function, component, activity, etc.).

Table 2 identifies the numerous knowledge sources regarding the existing enterprise ISs. This mapping is useful for the definition of IS workers and specification of the PLM workflows in order to guarantee the capture of the relevant knowledge.

6.4. Performance assessment module

As a result of the performance assessment module, feasibility checks, cost estimation, optimisation, etc. can be performed on heterogeneous data. The algorithms of this module are based on the AHP and the value-chain models. The integration of the AHP process for performance assessment is fulfilled through the following six steps (Figure 8):

- Step 1: Structure the hierarchy (the tree) from the value components (cost, quality, time and function fulfilment) which reflect the objectives of the decision-maker viewpoint through the intermediate levels that characterise the attributes of the value component.
- Step 2: Construct the matrix in which the results of each simulation are processed according to the criteria given in the lower level.
- Step 3: Evaluate the results for each alternative.
- Step 4: Construct the set of judgement matrices of each intermediate level.
- Step 5: Construct the set of pair-wise comparison matrices for each of the lower levels (leaves of one branch).
- Step 6: Analyse the AHP process result for each benefiting entities point of view.

Figure 6. Worker process for knowledge capture.
7. KB and performance assessment module

7.1. Application architecture

The integration of KB and performance assessment module is the key to enhance the process of manufacturing performance assessment. This module manages capitalisation (Figure 9(a)) and exploitation (Figure 9(b)) of design and manufacturing knowledge to assess performances.

Based on the previous propositions, a software application (performance assessment module) has been developed in order to deploy a value-chain process. Figure 10 presents the main menu of the proposed software application. The graphic user interface is composed of four main panels (tabs) covering the management of all necessary knowledge.

- The tab ‘References’ is used to open new or an existing project and to define/modify its related information (name, date of beginning, type, etc.).
- The tab ‘Design knowledge’ contains all information about the functional, structural or technical view of the current product.
- The tab ‘Manufacturing knowledge’ describes the manufacturing process in terms of activities, resources and the details of value chains.
- The tab ‘Simulation’ proposes a set of tools for: (1) the definition of simulation settings; (2) the creation of value chain to evaluate and (3) the creation of comparison reports.

Figure 11(a) illustrates the global process of human and system interaction in order to perform new value-chain simulation. At the beginning, the user creates new value chain by means of the user interface shown in Figure 11(b). The new value chain is affected to the current project (and its related product) in order to manage the knowledge capture and the storage of the simulation results. Within an interactive process, the user captures different knowledge from the KB and completes the definition of the value chain progressively. At any time, the details of the value chain should be displayed in the interface of Figure 11(c).

According to the reference of product, the system uploads all associated functions from the database. Then, the process of knowledge capture begins as it is shown in Figure 12(a). For each selected function, the

<table>
<thead>
<tr>
<th>Knowledge</th>
<th>IS</th>
<th>IS acronym</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function satisfactory Cost</td>
<td>Customer relation</td>
<td>CRM</td>
</tr>
<tr>
<td>Resource</td>
<td>Finance resource planning</td>
<td>FRP</td>
</tr>
<tr>
<td></td>
<td>Manufacturing resource planning</td>
<td>MRP HRM</td>
</tr>
<tr>
<td>eBOM–mBOM Component</td>
<td>Product data management</td>
<td>PDM</td>
</tr>
<tr>
<td>Assembly alternative</td>
<td>Computer-aided design</td>
<td>CAD</td>
</tr>
<tr>
<td></td>
<td>Manufacturing process management</td>
<td>MPM</td>
</tr>
</tbody>
</table>

Figure 7. Data model for knowledge structuring.
system searches and displays all technical solutions that are able to fulfil this function and indicates all projects where these solutions are developed in order to get more knowledge about the creation context. Figure 12(b) presents a snapshot of the concerned interface. By adding a selected solution to the current value chain, the system displays the detail of each related micro-chain that is able to fulfil the selected solution (see Figure 12(c)). The user adds chosen micro-chain to the value chain and decides to continue the knowledge capture before the validation of the value chain.

When the necessary knowledge to process simulation is collected from the KB and completed by the business expert, the user will return to the main menu and will perform new simulation. The Arena simulation software is launched, and the simulation expert checks and finalises the simulation model by means of the Arena simulation module (Figure 13(a) and 13(b)). The results of this simulation are stored in new file and added to the comparator as it is shown in Figure 13(c).

7.2. Industrial results
The industrial stake is to improve to outcomes of management of performance indicator in order to make relevant decision in quick time at the early stages of product development. An issue is to capture knowledge from PLM and to structure KB for performance assessment purposes.

The capture can act at different steps of the definition process of value chain to provide expert support:

- Capture of relevant technical solution to fulfil product function;
- Capture of relevant value chain to manufacture technical solutions;
- Defining differentiating parameters of design or manufacturing;
- Defining the weight of each performance indicators (cost, quality, time, function) of benefiting entities to estimation their preference to define value indicator.

For the industrial case, the studied product is an automotive lighting support, a ballast system. In the development phase, the expert expresses all its functions. Based on the KB, a capture links to these different types of functions. This electronic system is composed of two carters, one connector element and one printed circuit board. In this case, the identified benefiting entities are customers, designer, manufacturer and shareholders.

In this industrial case, there are two manufacturing parameters: number of board per panel and yield. In the KB, it was found to possible manufacturing parameters regarding the number of board per panel depending of the size of the panel and the manufacturing capability. Moreover, different workstations can be used to process the board that have different characteristics such as yield.

Based on these manufacturing parameters, four scenarios (or value chains) are planned and analysed (Table 3). The KB is called for link functions to technical solutions, and technical solutions to activities. Based on each definition of value chain, a
Figure 9. Global architecture: KB and performance assessment module integration. (a) Knowledge capitalisation and (b) knowledge capture.
simulation is run to evaluate its performance relative to product manufacturing (Table 4).

To conduct an AHP analysis, it is necessary to define the value indicators (hierarchical tree of criteria) and their weights for each benefiting entities (see Figure 14). This step can be support by the capture of previous analysis weights regarding the chosen criteria.

The evaluation of value indicator for Scenario $i$ for benefiting entity $b$ (designer example, Figure 15) is established by the formula:

$$V_{S_I}(b) = w_b(C) \times C_{S_i}(b) + w_b(T) \times T_{S_i}(b) + w_b(Q) \times Q_{S_i}(b) + w_b(F) \times F_{S_i}(b)$$

With cost indicator for Scenario $i$:

$$C_{S_i} = w(PC) \times PC_{S_i} + w(VCCI) \times Vcci_{S_i}$$

Product cost indicator for Scenario $i$:

$$PC_{S_i} = \frac{\sum_{j=1}^{n} PC_{S_i/j}}{n}$$
Figure 12. Process of knowledge capture and related snapshots.

Figure 13. Snapshot of value-chain assessment results.
PC_{S_j/S_i}: AHP index for S_j related to S_i regarding product cost, etc.

An AHP analysis of simulation results gives indication to choose the better scenario by taking into account the point of view of benefiting entities (Table 5).

The results are capitalised and exploited to add knowledge to product.
8. Conclusion

In this article, the utility of the PLM approach has been underlined in order to support knowledge capture for reuse purposes and to assess managerial and technical decisions. In the proposal, the knowledge capture system increases the efficiency of value-chain assessment methods by giving more precision on product and process characteristics.

The value-chain modelling gives an appropriate support to performance evaluation in the way that this kind of modelling is understood by all the actors and that all the modelling elements can be connected by (and/or to) the basic principle of activity. The final solution would be the simulation and the generation of value-chain alternatives in order to find best technical solutions in detailed design stage.

The main idea of the proposal is to support the capitalisation of structured knowledge from different business systems as complement to the classical capitalisation methods of expert knowledge. On one hand, because of the daily use of business IS, the experts store regularly different data in the associated database. Thus, each kind of these systems should encapsulate great part of expert knowledge. On the other hand, PLM systems offer the possibility to get multi-connection facilities with business tools. By means of these conveniences, PLM system can be used to retrieve in the databases, the relevant data that represent a part of expert knowledge.

Within this approach, the process of value-chain assessment should be more assisted by automatic functionalities. The application of the framework in a simple industrial case study demonstrates the advantages of the system in terms of time, results precision and expert effort.

However, the role of experts still remains essential. For each involved IS’s component, a key user has to be defined to determine which data are interesting to be captured and to be used in the assessment module. Then, they have to check and validate the final results.

Further developments and works have to be considered to make operational this system in industrial context (for instance, development of specific APIs).

Table 5. Value-chain analysis results.

<table>
<thead>
<tr>
<th>Benefiting entity</th>
<th>Case 01 Scenario 1</th>
<th>Case 01 Scenario 2</th>
<th>Case 02 Scenario 1</th>
<th>Case 02 Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value index (notation)</td>
<td>Designer</td>
<td>0.083</td>
<td>0.555</td>
<td>0.140</td>
</tr>
<tr>
<td></td>
<td>Manufacturer</td>
<td>0.080</td>
<td>0.590</td>
<td>0.114</td>
</tr>
<tr>
<td></td>
<td>Clients</td>
<td>0.101</td>
<td>0.366</td>
<td>0.267</td>
</tr>
<tr>
<td></td>
<td>Shareholders</td>
<td>0.122</td>
<td>0.159</td>
<td>0.405</td>
</tr>
</tbody>
</table>
References


