Product Lifecycle Management: Closing the Knowledge Loops

Farhad Ameri[1] and Deba Dutta[2]

[1]The University of Michigan, Ann Arbor, amerif@umich.edu
[2]The University of Michigan, Ann Arbor, dutta@umich.edu

ABSTRACT

Competitive success of manufacturing firms is by and large determined by the success of the products they introduce to the market. This is why companies continuously try to improve the efficacy of their product realization process. Product Lifecycle Management (PLM) is a business solution which aims to streamline the flow of information about the product and related processes throughout the product's lifecycle such that the right information in the right context at the right time can be made available. Yet, few organizations are positioned to reap the true benefits of PLM. One major reason for this is a lack of clear understanding of what PLM is, its core features and functions, and its relationship to the myriad of current software tools. This paper aims to do that and also elaborates on the role of PLM as a knowledge management system.

Keywords: PLM, Knowledge Management, Product Realization Process, Extended Enterprise.

1. INTRODUCTION

On August 10, 1682, the Royal Swedish Navy's newest warship, Vasa, set sail on its first voyage. Vasa was Sweden's most expensive engineering project ever and cost over 5 percent of Sweden's GDP. After sailing for less than a mile, the ship keeled over and capsized in Stockholm harbor claiming 53 lives. Kessler et al. [10] took the Vasa case as an example of failure in the new product development process and illustrated common problems which bar the success of such projects. They identified seven key problems among which lack of learning capability, feedback system failure, communication barriers and poor organizational memory were the most prominent. Today, in the contemporary organizations, these problems still continue to be major causes of failure in the product development process.

In modern product development, as the complexity and variety of products increase to satisfy increasingly sophisticated customers, so does the need for knowledge and expertise for developing products. Co-located and monolithic design teams can no longer efficiently manage the product development effort in its entirety. In order to avoid lengthy product development cycles, higher development costs and quality problems, collaboration across distributed and multidisciplinary design teams has become a necessity. Today's knowledge-intensive product development environment requires a computational framework which effectively enables capture, representation, retrieval and reuse of product knowledge. This is the essence of Product Lifecycle Management (PLM).

PLM, in simple terms, is a business strategy for creating a product-centric environment. Rooted in computer aided design (CAD) and product data management (PDM) systems, PLM is aimed at connecting various product stakeholders over the entire lifecycle of the product from concept to retirement. As a technology solution, it establishes a set of tools and technologies that provide a shared platform for collaboration among product stakeholders and streamlines the flow of information along all the stages of product life cycle. But, what makes PLM distinct from many other technology solutions is not its state-of-the–art tools. Instead, it is the establishment of a sustainable corporate strategy via PLM.

In this paper, PLM is addressed from conceptual and functional points of view. The emphasis of this paper is on describing the role of PLM in supporting knowledge-intensive processes throughout product lifecycle. For this purpose, a middle-out approach is adopted. In other words, instead of moving from a highly conceptual level to a highly detailed level (top down approach) or vice versa (bottom up approach), PLM is first explained through one of its more tangible aspects (knowledge management) and then the high level and low level perspectives are presented respectively.

The remainder of this paper is structured as follows: Section 2 reviews the evolution of PLM. Section 3 provides an abstract model for knowledge management through PLM. In sections 4 and 5, the internal and external drivers for developing a PLM strategy are discussed to clarify how knowledge management capabilities of PLM pave the road towards competitive success. Section 6 provides a conceptual view of PLM in terms of its role in integrating people, processes and information. Section 7 focuses on the core features, functions and components of PLM. In section 8, PLM is discussed from a cultural perspective and finally in section 9, research issues in PLM are discussed broadly.

2. THE EVOLUTION OF PLM

With the advent of Computer Aided Design (CAD) systems in the early 1980s, engineering design entered a new era. CAD systems enabled the creation of a geometric model of the product in the computer, to be reused and manipulated by the designer as needed. Each new CAD system provided more/better features and functions than earlier ones. CAD systems were, and remain, highly technical softwares with extremely rich features and functions for detailed design work. In parallel with the development of Computer–Aided Design, Manufacturing and Engineering (CAD/CAM/CAE) tools, Product Data Management (PDM) systems appeared during 1980s to control and manage the product information created by various information authoring tools. The need for easy, quick and secure access to valid data during the product design process was the major driver for the development of PDM. The core functionality of early PDM systems, therefore, was to provide users with required data through their central data repository and to insure integrity of the product data by continual updating as well as controlling the way people create and modify the data.

Over time, PDM solutions were supplemented with new functionalities like change management, document management, workflow management and project management that promised concurrent engineering and streamlined product development processes within the enterprise. The first generation of PDM systems, although effective within the engineering domain, failed to encompass non-engineering areas within the enterprise such as sales, marketing and supply chain management as well as the external agents like customers and suppliers. Two major constraints hindered further expansion of PDM systems. First, they had a limited scope, in terms of data. The information managed by early PDM systems was limited to the engineering information like geometric models, BOM and FEA models. It was because these systems were designed at the outset to support and supplement CAD/CAM/CAE systems. Second, working with PDM systems was not always easy and usually required an engineering/technical background.

In the 1990s, PDM vendors began offering systems with web-enabled front-end together with more powerful and user-friendly visualization tools to broaden the user base. The Web provided the necessary infrastructure for developing lightweight, generic user interfaces with extremely low support cost. Due to the universal, inexpensive and ubiquitous nature of the Internet, web-based PDM systems became more accessible throughout the extended enterprise. Nevertheless, their core functionalities remained focused on managing engineering documents [11]. Therefore, they remained inadequate to support all tasks in the management of a product data throughout its lifecycle.

Almost concurrent with the evolution of PDM systems, the first wave of enterprise applications such as Enterprise Resource Planning (ERP), Customer Relationship Management (CRM) and Supply Chain Management (SCM) were introduced. These were aimed at further streamlining and improving the manufacturer's business practice. These solutions, each focusing on some specific lifecycle process, are quite dependant on product information. However, PDM systems could not provide the necessary support for ERP/CRM/SCM (unlike CAD/CAM/CAE) simply because the internal piping of PDM systems was designed specifically for handling engineering data.

The concept of Product Lifecycle Management (PLM) appeared later in the 1990's with the aim of moving beyond engineering aspects of a product and providing a shared platform for the creation, organization and dissemination of product related information (cradle to the grave) across the extended enterprise. PLM seeks to extend the reach of PDM beyond design and manufacturing into other areas like marketing, sale and after sale service, and at the same time addresses all the stakeholders of the product throughout its lifecycle. It extends PDM functionalities to include the creation of product definition information as well management and control of such information. In other words, whereas PDM is focused on the management of data created by information authoring tools, PLM also includes the authoring tools. PLM seeks to fill the gap between enterprise business processes and product development processes. In addition, PLM has one major identifier: it is all about *knowledge management*. Unlike PDM systems which focus on managing data, PLM, at its core, is a process which supports capture, organization and reuse of knowledge throughout the product lifecycle.

Indeed, PLM has captured the imagination of the corporate world. Based on market research results, PLM is one of the fastest growing markets for IT within the enterprise and is projected to grow (in total revenues) from slightly more than $2 billion in 2001 to more than $7.5 billion in 2006 [7]. But the question is whether PLM has evolved and is mature enough? Do vendors and users have the correct, and shared, understanding of PLM in terms of scope, functionalities and business implications? PLM is an enterprise application which, in comparison with its counterparts, has the biggest influence on the overall business. Without a correct understanding of PLM (the strategy and its implementation ramifications), users will fail to correctly utilize its capabilities and be diverted from their established way of business. Without a clear understanding of users' needs, PLM vendors will not be able to provide efficient solutions.

An August 2003 survey of 50 North American companies revealed that despite the high growth in spending in PLM solutions, PLM still ranks the lowest among the IT spending priorities of those companies [12] (Figure 1).

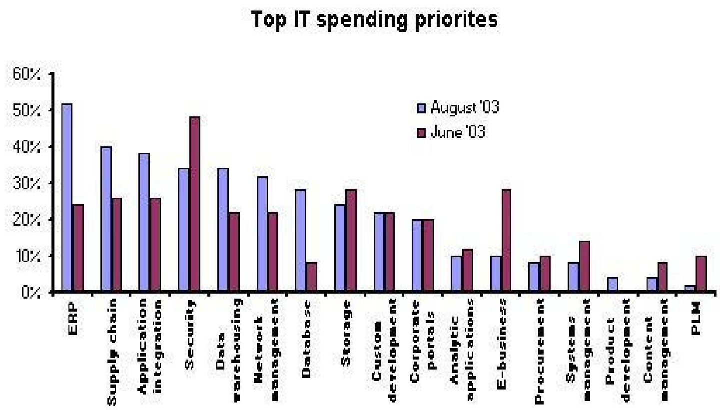

Fig. 1. Top IT priorities of companies

A careful look at the list of other priorities reflects a note-worthy fact. Neither the users nor the vendors have correctly recognized what PLM is. Application integration, data warehousing, security, custom development, product development and content management software are among the software solutions that, in a CIO's viewpoint, have higher priority than PLM. However, most of these are components or enablers of PLM! PLM is not peer to enterprise applications like ERP, CRM and SCM, rather, it provides a foundation on which other applications can operate in a more integrated fashion. Viewing PLM as a new IT solution is bound to diminish its real value. True benefits of PLM solutions will be gained only when both users and system developers have a clear understanding of PLM in terms of definition, components, functionalities, scope and its relative positioning within the enterprise.

3. KNOWLEDGE MANAGEMENT THROUGH PLM

As we move from the industrial age into the information age, knowledge is critical to competitiveness. In order to leverage knowledge properly, it is necessary to understand its nature accurately. Data, information and knowledge are three concepts which are sometimes used interchangeably. Although it is not always easy to draw sharp borders between them, these concepts have some delicate distinctions. Data represents unorganized and unprocessed facts. Information can be considered as an aggregation of processed data which makes decision making easier. Knowledge is evaluated and organized information that can be used purposefully in a problem solving process. Data and information are much easier to store, describe and manipulate than is knowledge. As a consequence, systematic management of the organizational knowledge is a demanding task [2]. Research indicates that, in a typical organization, only 4% of organizational knowledge is available in a structured and reusable format and the rest is either unstructured or resides in peoples minds [16]. The structured knowledge, although small in volume, has high value for companies because it can be accessed easily, mined and used for decision making. Generating structured knowledge, through transformation from tacit form into explicit form, is one of the critical steps of knowledge management.

For the purpose of this paper, we use Newman's definition of knowledge management as the collection of processes that govern the creation, dissemination, and utilization of knowledge [13]. Also, we define *lifecycle knowledge* as 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. PLM KB in not necessarily a physically centralized repository of knowledge. Instead, it is an interconnected network of dispersed knowledge repertories which are virtually unified using IT solutions. Like in any other knowledge based system, PLM agents interact with PLM KB in two ways: either they add new pieces of knowledge to the KB (TELL) or they query the KB to find the answers for their questions (ASK).

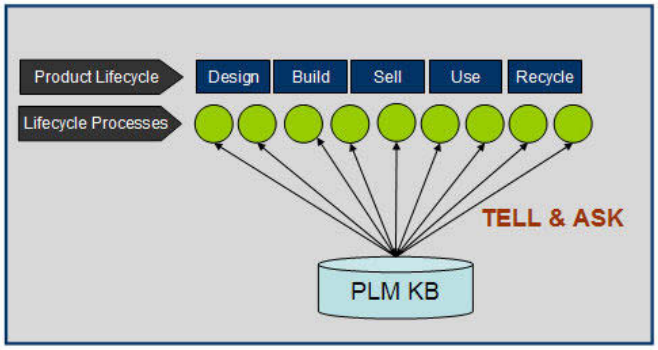

Fig. 2. Through a TELL & ASK mechanism, different lifecycle processes interact with PLM knowledge base.

Figure 2 demonstrates a simplified model of TELL and ASK mechanism in the PLM framework. The volume, type and richness of data, information and knowledge moving along different TELL & ASK vertices vary based on the nature of lifecycle process associated with each vertex. For instance, usually design processes are more knowledge intensive whereas, sell and distribution processes are mainly in need of some operational information like sales report. Through this model, a PLM system collects lifecycle knowledge that can be used in improving the efficiency and effectiveness of different lifecycle processes with specific focus on the processes related to the design phase.

Table 1 shows some examples of TELL and ASK instances in different lifecycle processes. For example, during material selection process in a design phase, the design team might come to the conclusion that aluminum does not fulfill the technical requirements of product A in terms of mechanical properties. This piece of knowledge, if captured and codified properly, can be quite valuable in designing similar products. Toyota's "engineering check sheets" demonstrate good examples of knowledge reuse under TELL & ASK framework in the product development domain. Engineering check lists or lessons-learned books serve as the knowledge repositories for different functional domains and have evolved over time [19]. For instance, a Toyota die designer usually has several lessons-learned books for different parts of auto body which contains the manufacturability guidelines. The lessons-learned books map the known area of feasible design space. This books are consulted frequently during the design phase (ASK) to ensure conformity of design with the existing manufacturing capabilities and, at the same time, new insights and earned knowledge are added to the books incrementally (TELL). There exists a plethora of TELL & ASK knowledge pieces throughout the product lifecycle which if harnessed properly, will make the lifecycle processes more lean and efficient. The IT infrastructure of PLM should be able to facilitate the TELL & ASK process by improving the accessibility and usability of PLM knowledge base.

As can be seen in Figure 3a, the flattening of the knowledge accumulation curve can be delayed through improving the learning capacity of the organization. The learning organization is "an organization which facilitates the learning of all its members and continuously transforms itself" [22]. In organizations with a well established knowledge management system, learning by the people within an organization becomes learning by the organization. The accumulated knowledge, if leveraged properly, can transform the cash flow pattern associated with different organizational activities like product development (Figure 3b). A quicker realization of the positive cash flow as well as higher peak and longer growth period are typical of the changes enabled by knowledge management systems. In short, PLM, as a knowledge management system, improves the learning capacity of the organization and consequently, increases the rate of knowledge accumulation in the corporate knowledge base.

Phase	Process	TELL	ASK
Design	Material selection	Aluminum is not a suitable material for product A.	In designs similar to product A, what material has been used?
Build	Quality control	Machine XYZ is not reliable in precision levels below .02 mm.	What is the average scrap rate of Drill ABC for aluminum parts?
Build	Vendor Selection	Supplier A's lead time is usually 10% longer than the planned lead time.	Does supplier X have enough technological capabilities for manufacturing product Y?
Distribution	Shipping	Shipping of product A under condition C resulted in some malfunctions in the product.	Shipping conditions in terms of suitable temperature and humidity.
Service	Oil change	In mileages above 70 k, Ford xyz needs oil change every 2000 miles.	What is the recommended mileage for next oil change for a certain vehicle?
Retirement	disassembly	Due to obstructed views, disassembly of part 15237 is not easy.	How much steel is used in product 657694?

Tab. 1. TELL and ASK in different lifecycle processes

A rich knowledge base, in turn, can potentially improve the efficacy of knowledge-intensive processes, thus resulting in better overall cash flow and competitive standing. The next two sections provide a more detailed discussion on the role of PLM in the competitive success of firms.

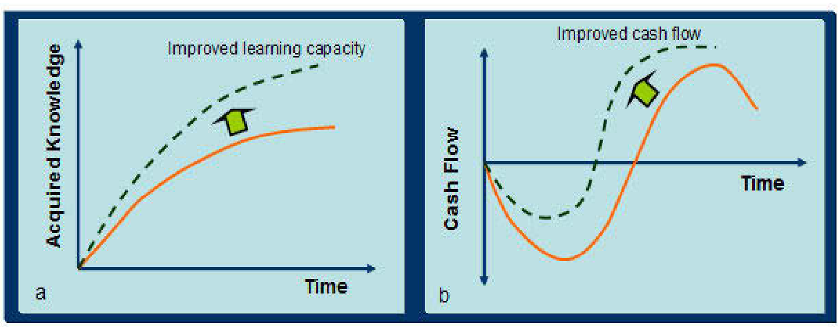

Fig. 3. a) PLM improves the learning capacity and knowledge accumulation rate
b) By the expansion of knowledge, pattern of cash flow shifts toward quicker realization of positive cash flow with larger peak and longer growth period.

4. WHY PLM? – INTERNAL FORCES

A decade ago, reducing operational costs through increasing operational efficiency used to be a powerful means of achieving competitive advantage. However, that is no longer the case. Today *product innovation* and *customer intimacy* together with *operations excellence* have become the most important areas of focus for a corporation that wants to gain competitive differentiation. These three measures of success are mainly influenced by the internal dynamics of corporations. Hence, we refer to them as the internal forces for the competitive success of a company. In this section, the role of knowledge management in promoting innovation, customer intimacy and operations excellence is discussed in order to shed some light on the way PLM enables competitiveness.

4.1 Need for Innovation

Usually the first two companies that create a new product/service category control 80% of sale of that category. This is why leading companies are seeking the ways of introducing innovative products and services. Chrysler minivan is a good example for demonstrating how companies benefit from innovative products. Chrysler invented the minivan in 1983 and it has sold more than 10 million minivans in more than 70 countries since then. After two decades and despite the emergence of many competitive models, Chrysler minivans remain the world's best-selling minivans [18].

According to the theory of "economics of ideas" developed by Paul Romer [17] in 1993, making people knowledgeable brings innovation and continued ability to create products and services of the highest quality which will eventually lead to the economic growth both company-wide and nation-wide. Innovation relies on creativity and creativity is most likely to happen in open environments which facilitate inclusion of the best ideas. In a creative environment, the pool of talent is expanded and collective body of knowledge is accessible for individuals. A creative environment is highly collaborative and keeps all players always informed thus, facilitating communication among different parties. When the greatest possible numbers of creative minds collaborate, they will innovate. With a knowledge management system in place, product-related knowledge can be systematically shared among knowledge users.

4.2 Customer Intimacy

Maintaining customer satisfaction and loyalty is a top priority for competitiveness. Customers are beginning to expect to buy products that can be customized to suit their personal needs and desires. Moving from make-to-stock and make-to-order to mass customization and personalization is becoming a common practice. Many vendors in different consumer industries like computers, automobiles, watches and shoes now provide their customers the ability to customize their products based on their desires. Mass customization pulls the customers up in the design process. Learning more about customer's needs and behaviors would help in developing the intelligence that leads to design of products which properly meet their expectations. Poor communication will result in an incomplete picture of customer requirements. To ensure a rich and effective communication, the upstream and downstream flow of information between customers and manufacturer should be as seamless and direct as possible. Customers are valuable sources of knowledge since they are in close contact with the product and their ideas about possible improvements in the product can considerably help the design teams in modifying product features. However, in the absence of a disciplined methodology for capturing customer's knowledge of products, it is almost impossible to incorporate such knowledge in the product development process.

4.3 Operations Excellence

Any business can be described by using the concept of value chain [14]. One simple definition for the value chain is "the activities in the business that add value to a firm's products or services". Competitive advantage is not only derived from the individual activities throughout the value chain but also from the linkages among the activities. By focusing on specific activities or links, companies can gain competitive advantage [3].

Focusing on an *activity* typically results in attaining operational excellence such that the activity becomes low cost and quick through process improvements. For instance, the geometric modeling activity, as a stand-alone activity, has become highly mature and CAD tools with myriad of functionalities efficiently support its different phases. However, when it comes to *linking* geometric modeling to other activities of similar or different types, then the indicators of excellence are qualities like interoperability and usability which are essentially the measures of richness of communication.

In product design, while individual CAD tools usually perform well on their own, they might fail when operating in a collaborative environment if they are not enhanced with interoperability features. One way to gain operational excellence is to reduce the waste both in the value chain activities as well as in the linkages among them. Research indicates that wasted time comprises about 60 percent of total operational time in most businesses. The major portion of this waste can be attributed to the absence of an efficient knowledge management system. Searching and waiting for data, data translation, working with wrong data and reinvention of the existing knowledge are very common problems in the value chain (Figure 4).

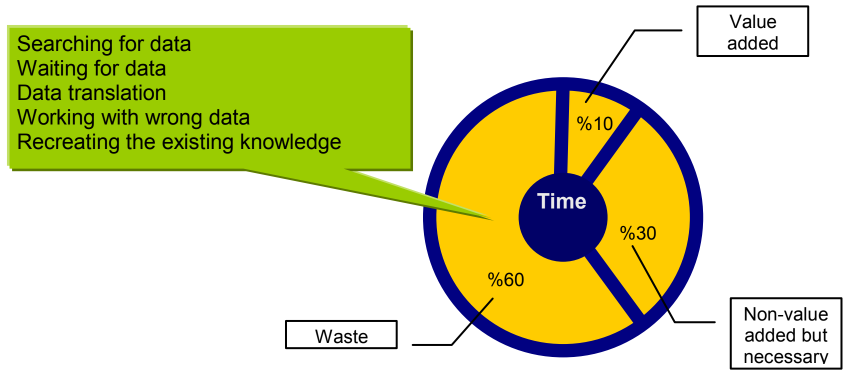

Fig. 4. Inefficient communication is a major source of waste in the product value chain

To reduce waste in the value chain, it is necessary create an environment characterized by systematic capture, management and dissemination of knowledge and to eliminate the deficiencies that time, distance and differing professional disciplines introduce into the value chain.

5. WHY PLM? – EXTERNAL FORCES

Over the last few years, universal trends like globalization, environmental awareness, shrinkage in product lifecycle, increase in product complexity and the push into supply chain have posed new challenges for corporations.

5.1 Globalization

In 1995, U.S government helped organize and fund the Next-Generation Manufacturing (NGM) Project, an elaborate effort to forecast manufacturing business conditions for the next 10 to 15 years. The NGM project identified several drivers for the change among which "Globalization of markets and business competition" was the most prominent one. Globalization today is the most visible mega-trend and has considerably changed the rules of business in the manufacturing world. With the increase in the cost of resources, manufacturers no longer rely on domestic recourses and on a world-wide basis they seek for partners who can economically provide them with necessary materials, components and services. Today, collaboration of globally dispersed product development teams has become a common practice in most firms. In dispersed environments, knowledge management becomes more difficult because sources of knowledge are not co-located. Furthermore, virtual design teams are usually short-lived and are dissolved once the design phase ends. The transient presence of knowledge owners poses more challenges into the knowledge management initiatives.

5.2 Product Complexity

The need to address a wide range of customer needs in a more efficient and reliable fashion is giving rise to increasingly complex products. Such products often have complex designs which in turn results in formation of a complex development environment that is characterized by complex information structure and flow. Consider the Xerox copy center is an example. Having more than 2000 significant parts, its development involved solving 12,000 engineering problems through 1,000,000 decision making steps [7]. The efficacy of decision making process in complex design environment depends highly on the availability of decision support system which enables reuse of existing knowledge. A complex product is more susceptible to engineering changes and to manage the changes efficiently, an intelligent change management system is required. Furthermore, in a complex product, there is likely to be more discrepancy between the as-designed, as-built, as-installed and as-maintained versions of the product [13]. Therefore a systematic approach for preserving data integrity is a major challenge posed by complex products.

5.3 Shrinkage in Product Lifecycle

Given the high rate of introduction of new products to the market as well as the speed of change in customer needs, products with lengthy development process are likely to be outdated sooner than the expected. With shrinkage in the length of product life, the product development process also has to become shorter. However, there exist trade-offs between time-to-market and developments costs, product quality and product performance. For example, Xerox developed its 1045 model on an accelerated schedule in early 1980's but shortly after launching the mass production of this new product, a major design problem was discovered which eventually cost Xerox more than $1million. Chrysler's Neon compact car was rushed to market without sufficient road tests. Chrysler had to recall the car within the first month of sale resulting in dampened consumer and dealer enthusiasm for Neon [10]. To speed up product development process and at the same time improve its performance in terms of cost and quality, new product realization process needs a collaborative environment with open sources of knowledge. Such an environment promotes rapid decision making and facilitates the concurrent performance of operations, thus reducing time-to-market.

5.4 Push into the Supply Chain

Since early 1990's, major phases of the product life cycle, from conception to retirement, have been characterized by extensive outsourcing. In 2002, U.S. companies spent more than $1trilion in supply chain related activities. A survey of 83 U.S. firms in 1997 by Ragatz et al. [15] suggested that integration of suppliers into the New Product Development (NPD) process is of increasing importance and an early involvement of suppliers in the design process, if applied and managed properly, usually leads to significant improvements in the overall performance of the NPD process. The same study revealed that the ability to share intellectual assets (such as technological now-how, product-related knowledge and customer requirements) with suppliers is the foremost determinant of success in joint NPD practices. Accordingly, knowledge dissemination, as one of the core concepts of knowledge management, becomes a vital requirement for integrating suppliers into the design process.

5.5 Environmental Issues

Due to increasing environmental regulations worldwide, companies are required to identify, evaluate and minimize the environmental impacts of their products over the lifecycle and to take the responsibility of retirement of their products once they become obsolete. To address these requirements, manufacturing companies are increasingly adopting Lifecycle Assessment (LCA) methodologies. But, the effective implementation of LCA is usually hindered by paucity of valid data. Detailed implementation of LCA requires information about the inputs and emissions of all the sub-processes in the life cycle of the product. Often times, such data is difficult, or even impossible, to acquire. Clearly, the LCA process can benefit immensely if integrated with an efficient system that gathers accurate data, stores and uses past knowledge, and updates the assessment dynamically [9].

6. WHAT IS PLM? – A CONCEPTUAL VIEW

Thus far, we have argued that PLM is a *knowledge management* solution which supports different *processes* throughout the *product lifecycle* within the extended enterprise. Also, we discussed why in modern product development practices, knowledge management is becoming a necessity. Before going down one more level and describing the actual tools and technologies which enable knowledge management, we take one step back and address PLM from a more conceptual perspective. In the previous sections, the role of knowledge management in the competitive success of firms was discussed. No matter how knowledge management supports different lifecycle processes, its underlying intention is always the same. Knowledge management, in its core, is about integrating different processes and their corresponding agents through a shared body of knowledge. To investigate why *integration* is such a critical issue for the enterprise, a historical perspective on the evolution of design and manufacturing is beneficial.

Product design and manufacturing are concepts that have been around since the early days of human history when man started using his mental and physical power to design and build basic tools for performing daily activities. These concepts have evolved over time to become very complicated and knowledge intensive processes of the present time. Despite great advances in tools and techniques of product development, the basic idea is still the same: determining a certain set of needs and developing a product that satisfies those needs. Product development used to be a highly integrated process and in many cases, the final user of a product was actually its designer and manufacturer. This "mono-agent" model, in its first step of evolution, separated the user from the unified product development enterprise. This evolution was mostly the result of social and economical development of human societies and not brought about by concerns for improving efficiency in product development model/process.

Fig. 5. People, Information, Processes are the three basic elements of an organization

The cobbler is a typical example of "double-agent" model. Based on the inputs from his customers, he designs and manufactures the product [6]. Cobbler model continued to be a prevailing model of manufacturing for a long time and even today, it is the most efficient model for some of the highly customized products. In both mono and double-agent models, the product is likely to perfectly meet the basic requirements upon which it is designed simply because all the pieces of information and knowledge are aggregated in a single location, i.e., in the mind of the cobbler. In this situation, the accessibility and usability of product information and knowledge is always guaranteed. In other words, people, information and processes, as the basic building blocks of each organization (Figure 5), are highly integrated in both mono and double-agent models. Therefore, the knowledge loops are closed and the tacit knowledge expands in an ongoing process of enrichment and reuse. Failures in such integrated environments could be due to lack of knowledge or unavailability of (workman) tools and not due to lack of communication or collaboration.

The major caveat of the cobbler model is the lack of scalability. As the quantity, complexity and variety of the products increased, the simple cobbler model became inefficient and insufficient. Scalability required the design and manufacturing processes which formerly used to be performed by a single agent, to be fragmented into several pieces. Each piece required less skill and information and simpler tools. Later on, this approach gave birth to the industrial production of consumer goods in which the design and manufacturing broke down into several smaller jobs with different requirements in terms of information, skills and processes. Eli Whitney who in 1798 successfully applied his revolutionary "Uniformity System" of manufacturing interchangeable components in the production of muskets, pioneered the era of mass production and modern manufacturing methods. The production of long-runs of standardized goods for a mass market was introduced at the beginning of the 20th Century by Henry Ford whose theory, known as Fordism, has been described as "the mass production of standardized goods, using dedicated machines and moving assembly lines, employing unskilled and semi-skilled labor in fragmented jobs, with tight labor discipline, in large factories". Applying this theory, the assembly time of Model-T reduced from 14 hours to 1 hour and 33minutes and the selling price fell from $1000 to $360.

Although fragmentation of design and manufacturing processes addressed scalability and drastically reduced the manufacturing costs and time-to-market, it adversely affected the integrated quality of design and manufacturing model. Product definition information was no longer in a single location but was dispersed among various agents each of whom had their own abstraction and conception of product and its related information. Disintegration of people, information and processes was a major consequence. Computer Integrated Manufacturing (CIM) and Concurrent Engineering (CE) are among the concepts which appeared later to reintegrate people, information and processes and to create a common product-centric language throughout the enterprise. But they were confined to a subset of the product life cycle and were mostly limited to engineering aspects of the product only within the four-walls of the company. In other words, they created domain-specific islands of knowledge.

This shortcoming triggered the need for a more comprehensive knowledge management solution which addresses all phases of the product life cycle from planning and conception to retirement and includes all stakeholders of the product namely customers, product engineers, suppliers, marketing personnel and service technicians. This solution is referred to as PLM. Philosophically, PLM aims at reintegrating the manufacturing organization by closing all the knowledge loops and positioning the product at the focal point of the whole organization. It is about reinventing and revitalizing the cobbler model for the information age (Figure 6).

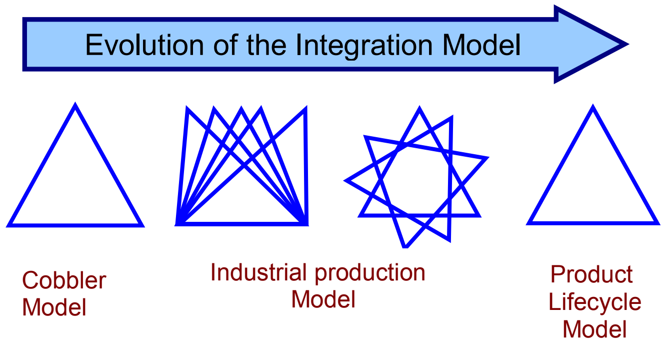

Fig. 6. Product Lifecycle Model retains the integrity of a manufacturing organization

Manufacturers are realizing that keeping the focus on the products and creating a common language around the product is more than just a philosophical viewpoint, it is fundamental to success.

7. WHAT IS PLM? – COMPONENTS

PLM is often thought of as a huge bundle of complex IT tools and applications which support digital design and manufacturing practices in several ways. However, this view of PLM overshadows the underlying concept of PLM which is knowledge management. The technology components of PLM are the enablers of knowledge creation, transformation and sharing throughout product lifecycle. A PLM component can be as simple as a notebook which is used for transforming knowledge from tacit form into explicit form. Also, standard technologies like telephone and video conferencing can be considered components of PLM (suite of tools) since they are used for sharing tacit knowledge between individuals. Appropriateness of different tools and technologies within a PLM framework is determined by their knowledge management capabilities and not by their level of complexity and novelty. In this section PLM components are presented based on their utility in knowledge creation, transformation and sharing.

Knowledge management starts with knowledge creation. To explore the technological implications of knowledge creation, it is necessary to first build a clear understanding of this phenomenon. Information becomes knowledge once it is processed or internalized in the mind of an individual. The resulting knowledge is referred to as tacit knowledge. Creation of tacit knowledge is mainly a mental process which is independent of technological intervention. However, technology can serve as a catalyst as it can permit individuals to access required pieces of information in the right context, thereby providing the essential support role in the creation of tacit knowledge. But when it comes to creation of explicit knowledge, technology takes a more active role. *Data Mining* and *Data Warehousing* are two technology components which are collectively used for deriving valuable pieces of knowledge (in form of trends, patterns and rules) from hoards of data. The resulting knowledge, since created by machine agents, is explicit in nature, hence machine-understandable. No matter how knowledge is created, to be useful, it needs to be stored (TELLed) in the PLM *knowledge base* (KB) which is regarded as one of the core components of any PLM solution. Knowledge users can query (ASK) the PLM knowledge base to find suitable answers for their questions. The contents of a knowledge base can either be only useful for human (like free format text written in natural language) or it can be more formal to enable machine-usability as well. The level of formality of PLM KB contents is determined by the underlying *knowledge representation (KR) language* which is another component of PLM. First-Order Logic and Description Logic (DL) are among the KR languages which support codification of semantics, thus supporting machine-usability.

Knowledge is either exchanged as-is or undergoes several types of transformations to be exchangeable. Knowledge transformation has four distinct formats as described below[13]:

- **Socialization**: The sharing of tacit knowledge between individuals. *Web meeting applications, video conferencing systems, collaboration and visualization tools* are the major technology components which govern socialization in different processes during the product life cycle.
- **Externalization**: Tacit knowledge is made explicit. *Information authoring tools* (like CAD systems) are among the most widely used tools for externalization within a PLM environment since they encapsulate different types of design knowledge. Simple *text editors* can also be regarded as knowledge externalization tools.

- **Internalization**: Transforming explicit knowledge into tacit knowledge through learning. There are several tools in a PLM solution which directly or indirectly support internalization. *Search engine* is an example of a tool which helps users in locating the required pieces of explicit knowledge. Similarly, *document management, change management and work flow management* have a supportive role in the internalization process since they make explicit knowledge more organized and retrievable.
- **Combination**: Combining two or more pieces of knowledge to generate new explicit knowledge. Expert systems, for instance, perform combination through inference. A PLM solution might be equipped with an expert system which classifies components based on their similarity in geometry. The new piece of knowledge generated as the result of the classification process (Part 123 belongs to group X), is obtained by combining properties of part 123 (one piece of explicit knowledge) with properties of group X (another piece of explicit knowledge).

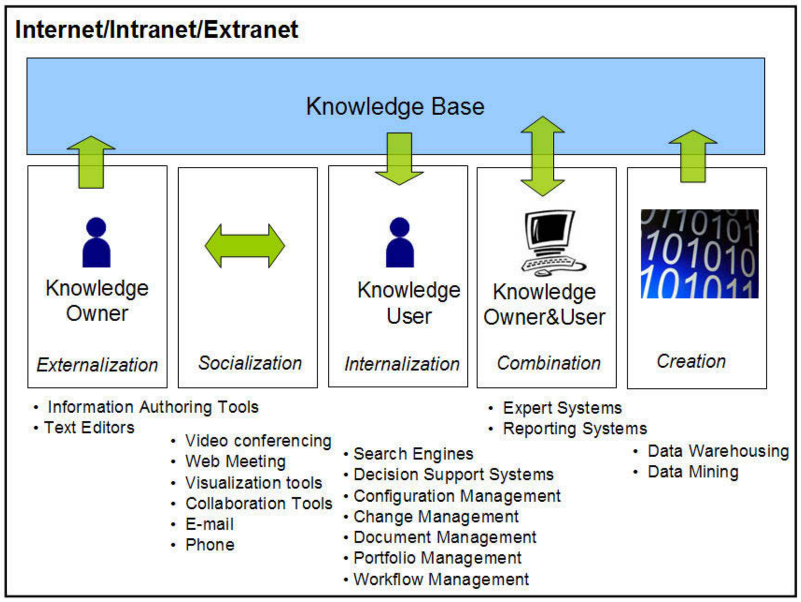

Fig. 7. PLM components

Figure 7 shows the major components of a typical PLM system which is framed as knowledge management system. As can be seen in this figure, different technological modules are integrated through Internet (or Intranet/extranet) as the common communication platform. Ubiquity of the Internet has made it an excellent medium for knowledge sharing in dispersed environments.

PLM is still in its growth phase and a *dominant design* for PLM systems has not emerged yet. In other words, the core components of a PLM system are not limited to those of today's state-of-the-art solutions and as PLM solutions gain more maturity, the necessary and sufficient elements of the system will become clear. The commonly used technology S-curve provides a suitable framework for analyzing the maturity state of PLM. The S-curve theory, in general, suggests that the magnitude of improvement in the performance of a product or process in a given period of time differs as the product or process and its corresponding technologies become more mature. In the technology's early stages, the rate of progress in the performance is relatively slow [4]. As the technology becomes better understood, controlled and diffused the rate of technological improvement increases. In its mature state, technology approaches its natural or physical limits. In Figure 8, we illustrate the S-curves for both PDM and PLM systems. Let us consider the performance axis where lower regions refer to data management and as we move up we are into the knowledge management domain. Data management being the core concept of PDM systems they have reached maturity (now) as shown. But as we move higher on the performance axis and into knowledge management the PLM S-curve begins and indicates the early stage of development. If PDM vendors do not identify their position on the PLM technology S-curve and do not switch to it in a timely manner, they will remain on the flat section of PDM S-curve where further growth and performance improvement is very difficult.

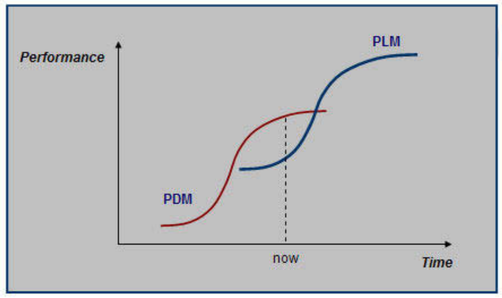

Fig. 8. PLM vs. PDM S-Curves

8. PLM AS A CULTURE

It is always easy to buy the state-of-the-art technologies, implement best practice approaches and adopt high-tech solutions but neither guarantees competitive success because they can all be copied by the competitors relatively easily. A competitive strategy should be able to give the organization a unique quality which cannot be easily replicated.

For any organization, key to long-term success is to consistently do certain things better than the competitors and continuously remain aligned to the corporate strategy [5]. Great manufacturing strategies are those which develop a sustainable and dynamic culture in the organization because culture is intrinsic of an organization and cannot easily be copied. Different business solutions cultivate different capabilities and skills in the organization over time but if the acquired capabilities do not reflect the company's long term strategy they are unlikely to give the company a sustainable competitive advantage

Lean Manufacturing is a good example of a competitive strategy which is rooted in organizational culture. The reason why many American companies failed to correctly implement Lean Manufacturing is simply because they focused on handful of lean tools like Kanban, 5s, Andon, Poka Yoke, etc., while ignoring the cultural imperatives. Lean Manufacturing, if viewed as a long term strategic plan and not a point solution, requires within the corporation the ethics of long-term thinking, respect for people and partners, challenge seeking, continuous improvement and tendency to reduce sources of waste.

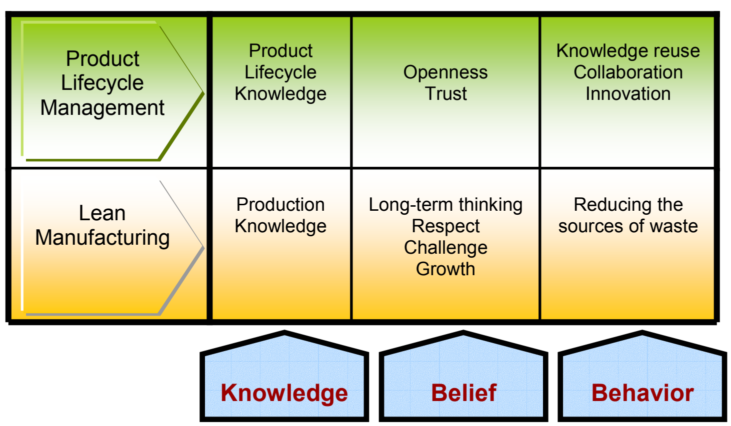

Fig. 9. A comparison between types of cultures generated by PLM and Lean Manufacturing

PLM is a culture generating solution which can give the company a unique competitive advantage through its institutionalization. It is not a single process or function but one that pervades the whole organization and therefore, its social and cultural aspect is as important as its technological side. Merriam-Webster defines culture as: "the integrated pattern of human *knowledge, belief, and behavior* that depends upon man's capacity for learning and transmitting knowledge to succeeding generations". PLM will lead to a culture which in spirit is the intellectual asset and almost always the unique identifier for the company and is by and large non-replicable. The social process of knowledge sharing is one of the pillars of PLM culture. New knowledge emerges as the result of interplay between individual effort and social interactions. Employee's attitude to sharing knowledge is central to the success of knowledge management practices like PLM. PLM, as a corporate strategy, provides a formal framework for aggregations, organization and dissemination of the intellectual assets of the company and constructs a non-replicable competitive strategy. PLM implementation starts with the development of a PLM vision and strategy and not by installing a suite of PLM tools.

9. RESEARCH ISSUES IN PLM

Earlier in this paper, PLM was described as a knowledge management system which support different lifecycle processes (e.g., geometric design, repair, recycle). Knowledge management in each process has its own challenges and might require different approaches. Therefore, in a broad term, knowledge management in each lifecycle process is an independent research problem with its own contingencies and needs to be addressed individually. For instance, complexity of design knowledge and its evolution path is quite different from those of after sales service knowledge. Therefore, knowledge capture and codification in these two processes will not be similar. Similarly, knowledge generation and dissemination in different lifecycle activities raise different technical problems. Accordingly, in each lifecycle process, four major research areas are defined:

Knowledge Representation: Different lifecycle processes need different approaches for knowledge representation. Database schemas, while quite efficient for representing structured information, sometimes fail in encoding the semantics associated with the information. Recently ontology-based knowledge representation has become an active area of research and several ontologies in different domains have been developed using different languages like OWL and KIF. With ontological representation of information, search and query in knowledge repositories becomes more intelligent, hence more precise. Some processes, like geometric modeling, need more elaborate knowledge representation formalism since their associated knowledge is more complex whereas, some other processes like quality control usually do well with schema based models.

Knowledge Capture: Knowledge capture is mainly a social process but communication technologies can serve as a major catalyst in permitting individuals to share enormous amounts of information unconstrained by geographical boundaries. Therefore, issues in knowledge capture can be divided into two major categories: organizational and technological. In the organizational front, the major challenge would be how to persuade individuals to effectively share their tacit knowledge whereas, in the technological side, application of collaboration and communication tools constitutes the technical problem. The use of collaborative tools in the product development environment has been extensive in recent years. However, in other phases of product lifecycle there is no systematic methodology available for collaboration among knowledge owners.

Knowledge Generation: Data mining and data warehousing are the major technologies used for knowledge generation and are widely used in some areas like marketing, e-commerce and customer support, but in the product engineering domain they have not received enough attention. Shop floors, service centers and recycling centers are all sources of raw data for the product lifecycle. By themselves, they are of low value. But if excavated, analyzed and contextualized, they can yield valuable pieces of knowledge. The technical problems, therefore, are 1) how to collect data and 2) how to mine the collected data in different lifecycle processes.

Knowledge Dissemination: Knowledge dissemination mechanisms in PLM must support the delivery of right information in the right context at the right time. While knowledge repositories and corporate memory databases have been long in use but they are often referred to as "knowledge junkyards" due to their inability to provide relevant information when needed.

10. CONCLUSION

In today's global manufacturing environment, proper utilization of corporate intellectual asset is the foremost determinants of success. PLM is a strategic business solution for integrating people, information and processes across the extended enterprise through a common body of knowledge. The body of knowledge within an enterprise is comparable to a living organism which its health directly affects enterprise's ability to operate and compete effectively. Dynamic creation, expansion, renewal and exchange of knowledge are the symptoms of livelihood in the knowledge body which are enabled through systematic knowledge management. This paper described PLM as a knowledge management system which supports the entire product value chain. PLM closes different knowledge loops throughout product lifecycle by enabling reuse of lifecycle knowledge in the development phase.

While the need for product innovation, customer intimacy and operations excellence constitute the internal push towards PLM, globalization, mass customization, product complexity, shrinkage in product life cycle, push into the supply chain and environmental issues are some of the external forces which drive PLM initiatives. In order to completely utilize the capabilities of PLM, both users and vendors need to gain a clear understanding of PLM in terms of scope, components and functionalities. The IT infrastructure of PLM is the enabler of knowledge management through supporting systematic knowledge creation and transformation. Attempts to implement state of the art PLM technology will fail unless PLM is embraced as a business vision and strategic approach. Many organizations have realized that a PLM strategy is rapidly moving from a competitive advantage to a competitive necessity. Finally, a nonreplicable competitive differentiation will result from the company's PLM culture.

11. ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support from the University of Michigan PLM Alliance [http://plm.engin.umich.edu]

12. REFERENCES

[1] ARC Advisory Group Whitepaper, PLM Strategy, Key to Future Manufacturing Success, October 2001
[2] Bohn, R. E., Measuring and Managing Technical Knowledge, *Sloan Management Review,* 36(1): 61-73, 1994
[3] Brown, C., D. DeHayes, et al., Managing Information Technology: What Managers need to know, *New Jersey, Prentice-Hall Inc*. 1994
[4] Christensen, C. M., Exploring the Limits of the Technology S-Curve. Part I: Component Technologies. *Production and Operations Management* 1(4): 334-357, 1992
[5] CIMdata Whitepaper, PLM: Improving Top Line Performance of Industrial Equipment Manufacturers, 2003
[6] Dutta, D., and Wolowicz, J., An Introduction to Product Lifecycle Management, Proceedings *of the 12th ISPE International Conference on Concurrent Engineering: Research and Applications*, Ft Worth/Dallas, USA, 25 - 29 July, 2005
[7] Hauser, J ., Challenges and Visions for Marketing's Role in Product Development Processes, *Marketing Science Institute*, April 25, 2002.
[8] Hayes, R. H. and G. P. Pisano, Beyond World-Class - the New Manufacturing Strategy, *Harvard Business Review* 72(1): 77-86, 1994
[9] Joshi.N., Dutta.D., Enhanced Life Cycle Assessment under the PLM framework, *Proceedings of IMS Forum, Cernobbio, Italy, 2004*
[10] Kessler, E. H., I. Paul E. Bierly, et al., Vasa Syndrome: Insights from a 17th-Century New-Product Disaster, *Academy of Management Executive*, 15(3): 80-91, 2001
[11] Lee, K., Principles of CAD/CAM/CAE systems. *Reading, Mass., Addison-Wesley*, 1999
[12] Maynard, J,., CIO Survey Results: August 2003 Spending Survey, *Merrill Lynch Research*, August 2003
[13] Newman, B., An Open Discussion of Knowledge Management, *The Knowledge Management Forum*, http://www.km-forum.org/what_is.htm , August 2002.
[14] Porter, M. E., Competitive advantage: creating and sustaining superior performance, New *York Press*, 1998
[15] Ragatz, G. L., R. B. Handfield, et al., Success Factors for Integrating Suppliers into New Product Development. *Journal of Product Innovation Management*, 14(3): 190-202, 1997
[16] Rasmus, D., Collaboration, Contents and Communities: An update, *Giga Information Group Inc*., May 2002
[17] Romer,P. , Idea gaps and object gaps in economic development, *Journal of Monetary Economics*, Vol. 32, pp. 543-573, 1993
[18] Smith,D. , Visnic, B. , Chrysler's Minivan Metamorphosis, *Ward's Auto World*, March 1, 1995
[19] Ward, A., J. K. Liker, et al., The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster, *Sloan Management Review* 36(3): 43–61, 19