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EXPERT SYSTEM APPLICATION INTO A PLM FRAMEWORK IN SUPPORTING DFX PROCESS

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ABSTRACT

This thesis presents a framework, a model and a methodology to bring together Product Life-cycle Management (PLM), Product Data Management (PDM) System Expert System (ES) and Design for X (DFX).

The framework presented here gives a general overview on how Product Lifecycle Management and Expert Systems technologies fit together. The goal is to improve DFX process, and the proposed way to do it is through information and knowledge management. The PLM model not only includes product management information across the product lifecycle, but also product processes, people involved in that processes and digital product engineering tools supporting each product lifecycle stage The methodology will define a way to improve DFX by means of the PDM and Expert System. It consists of three steps which are (1) getting customers' needs, (2) getting product information, (3) product data-information management through a PDM system and (4) DFX knowledge-expertise capturing into an Expert System.

The case of study was taken from the PURDUE solar racing car project which involves the construction of the 7th generation of a solar racing car. This project started in September 2006 and will finish during spring 2009, and is being developed by both students and professors from the Mechanical, Technology, Electrical, Industrial, Management and Marketing areas.

In this case, Teamcenter Community® is used as a PDM system. The focus is on how to share 2D/3D files, documents and data between all actors across the solar racing car lifecycle.

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CHAPTER 1 INTRODUCTION

Humans have made products for thousands of years. These range from rudimentary recipients to supersonic trains. Manufacturing methods have been evolving dramatically over time due to many social, economic, environmental and politic aspects. Nowadays, the most important driver for this change is globalization—and its high competition levels. Many approaches have been developed to support product development as an answer to global competition (Stark, 2006). Product Lifecycle Management (PLM), Design for X (DFX) and Knowledge Management are some examples of these approaches. The three of them will be presented in this study. Knowledge Management tools will be represented by Expert Systems.

1.1 Statement of the problem

DFX tool is built on a set of knowledge-based rules which come from each stage of the product lifecycle. In addition, designers create expertise and knowledge on a daily basis, which can be reused to improve the DFX process (Giarratano, 1998). The need to share that information led to the separate development of Product Data Management (PDM) systems and Expert Systems. However, there is still a need to integrate them into the DFX process (Boothroyd, 2004). On those bases, this thesis is focused on (1) how to capture the expertise and knowledge created daily by designers and, (2) how to manage the product information needed in the DFX process.

1.2 Justification

The main issue of this thesis is the improvement of the DFX process, which is part of the product development process. The impacts of this work on the product development process are mainly two: shorter product-launching time and money saved in resources and materials. These benefits come from the synergy made by the use of both Expert System and PLM.

Shorter product–launching time is achieved through experience in design and product information management, while money saving in resources and materials is achieved by using digital manufacturing tools.

1.3 Aim

Create a new approach to improve DFX process using Expert System and PLM tools.

1.4 Objectives

- Explore and understand the PLM approach.
- Explore and understand the information and knowledge needed to support DFX.
- Explore and understand Expert Systems as well as its construction principles.
- Design a methodology to improve DFX process.

1.5 Thesis Scope

The present thesis explores a PLM, PDM, DFX and Expert Systems research concepts and is not intended to be used to develop a commercial application.

The thesis work includes an exploration of the PLM, PDM, DFX and Expert System concepts. Although PLM encompasses the entire lifecycle, this thesis is focused on the Product Development stage only. PDM is a broad concept as well, but the focus of this thesis is on the product data sharing and collaborative work only. This work explores the DFX concept in different areas (manufacturing, assembly costing, etc), but the case study shows mainly knowledge related to manufacturing environment.

This thesis also includes a case study taken from a Purdue Solar Racing Car project to test the proposed methodology. The case study implemented to demonstrate the methodology uses two commercial applications. A PDM system called Teamcenter Community and Expert System called CLIPS.

1.6 Research environment

All products have a lifecycle. A general way to define a Product lifecycle is through six stages: Product Development, Process Development, Facility Development, Production and Sales, Use-Maintenance and Disposal (Aca, 2004). All these stages are included in the

PLM concept, which is an approach that encompasses the management of data, information, process and technologies related to the product across its entire lifecycle (Grieves, 2006).

The present thesis was made in a collaborative environment between the PLM Laboratory, which is part of the Innovation Center for Design and Technology at ITESM, and the PLM Center of Excellence in the Center for Advanced Manufacturing at Purdue University. This is why PLM is the main issue in this thesis. In addition, the main researchers in these PLM centres are involved in Knowledge Management issues, especially in Expert Systems, which is why this subject is included as well. Finally, Design for X was added to this thesis to collaborate with the Purdue Mechanical Engineering School.

This collaborative work made the relationship between ITESM and Purdue University stronger. This is reflected in the agreement for future common research works and student academic exchanges between both PLM research centres.

David Guerra has worked on the design and manufacturing knowledge structures that support the product development process. This includes information and knowledge modeling techniques, tools and methods. His recent focus has been on knowledge administration in the product's and processes' life cycle by means of PLM platforms.

Mileta Tomovic has worked on Expert Systems in the field of Mechanical Engineering and, most recently, has been focused on PLM.

1.7 Thesis structure

This thesis is organised in five chapters:

1). - Introduction: provides the introduction to the research contribution outlining aims, objectives, scope of the research, and gives a description of the research environment defining the tools used in this research.

2). - Literature review: includes an overview of PLM, PDM, DFX and Expert Systems. It provides definitions, characteristics, elements, tools and importance of PLM. In addition, PDM and Expert Systems are depicted, and some of the capabilities for the available software of this kind are shown.

3). - A methodology to support the DFX process using a PLM framework: presents a PLM framework to support the DFX process, a DFX process framework and the steps for the methodology.

4). - Case of the study: includes a case study taken from the Purdue Solar Racing Car project to test the methodology proposed in chapter 3.

5). - Results, conclusions & further work.

CHAPTER 2 LITERATURE REVIEW

This chapter presents the concepts which the reader needs to know about PLM, PDM systems, Expert Systems and DFX. PLM will be fully defined as it is the basis on which the other subjects will be founded. PDM systems will be described as a major driver for PLM, and the difference between them will be depicted. Expert Systems will be introduced without a deep description on the concepts of neither knowledge, expertise nor their structures or representations; the main focus is on presenting some of the available tools for DFX. Finally, DFX will be introduced as well as its relationship to PLM.

2.1 Product Lifecycle Management overview

The first concept to be explained is Product Lifecycle Management. The section will present the following: definition, elements, model, characteristics, tools and importance of PLM.

2.1.1 Introducing Product Lifecycle Management (PLM)

The industrial and business environments change every day in many aspects: economic, social, technologic, politic, etc. (Kesavadas, M. 2005) Some of the most important results of these are:

- Ever increasing competition and tighter budgets.- Nowadays there are more and more brands of the same product or service which reduce revenues business and in this way companies have less money to investment. (Saaksvuori, A. 2004).
- Increase in digital information and tools. - With the advances on Information Technologies (IT) it is becoming very common to find information in digital format. Besides IT support many activities (design, manufacturing, etc.) which require good planning and interaction. (Grieves, M. 2006)
- Internationalization of business and changing geographical location of the product development skills. Sometimes, companies place factories in other countries like China, India and Mexico to reduce costs or increase productivity. Therefore each one is responsible for some part of the product's design, manufacturing, logistic, assembly, etc. (Stark,J.2006)

- Products getting more complex. - The development of and support for products are more intricate, due to their increasing functionality requirements. (Saaksvuori, A. 2004).
- More services are offered along with a product. – Some companies have found a niche in aftermarket activities (Alting, L. 1993).
- More requirements for product traceability. – High risk industries (e.g. aerospace and medical) continuously need to track their products and assure their quality. (Saaksvuori, A. 2004).
- Sustainable development is needed to ensure resources are available for future generations. - Companies have to make the most out of existing resources (Hines, P. 2005).
- A stock exchange mentality, with managers more interested in quarterly results than in the long-term well-being of their product and services (Bouras, A.2005).
- Company mergers. - Many companies are fusing with strategic partners to add and complement skills that give them both enough synergy to survive the competition (Sudarsan, R. 2005).
- Shorter delivery lag and less available time for new product development. - One of the most important requirements in this moment is a faster product delivery. More demanding customers drive companies to serve customers better and react more quickly to changing markets. For example, it is likely that customers are willing to pay more for a faster service or customized products (Xu, X. 2006).
- High quality requirements. - Product quality has been rising since the last centuries. Nowadays, the goals are to make flawless products and to satisfy customer requirements completely (McMahon, C. 2005).
- Regulations and common industry standards. – There are international standards like ISO-9000, ISO-14000, QS: 9000 and nation-specific regulations which should be followed to unify and measure the levels of processes performance around the world. These regulations sometimes even include the control the performance of automation processes (Saaksvuori, A. 2004).
- Product portfolios have expanded. – Customers, researchers and designers keep bringing new product ideas, thus creating new applications and services (Subrahmanian, E. 2005).

- Manufacturing has moved to sub-contracting and contract manufacturing. – Sub-contracting services is a common practice used by companies to solve unusual or unproductive problems (Aziz, H. 2005).

PLM manages products during their entire lifecycle - from conception to disposal - in the most effective way. It enables companies to take control of its products, makes product development better and faster, permits a better customer support in the product's use, clarifies the current status of the product, helps to get market opportunities and reduces waste (Stark,J.2006). PLM is focused on using the power of information and computers to reduce inefficiencies from design, manufacture, support and ultimate disposal of a product (Grieves, M. 2006).

PLM uses information technology and organizational practices and processes to improve the efficiency both within and across functional areas. One of the major advantages of PLM is that it enables a better information flow across the entire organization. Another advantage of PLM is that surpasses a simple cost reduction perspective through a revenue perspective to improve efficiency and productivity. PLM has the opportunity to increase innovation, functionality and quality by means of a better organization and use of the intellectual capital of an organization (Grieves, M. 2006).

At first glance, PLM is much more than just management across the lifecycle. PLM offers a new way of thinking about manufacturing industry (Stark, J. 2006). Table 2.1-A shows the way in which John Stark contrasts the ways of thinking before and after PLM.

Before PLM	with PLM
Think Product Manufacturing	Think product Lifecycle
Think vertically about the company	Think horizontal
think functionally about the company	Think lifecycle
Think about one activity of the company	Think about several activities
Think product development	Think cradle-to-grave
Focus on the customer	Focus on the product, and then the customer
Listen to the voice of the customer	Listen to the voice of the product
Think going forward in time	Think forwards and backwards
Think customer survey	Think customer involvement
Think product portfolio and proyect portfolio	Think integrated portfolio
Think bottom-up, starting with a part	Think top-down, starting with the portfolio
Think about product lifecycle management bit-by bit	Think about PLM in a joined-up, holistic way
Think PLM is for the techies	Think PLM is a top management issue
Think profit	Think profit and planet
Think our processes	Think standard process
Think our Data	Think standard information
Think our Systems	Think standard systems

Table 2.1-AWays of thinking (Stark, J. 2006)

PLM is a holistic business activity addressing many components which include product data, products themselves, organizational structure, working methods, processes, people and information systems.

"PLM rests on some fundamental premises. Four of the most important are: use information as substitute for time, energy, and material; the trajectory of computer technology development; the virtualization of physical objects; and the distinction between processes and practices". (Grieves, M. 2006)

2.1.2 Defining PLM

Product Lifecycle Management (PLM) is a relative new concept that started around mid 90's. The concept of PLM is focused on managing each product across its lifecycle from conception to disposal (Yang, X. 1996).

There is a current deficiency of shared understanding and agreement on PLM, which makes it difficult to include all its elements in a single statement. This section presents several PLM definitions to show the dispersion of conceptions on this subject:

Grieves, Michael

"Product Lifecycle Management is an integrated, information-driven approach comprised of people, processes/practices, and technology to all aspects of a product's life.

From its design through manufacture, deployment and maintenance-culminating in the product's removal from service and final disposal. By trading product information for wasted time, energy, and material across the entire organization and into the supply chain, PLM drives the next generation of the lean thinking".

Saaksvuori, Antt

"Product Lifecycle Management (PLM) is a systematic, controlled method for managing and developing industrially manufactured products and related information. PLM offers management and control of the product (development and marketing) process and the order-delivery process[1], the control of product related data throughout the product lifecycle, from the initial idea to the scrap yard. Almost without exception, the PDM and PLM abbreviations also refer to a data system developed to manage product data.

By CIMdata:

"A strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information across the extended enterprise from concept to end of life-integrating people, processes, business systems, and information".

Ford's definition presented at the University of Michigan's AUTO 2004 Conference for IT, engineering, and manufacturing automotive executives is:

PLM is concerned with processes, methods, and tools used from a product's inception through the end of its service life is the science of bringing these three disciplines together to create an environment that enables creation, update, access, and, ultimately, deletion of product data Extends across traditional boundaries, PD-Manufacturing, inter- Intra enterprise, North America-Europe Is not CAD, CAE, or any other discipline that exists to author or analyze narrow subsets of product data.

By CIO Magazine:

[1] In many fields of manufacturing industry, the order-delivery process is also called the costumer process due to the frecuency of buid-to-order production. The fulfillment of the costumer's purchase order, ie. The manufacture and delivery of the actual product, is already allocated to a certain customer and to a certain order. In this context the costumer process is considered a synonym for the order-deliver process and does not refer to customer relations management"

"Product lifecycle management is an integrated, information-driven approach to all aspects of product's life, from its design through manufacture, deployment, and maintenance- culminating in the product's removal from service and final disposal. PLM software suites enable accessing, updating, manipulating, and reasoning about product information that is being produced in a fragmented and distributed environment. Another definition of PLM is the integration of business systems to manage a product's life cycle".

By the National Institute of standards and Technology (NIST):

"A strategic business approach for the effective management and use of corporate intellectual capital".

Bouras, A

"PLM as an area for research is still seeking an identity and a community. PLM holds the promise of seamlessly integrating and making available all of the information produced throughout all stages of a product's life cycle to everyone in an organization, along with feedback from the later stages of the product lifecycle to the early stages of the product concept and development."

Kesavadas, M.

"PLM is defined as 'a strategic business approach for the effective management and use of corporate intellectual capital' (Pouchard, L. 2000) Product Life cycle Management tools allow companies to integrate various activities related to design, analysis and manufacturing including, discovering, marketing and maintenance of a product life cycle (Pouchard, L. 2000; Shah J. 1999). One of the important reasons for companies to use product life cycle management [tools] is to share data between different phases of the lifecycle. There is very little debate that such data sharing is very complex and often depends on the context in which it is viewed and interpreted. This is a major problem for design and manufacturing industries because of the growing complexity of information and increasing need to Exchange this information among various software applications."

As summary from the above definitions, it can be said that PLM is a business approach focused on the management of product data and product processes across the entire product lifecycle from its early conception to disposal. Being supported by means of digital product engineering tools as well as the people inherently involved with the product. The main goal of Product Lifecycle Management is to control the product to improve the productivity and increase the revenues of the company and its supply chain.

2.1.3 PLM Model

One of the best ways to represent PLM is by means of a model that includes all the stages across the entire product lifecycle, which are linked by information. However, PLM doesn't manage each stage in every aspect, but only in the issues that directly impact the product. For example, PLM isn't interested in how wages are paid in the sales stage, but in how salaries impact the product cost.

There are different views on the amount and names for the stages in the PLM models. For instance, the model proposed by Michael Grieves (view Figure 2.1-1) shows the information core at the center of the model, and the functional areas in the product's life are: plan, design, build, support, and dispose.

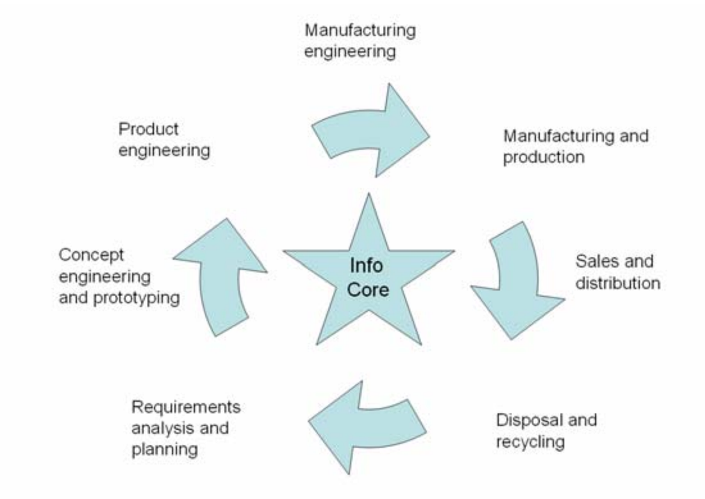


Figure 2.1-1 PLM Model (Grieves, M. 2006)

Other view comes from John Stark, who proposes five stages for the product lifecycle: (i) imagine, (ii) define, (iii) realize, (iv) support/service and (v) dispose/recycle. The difference between both PLM models is the conception of their respective lifecycles. In reality, the product lifecycle stages depend on the type of product. For example, a company that buys all its components, and that only assemblies parts has no product or manufacturing design stages, but facility development, sales and maintenance stages only.

2.1.4 PLM elements

Software technologies are the main component of PLM. However, it is not enough to develop a PLM initiative; there are more PLM elements, which need to be kept in mind to apply a successful PLM initiative. This section will describe those PLM elements: Human resources, technology, and process/practices

Human Resource

In many organizations, success or failure is determined by human resources. People are the most complex resource to manage in an organization, due that each person has different capabilities, capacity and motivation. Some people have limited capabilities, some have robust capabilities. The aspects that determines the capabilities of the people are experience, education, training, and support

Experience

Experience refers to the accumulation of information and knowledge about different situations. It enables the trade-off of information for wasted time, energy, and material. Human beings do this instinctively every time there is a situation or task from which experience and learning can be extracted.

Education and training

Education and training are ways to provide knowledge to people. They are common ways of trading information for wasted time, energy, and material. Training is when people are taught what to do. Education also teaches them why they do it. (Grieves, 2006)

Support

Individuals will also enhance or detract their capabilities through support. It is an extension of education and training, but it is performed during the execution of an assignment.

Change Capacity

The change willingness and capacity from people within the organization are determining factors in the success or failure of PLM. People in organizations who experience a wide number of changes have more capacity for change than people in organizations that keep doing the same tasks in the same manner for long time and don't have that change ability.

Organization

The two elements to be considered regarding organization are structure and the continuum enablement of authority. The first one is related to the appropriate organization structure that promotes the flow of information across functional areas. The second one refers to the authority that organization needs to take decisions and ask for information.

Process/Practice

Drilling, pocketing, casting, turning and process planning are some examples of the tasks that companies perform to make their products. They can be classified as processes or practices.

Processes are better defined than practices. Flowcharts or algorithms can represent them, and they are not obscure black boxes. Practices are much messier: the inner responses of the black box aren't clear; if inputs are provided the outputs aren't always given, and when they are, it is not always possible to explain why. Practices use both deductive and inductive reasoning, and require the participants to discern the patterns in a pool of seemingly unrelated data and information.

Regarding to PLM processes, consider the following: Firstly, understand the process very well. Then, ensure that it is explicitly (not tacitly) defined. Next, re-engineer the processes for a digital environment. Finally, integrate the processes across the organization

Technology

It leverages the majority of the key tasks that involve PLM to be developed. For example, Product Data Management could not be performed without software technology. CAD, CAM and CAE applications are other examples. The next section will describe these technologies (Grieves, 2006).

2.1.5 PLM tools: Digital product engineering tools.

As it was mentioned in the last section, PLM is supported by many product engineering computer technologies that make PLM possible. PLM is a holistic approach that combines all these technologies to conform a stronger one (Grieves, M. 2006). Some of these technologies are also named digital manufacturing technologies. All of them are the core of PLM and responsible to support the engineering product design development, engineering product manufacturing development, engineering product facilities development and product data sharing undertaken by all the people involved in each product lifecycle stage.

The tools we will examine are: Computer Aided Design (CAD), Engineering Data Management (EDM), product Data Management (PDM), Computer Aided Engineering (CAE) and Computer Aided Manufacturing (CAM) (Grieves, M. 2006) (Stark,J.(2006) (Saaksvuori, A. (2004).

Computer Aided Design (CAD) is a computer and graphics software application to aid or enhance the product design from conceptualization to documentation. CAD technology supports all levels in the product design process. It refers to mathematical descriptions of the physical representation of products. CAD software uses a system of mathematical descriptions to locate and replicate shapes in either two-dimensional or three-dimensional space. These systems started out as simple drawing systems to aid the designer in producing faster and more accurate drawings, hence, the name computer aided design. However, CAD systems rapidly developed functionality that moved them from a periphery system augmenting design to the focal system enabling and controlling design. Some examples of these CAD systems are CATIA® (from Dassault Systèmes®), NX® (from UGS) and ProEngineer® (from PTC®) (Tlusty,G. 2000).

Another PLM tool is Engineering Data Management (EDM) CAD specifications aren't enough to describe a product. Elements and information about the product are also necessary. Mathematical specifications describe the products from a geometric perspective, but do not fully describe them. CAD information needs to be augmented by other kind of information, called characteristics. Characteristics can be described as any information that is needed to describe the product and include tolerances, tensile strength, weight restrictions, adhesives, and conductivity requirements. In addition, information such as process for building the product, the methodology for coating or painting the product, the methodology for testing the product, the instruments and processes required to carry out the testing methodology, and the results of the testing procedure are needed to be associated and managed with the product. All the mentioned characteristics must be associated with the geometric information to describe, abstract and define the product in a better way. (Krar,S. & Gill, A. 2003).

Product Data Management (PDM) technology is defined as a tool which aids companies to manage all product-related data throughout the product lifecycle. It can organize CAD and EDM disparate formats in pre-structured databases. PDM systems arose as a way to organize and catalog the proliferation of CAD files that organizations began to accumulate rapidly. Then, the costs skyrocketed while the efficiency plummeted with geographically dispersed groups (internal or external) in need to access the CAD files and other types of information. PDM introduced the idea that the product data could safely and effectively be organized, maintained, and accessed in native form. Some examples of PDM software technologies are ENOVIA® (from Dassault Systèmes®) as well as Team Center® (From UGS®). In chapter third will be depicted the PDM technology in detail, due at the importance of this for PLM (Pol, G. 2005) (Stark,J.2006).

Computer Aided Engineering (CAE) is the analysis and evaluation of the engineering design using computer-based techniques to calculate product operational, functional, and manufacturing parameters too complex for classical methods (Rehg, J., 2005). CAE fits into the design process at the synthesis, analysis, and evaluation levels. The synthesis level includes manufacturability using design for manufacturing and assembly, while analysis an evaluation levels determinate the quality of the product design. The most frequent CAE application is Finite Element Design Analysis; however, tolerance analysis, and design verification are some other examples of it.

2.1.6 Characteristics of PLM

There are certain underlying characteristics that are an integral part of PLM, and need to be articulated for a deep understanding of the forces moving organizations to adopt PLM. These characteristics include: singularity, correspondence, cohesion, traceability, reflectivity and cued availability. Product Lifecycle Management systems will need to have these aspects to fully represent the information that they contain and present it to the end user. They are obtained by examining the Information Mirroring Model which is an ideal model of PLM that captures the relationship between physical products and the data and information about them. It is important to mention that before examining this model, it is necessary to understand how the product information is organized (Grieves, M. 2006). The definition of these characteristics is as follows:

Singularity

Singularity means to have the product data as a single and controlling version. “Controlling” is when everybody agrees that there is a correct data representation among many—the representation that everyone will work with. “Single” stands for unique.

Correspondence

A strong bond between a palpable object and the data about it is termed as correspondence.

Cohesion

By cohesion, the author refers to the fact that there are different representations or ways to perceive the product information. “Views of hidden surfaces and across sections will be cohesive by definition, because these views are always derivable from the geometric definitions.”

Traceability

Traceability is when the lifecycle of the product can be followed consistently to its origin in terms of time.

Reflectiveness

The information underlying within a real object changes at the same time that the object undergoes a modification (physically or chemically). If that information is to be separated and an image is to be created from it in virtual space, there exists the need of a mechanism to update the information in virtual space when the related information changes in real space.

Cued Availability

Cued availability simply means to be able to have the right information and processes when they are needed. The term cued indicates that such information and processes might or might not be requested, but they are presented, because of the current situation (Grieves, 2006).

2.1.7 Benefits of PLM

Until this moment the reader has been presented with a complete overview of PLM, including what PLM is, its elements, characteristics, tools, etc. However, some comments about the benefits of PLM in organizations also fit in the discussion. This section will present some of the most relevant economic benefits as well as a little about the future of PLM in the science field.

Some of the most important PLM benefits (Brown J., 2005) are:

- *Increased revenue* through: (i) faster introduction of new products to markets, (ii) offering new, valuable features to customers, (iii) avoiding being perceived as a commodity, and (iv) development of a product portfolio with more different capabilities.
- *Decreased product cost* through: (i) reduced part counts and product complexity, (ii) design for manufacturability, (iii) reuse of existing technology platforms, and (iv) design for service.
- *Decreased product development cost* through: (i) increased efficiency of designers, (ii) increased overall efficiency of new product development projects, and (iv) increased success rate of new product development projects.

This benefits can be verified in the reporting made by IBM PLM on Demand Business (IBM, 2005), which states that PLM's return on investment indicate high benefits in manufacturing industry. This information was taken from some of the commonly used strategic metrics to measure these issues. Manufacturing organizations with PLM initiatives developed are reporting 20% increase in design productivity and 50-80% reduction in the time required to modify complex design, ability to explore 50% more design options fostering innovation, conducting numeric control programming up to 10 times faster and machining up to 35% faster, 60% reduction in pallet manufacturing time, 40% decrease in the errors found at the final assembly stage, etc. Other benefits that PLM offers are the increase product options through mass customization as well as technology that can give manufacturers competitive advantage.

PLM also has a promising future. AMR Research (Williams, 2005) indicates in a recent report that in the next four years business worldwide will spend more than $80 billion to meet regulatory compliance demands on the product's impact on the environment. PLM can play a significant role in this issue by managing material information through the life cycle. PLM infrastructure also can have a profound effect in leveraging this task by integrating and vaulting product information for effective and cost efficient disposal and reuse. Additionally, it's important to mention that the applications of PLM are expanding rapidly. In 2002, companies worldwide spent more than $10.4 billion on PLM products and services, according to AMR Research Report (2003). That makes PLM one of today's largest and fastest growing enterprise application categories. According to CIMdata Inc. (2004), the overall PLM market grew to $14 billion by 2003 and they forecast that the overall PLM market will perform at a compound annual growth rate of eight percent through 2008, to exceed $20 billion. The Next Generation Manufacturing Report (Jordan and Michel, 2000), funded by NSF and based on opinions of close to 500 industry experts, envisions that manufacturing industry of 2020 will become highly dependant on Product and Process Lifecycle Management (PPLM) to "integrate, connect and combine people, processes, systems, and technologies of the extended enterprise to assure that the right information is available at the right location, with the right resources, at the right time."

2.2 Defining PDM in a PLM context

> *"The problem CEOs face today is not acquiring and storing data. Rather, it is turning that data into useful insight that enables them to better manage their businesses and seek competitive advantage. Creating an intelligent corporation, one that gets the right information to the right managers in a timely manner, requires (an) approach that embraces the entire information lifecycle." (Royce Bell. Chief Executive. New York: Nov 2005. Iss. 213; pg. 14, 1 pgs)*

This research has been dealing with PLM overview so far. This section discusses the concept of PDM (Product Data Management), its issues and its relationship to PLM will be discussed. PDM is important in this thesis; because it allows designers to get the data they need about the product to perform DFX. The following is an example which will help introduce PDM.

Some people know that silicon is not much more than dust. It is basically formed from silica, and there is a great amount of it all over the Earth. To produce silicon, silica and coke are heated in an electric furnace. This means that silicon itself is not very worthy from the marketing point of view. However, there is a great difference between having a handful of dust and having a cutting edge processor made up of silicon and metallic conductors. In other words, the technology embedded in the processor is much more valuable than any of its components. Processors have been around since the 1980's. Even when they perform the same basic function, i.e. adding 1's and 0's, each model is very different from the others, and every generation is faster and more energy-efficient than the previous. What allows these improvements is the data that designers use about electronics, manufacturing processes and other processors. As it is rather difficult for a single person to develop a processor from scratch, this process involves a group of people working together and sharing as much data as possible about electronics, materials technology, chemistry, computing systems and manufacturing. Once a new version has been deployed, these concepts are then kept in the company to make further improvements, and thus better processors. This example, with some variations, may be applied to many other types of productive companies. What is relevant here is to point out that the collective know-how of a company is represented by the data they can use, and it must be used as profitably as possible. Put differently, processors, automotive or any other companies would have a difficult time trying to improve, introduce new models or compete in the actual market without the data they need, that is, what people (customers, providers, employees, consultants, etc.) know about their product. In this way, data, as well as its management, should be taken as an important asset to improve competitiveness. This is the idea behind PDM.

2.2.1 Brief historical note on data management.

Nowadays, people still commonly use paper to sketch, take notes or communicate. Companies still print their invoices, bills and tickets, as well as procedures, reports, manuals and catalogues. Most of the time, this is done for simplicity. For example, it is still difficult that, in a metal extracting company, every miner carries an electronic device with the safety instructions loaded, or with the request orders for material. Traditional printed communication methods are going to remain here for some time. Companies have been able to work with the inefficiencies, errors and bulk due to paper. Air tubes, messengers, entire rooms for storage and many versions with their revisions are only some of the examples of those issues.

Another consequence of inefficient communication is the "islands of automation" (Stark, 2006). This term describes the difficulties computers or computer-integrated systems have in managing and sharing data with each other, e.g. a robot isolated from the rest of a manufacturing process or even the product development department in a company. The island of automation problem did not become apparent until the 1980's, so it wasn't until then that Information Technologies (ITs) started to deal with the issue. As a result, the processes are now more integrated.

About a PDM solution, Anders Romare, director of the PLM business office at Volvo Information Technology, said to the *Manufacturing Computer Solutions* magazine, "our goal is to reduce (lead time) by 20%. We now have much higher data quality. (An) engineer now has the full 3D model available so, he has the responsibility (to do things right)" (Shelley, 2005). This resembles how some processes in several companies are being improved due to PDM and PLM.

Boeing® uses ENOVIA® from Dassault Systèmes®, Rockwell Automation® implements UGS' Teamcenter®, and Masserati® makes a better use of data through PTC®'s Pro/INTRALINK. These are just some of the popular PDM software available in the market. It is evident that their scope is very broad, and more important, companies are having great results using them.

2.2.2 PDM system definition

By now, the reader should have some idea of what a PDM system is. However, there has not been a formal definition of the subject. Before defining PDM, it may be important to mention that even when there may be very archaic and purely manual ways to manage data (e.g. in old libraries or warehouses) either in the private or public sectors, the term PDM now refers to digital systems performing the management of product data. In other words, PDM requires a computer system.

This thesis will try to give a concise definition of what a PDM system is. It will also present its functions and elements in further detail in a separate section. By doing so, it is intended to clarify the differences and relationships that exist between PLM and PDM concepts, which drive many people into confusion. This and the following sections will allow the reader to clarify their differences and relationships.

To fully understand the term "PDM system" it is necessary to have a clear concept of its constituent terms. To begin with this clarification, the word "product" will be defined as the result from human and/or machine activities (intellectual and/or physical). In art or industry, a product may be any kind of software, good, tool, resource or service able to undergo a copying or reproduction process under certain specifications. A product may or may not be for sale, depending on the decision of the owner. On one hand, when referring to intellectual activity, the intention is to include any sketch, written idea, mathematic solution or visual representation developed by individuals, machinery or digital systems. An idea is not considered a product, unless it has been graphically expressed. In this sense, any intellectual property, such as books, expressions or drawings, may be a product. On the other hand, as a result of a physical process, a product may be any tangible object formed of a single or series of pieces or substances. For instance, a bearing is a product which could have rollers, lubricant, and races, which are products by themselves. Someone can provide a service and call it a product, for example, car maintenance.

It may seem simple to define data, because it is the basis for human activities. Without data, we could not take the single decision of putting one foot in front of the other. Even when we breathe or open our eyes, we gather data to know if it is safe to do it. Data relates solely to words or numbers, whose meaning depends on the context where it is used (Guerra et al., 2006). Information is structured data which provides meaning within a given context. Knowledge exists when the user within that specific context recognizes useful data relationships, or when the user is able to derivate those relationships from raw, but structured information database

If this was a sequence, the most logic following term to be described would be "management". However, there are so many and broad interpretations of this word that the effort would be out of scope. It is better to place our attention into "data management". This is a more focused approach, because the real interest is to know how to manage data, not management itself. However, very few authors actually define what management means in this context. Instead, they focus in the application or improvement of PDM systems

As it was implied in the last paragraph, companies don't need pure data, but the use of it: knowledge. Data management keeps data usable. In this context, management refers to all the related elements and actions needed to capture, store and retrieve data. These concepts will be explained in detail in a further section to specify the main functions that PDM systems comprise.

In the same way as such functions, there are several definitions for a PDM system. There are three major points of view: (a) the ones who think of PDM as a tool for engineering or project development only (Lin et al., 2006; Kumar & Midha, 2004; Smith, 2004), (b) authors who leave a wide margin to interpret their definitions by the use of phrases like "major functions", a series of characteristics followed by "etc." or "many others functionalities" (Ou-Yang & Chang, 2006; Merlo et al., 2005), and (c) the ones who present PDM as an important part of PLM (Benoît Eynard et al.; El-houry, 2005; He et al, 2003; Gao et al., 2003). It is probable that the variety comes from the fact that the PDM concept was coined after CAD was born in engineering and design environments. Besides, it is also a very important part for every PLM stage, and many people don't have a well-defined concept of the latter.

In this thesis, a PDM system is defined as a tool which aids companies in managing all product-related data throughout the product lifecycle. However, it does not comprise the tools needed to modify the integrity of such data. As it may seem a short definition, the following section explains the relationship between PDM and PLM.

2.2.3 What is the role and need for PDM in PLM

As it has been said, in the PLM introduction, the workflow needed during the product lifecycle can be very complex, because of the amount of involved people and entities. This complexity may make some practices run in parallel or in sequence, thus requiring iteration or repetition of a series of actions. The main role of PDM systems, within a PLM environment, is to provide support to the many activities of the lifecycle, such as design, the tracking of information in changing orders, the alternative designs management, and the product configuration control.

John Stark defines PDM systems as "one of the most important components of a PLM solution. They are the primary system component of PLM. They are systems to manage product data and product workflow" (Stark, 2006). To make this clear, look at the following picture (Figure 2.2-1) which shows that PDM's main function in PLM systems is to manage data all over the PLM stages. PDM systems, for example, could not provide the required tools to design or perform any kind of analysis. Instead, they provide the platform in which every kind of user can access the information to share it or modify it. Furthermore, PDM systems should be able to handle data disregarding the software being implemented, or its function. A good analogy for the PDM system would be that of a semaphore guiding data through lanes, waiting for lights to turn, so that they can get from one place to another. In other words, the objective of data is to get to a specific user, where the PDM system will guide this data to get to its final destination, but won't change its nature.

The picture (Figure 2.2-1) shows some examples of the data generated with the product lifecycle tools (CAD files, CFD data, change orders, NC codes, marketing results, user manuals, etc). These types of files and data are not the only ones which can be produced during the product lifecycle, but represent the idea of having many sort of digital data. In this sense, the picture depicts that the data being produced by the PLM tools will be managed by the PDM system, regardless of the company department or stage in the PLM. On the other hand, every stage of the PLM needs a determined tool for a specific user. Thus, the rest of the PLM tools may exist without the PDM system and work as stand-alone software to comply with one specific function. It is through PDM that they unite their strengths. It is until all the specialized tools for every stage of the PLM and the PDM system are working together, that it is possible to deal with a PLM environment. That is, the PDM system by itself is not enough to support all the PLM, but it is only a part of it.

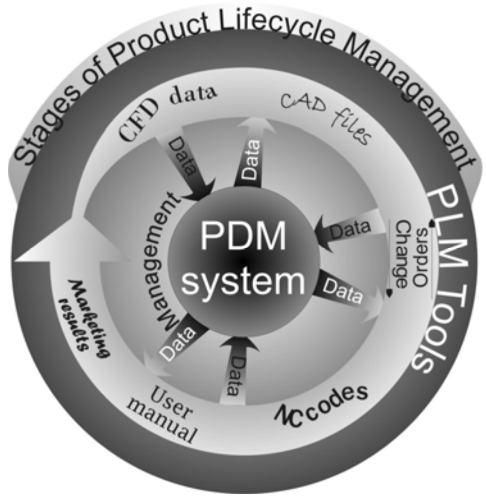


Figure 2.2-1 Type of data managed by PDM systems

2.2.4 The goal of PDM systems for enterprises

The main goal of PDM systems for companies is to be an efficient, secure and reliable provider of the product data for the ones who need it (Kumar & Midha, 2004),. This is a simple statement that involves some of the following benefits: systems integration, time minimization, better communication with clients, and more efficient communication within the company, scrap reduction and shortening distances. Others include better communication with suppliers, reuse of data and more compatibility among software.

Systems integration entail both software and workflow management (Stark, 2006; Kumar & Midha, 2004). The first objective improves productivity and cost by reducing the need to buy new software and making it easy to handle file types. Without this capability, companies would require other means to open files from different applications. Consider a hypothetical case in which a person works with software “A” in America, but needs some files from Europe which are in “B” format. Even when “A” and “B” may have similar functions, (e.g. they are both CAD software) their formats may not be originally compatible. PDM systems reduce this bias by incorporating reformatting functions, so that different software becomes compatible.

In the case of workflow management, PDM systems improve product quality and reduce development time (Stark, 2006). As implied before, PDM systems diminish paper use as far as possible, and improve the way in which data is transferred from one place or person to another. When reducing paper use, PDM systems make the capture, storage and retrieval of data more efficient, while demoting duplicated instances of it. Here, capture means the action of introducing new data or a new data structure into the system. In this way, a user captures data by changing a given file or by creating it from the beginning, Storage refers to the way in which data is put into a database or memory space. It regards the data organization and the modifications it may suffer from its original state to fit in the given database or memory structure. Finally, retrieval comprises the search and presentation of such data.

The first advantage of PDM systems is that there would be no more need to have an information management department. Even if the reader disregards the advantage of having fewer employees in an activity which produces virtually no asset, consider the convenience of having these managing functions in an overseas fashion. This could not be attained by the former department due to geographical and physical boundaries.

Another benefit is the time reduction for people to get the right information (Stark, 2006) because they would not be required to visit the information management department, fill forms or wait for someone to retrieve documents from file storage. Instead, check-in and check-out reports are automatically generated with the user information, which would have been previously verified for access rights. Even when the required documents were in digital format, the time it takes to find many of them in the absence of a PDM system varies broadly. In the worst cases, the file is not found, and users usually duplicate or create new data (Grieves, 2006). The problem that arises is that one instance of such data duplication or creation won't be updated anymore or it would take more time to do so. Thus, there could be data and time loss. Moreover, there are cases in which users cannot access the information at all, so they can't do their job (e.g. it is stored in an island of automation). A PDM system can boost productivity by filling that gap.

All of the above introduces the issue of capturing data, and envisions one of its relationships to retrieval: a PDM system should enable a user to know when a file is being used, so that he or she is aware that changes are being made. By doing so, they should be able to work collaboratively, or prevent information loss, to say the least.

Capturing information should be an easy task for the users despite their profiles. The computer programs and hardware they utilize may not be always the same, but the type of data does (e.g., CAD files regardless of the program being used). Some other times, multiple instances of data may be useful for the same task, and have different structure or representation (Guerra, 2004). For example, solving a determined problem may need data tables, pictures and videos at once. The PDM system then provides a friendly way to capture these types of data, and links them in certain way, disregarding where they were created. The security embedded in the PDM system capturing module comes in handy by assuring that these multiple types of files are not viruses or malware. The time that would usually take a team to create the virtual structure to organize the information, including notes, folders and shortcuts, could be used for more productive activities.

Once the data has been captured, the storage section of the PDM system makes sure that the information is saved in the right place, both physically and digitally (i.e. the right server and the right memory slot). The PDM system could also optimize the way in which data is stored. For instance, it can compress or debug files to make them smaller in memory space.

PDM systems also provide the infrastructure for users' access rights, so that only the right people are able to capture and retrieve data (Kumar & Midha, 2004).

Then, the major goals of PDM systems in enterprises are to reduce operations time, improve product/process quality, provide data security and integrity, prevent information loss and reduce costs (Watson, 2004). Another benefit commonly mentioned is being able to audit data, thus having the possibility to undertake certain certifications like ISO. Most of these benefits link together. For example, a PDM system enables the reuse and update of data, instead of duplication or loss, so that once there is a product developed, the need to focus on what has already been done and tested is not performed anymore (e.g. past analysis). This both saves time and increases product/process quality, because designers and engineers can focus on innovation.

Before finishing this section, recall that the PDM functions only involve the management of data. In every case, the users, clients or providers should make the decisions of how to use such data, as well as selecting the appropriate tools to do it.

2.2.5 PDM Characteristics

This section will show what is technically required for a PDM system, and which are its main elements from a theoretical point of view.

It may be evident now that the development of a standard definition for a data item must comprise the requirements of several users and software to make use of such information during the data lifecycle (Stark, 2006; Watson, 2004). This is not an easy task, as anyone can imagine. Instead, it is an exhaustive and complex activity. When it is done, the PDM system will start with a good foundation regarding data sharing.

Following Stark's classification, a PDM system should basically be built from a warehouse or vault, a management module, a user interface, and several functions for information, workflow and systems administration. In any case, the PDM system must be able to keep data shareable, transportable, secure, accurate, timely and relevant (Stark, 2006).

Shareable refers to data that can be easy and instantly viewed or used by more than one person at any instant; transportable regards the capacity of data movement in an easy fashion; when data is secure, it means that it can be protected from unauthorized destruction, modification or use; accurate data is reliable and precise; if it is current and up-to-date, it is timely and can be called relevant if it is really useful for the decision in turn. (Watson, 2004)

The warehouse is basically a repository in which the data is stored (Stark, 2006; Watson, 2004). In other words, it is the memory of the system. The management module is used to capture, store and retrieve data, including its security, integrity, concurrent use and recovery (in case of errors) (Stark, 2006). The user interface is fundamentally how the information is presented to the people who use it through Graphic User Interfaces (GUIs) queries, menus and forms. Bringing the last two terms down to raw definitions, the management module distributes and organizes the data where it belongs, while the user interface is the way in which the human both receives and gives outputs and inputs to and from the computer.

The most important part of the PDM is, by definition, the management module. The PDM system requires some degree of certainty to implement its administrative functions. In this way, it is essential that information and workflow have their own definitions. These must include a standardized structure for every type of file. The PDM system must be able to recognize the type of file (CAD, CAE, CAM, etc.) for many file extensions. It is important to remember that every application uses its own file extension and that there is much software to work with each type of file. Thus, having the right definitions is an important part for the PDM system to separate and place each data item in its right place to access it efficiently (Watson, 2004). It is also essential to have a function to manage the structure of files, because it is not enough to know what type of file the module is managing. The structure may be useful to fix errors, retrieve important data for fast review (thumbnails for 3D product representations, for instance), perform searches, etc. (Stark, 2006)

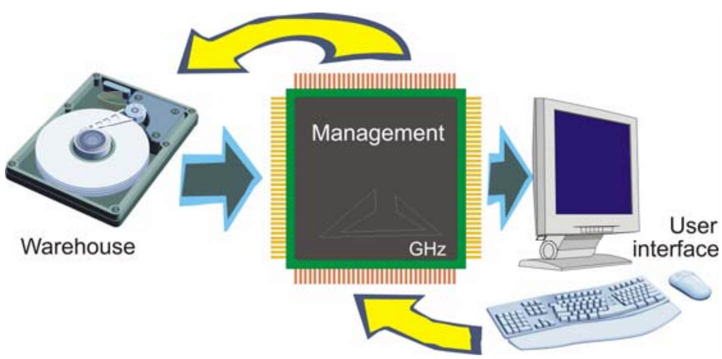


Figure 2.2-2 Major elements of a PDM system.

All of the above are essential for the user and the applications. However, there are other functions regarding systems administration that should be entitled. For example, there should exist an easy way to setup, maintain and access both data and the PDM system. These functions include access rights, registry files modification and update, GUI update, etc. This is a big challenge for the system administrator, because the support cycle is longer and produces more data than the design and manufacturing process (Stark, 2006).

The most important issue of PDM, relating to PLM, could be to maintain control and be flexible enough to allow changes as work is being performed. A real challenge is to manage both paper-based and computer-based activities. At the same time, PDM systems should be able to handle different levels of data definitions and representations. It is essential that data representation relates to the same underlying data, i.e. there is no case in modifying superficial representations of the product data only (Stark, 2006).

The current PDM applications are on product development projects, managing the product information involved (Mesihovic, S. 2004).

Recent developments of the PDM systems have been oriented towards web-based solutions that support the full product definition lifecycle; for example, TeamCenter Engineering (UGS PLM Solutions, 2003), Windchill (PTC, 2003), Enovia (Dassault systemes, 2003) (Mesihovic, S. 2004).

The software used in this thesis to manage the product information is Teamcenter Community. However, it is important to notice that Teamcenter community is just a tool for team collaboration and to manage product information. The tool does not accomplish all the functions that a PDM system must do.

2.3 Expert systems overview

The present section will introduce the concept, advantages and examples of expert systems. Firstly, the relationship between expert and expert system is presented. Then, expert systems are defined among its advantages. The section will also exemplify some of the most recent advances in academic and commercial expert systems in the design area, as well as tools that facilitate the development of such systems.

Experts are one of the most expensive and limited resources in an enterprise (Turban, 2005). Furthermore, they are in the enterprise for a limited time, so they can leave a company with their knowledge and experience in any given time. In response to this problem, expert systems were created to emulate these experts. These systems' principle consists basically of two parts: capture the resulting knowledge from those experts' experience, and structure it into rules that allow the non-expert user to make better decisions.

The advantages of these expert systems are that the knowledge and experience are stored in a computer system which remains in the company without the uncertainty of losing it. By the contrary, experts store knowledge in their minds which makes this knowledge susceptible to be lost in any moment. Another advantage of the expert systems is that they allow the undertaking of the same tasks developed by experts by less capable resources without losing efficiency and quality in such processes. Actually what does gets reduced are the labor costs.

Turban gives a formal definition of expert systems: “an expert system is a computer system that emulates the decision-making ability of a human expert” (Turban, 2005)

There are actually expert systems in diverse knowledge areas. Some of the ones developed in the product design area are:

Expert system for product manufacturability and cost evaluation: (Chan, 2003) Developed by Danny S.K. Chan from the Hong Kong Polytechnic University. This system is an evaluation tool for product designers to evaluate manufacturability of product designs. It requires the input of information related to product geometry and product design specifications. The geometry corresponds to a raw and rectangular block, while the specifications correspond to parameters such as “surface finish and accuracy, production volume or quantity of production, whether the product is an integral construction or assembled from components, the form of raw material, and material property requirements”. The three modules that give the structure to the expert system are: material selection module, manufacturing process selection module, and the product costs estimation module. The knowledge base about the product material includes information of commonly used metals (steels, cast iron, nickel, copper, aluminum, and some alloys) which are specified by their mechanical properties (elasticity modulus, tensile stress, and hardness). When the required mechanical properties match the conditions of a rule, it activates the recommendation of a given material, and activates the proper operations in the other two modules.

Chan states that the expert system includes all the conventional production processes used for metallic components: (a) machining: turning, milling, drilling, boring, grinding, broaching; (b) net-shape: sand, die and investment casting, and forging; (c) sheet-metal: shearing, bending, deep-drawing; (d) joining: welding. To select the process, the user must input the “production volume, surface finish, dimensional accuracy, product integrity, material form, mechanical properties, and product geometry”. The result from this module is used for cost estimation.

The cost estimation module uses the previous resulting data, tooling costs product data (size, volume and shape), production data (volume, processing time and labour rate), material data (densities and their cost rates), and overhead (expressed as a percentage; the default is 250%)

Product audit tool: (Moultrie, Clarkson & Probert, 2006) Moultrie et al. present a tool to asses products for novelty, desirability, usability, and producibility. Without being a benchmarking tool, the perceptions towards product characteristics are evaluated through simple checklists using the previous list of criteria. This tool helps the designer to perceive how good a design is.

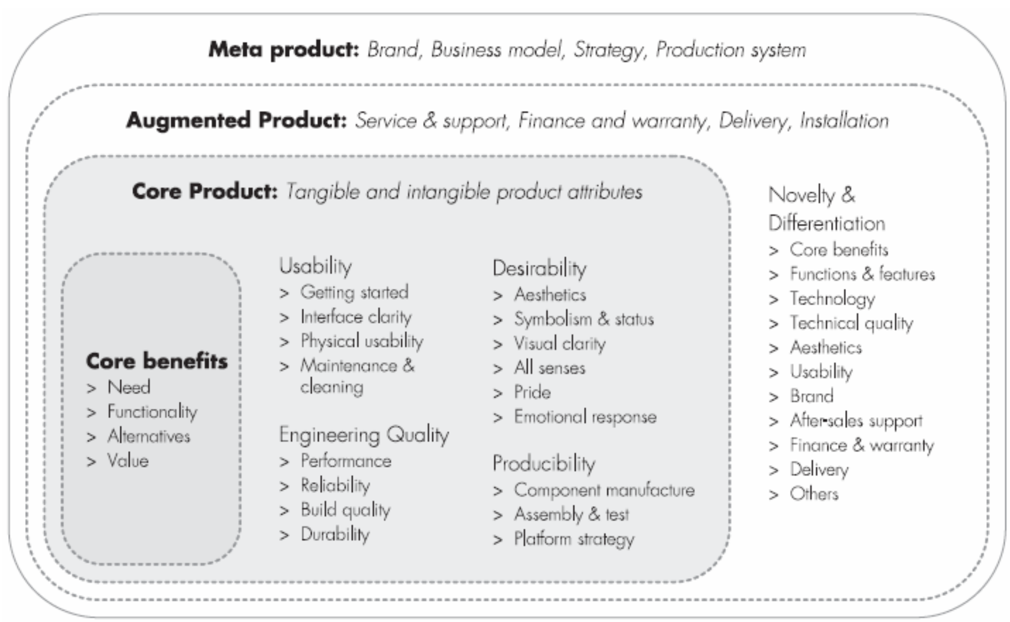


Figure 2.3-1Architecture of the product audit (Moultrie, Clarkson & Probert, 2006)

ProPlanner: (Pham & Gologlu, 2001) According to its authors, “ProPlanner automates information acquisition, product design interpretation, manufacturing operation planning, cutting tool selection, set-up planning and operation sequencing.” They state that it assesses design to determine its errors prior to manufacturing. It is also intended to give feedback on how to correct errors and give suggestions on design alternatives. ProPlanner is a tool to improve a concurrent engineering process. It allows the change in design of a part based in the existing capabilities of the facility (shop level). The system tries to overcome the stand-alone functionalities and requirements of human experts' input of CAD systems through the combination of feature-based CAD and knowledge-based modules which also include embedded expertise. The designs are created in a solid modeller which uses feature commands to generate several types of design features.

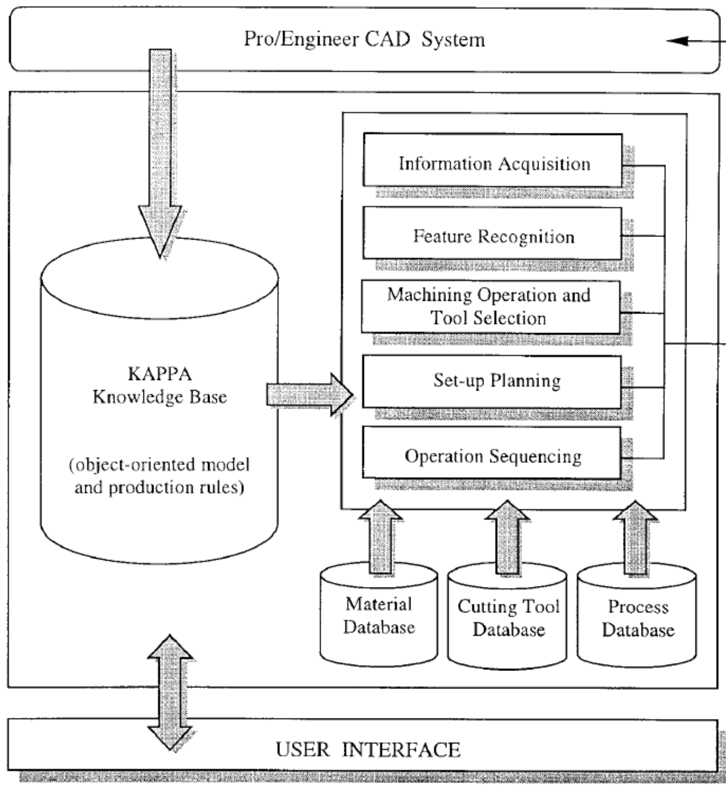


Figure 2.3-2 ProPlanner modules (Pham & Gologlu, 2001)

ProPlanner incorporates the capabilities of different machining operations and manufacturing constraints (e.g. initial conditions of machining operations). It extracts the information related to the product model from the CAD model automatically. ProPlanner incorporates a feature recognition module to achieve this. "The module uses a hybrid approach based on an inductive learning algorithm to recognize the [created features]". The goal is to translate the given features into appropriate process definition. The system also chooses the required tools. ProPlanner is able to suggest several operations and tools to produce the part. In case the system does not find an operation or tool to produce the part, it then suggests design changes.

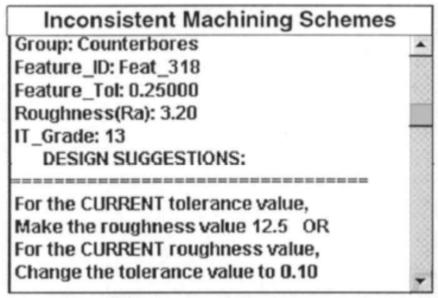


Figure 2.3-3 Segment of the "machining operations window" in ProPlanner showing a design change recommendation (Pham & Gologlu, 2001)

ProPlanner has other functionalities related with part production which won't be discussed here.

Boothroyd and Dewhurst have developed a commercial DFMA software suite which may be the most famous software of its kind (Huang, 1993). The most recent version of this software is DFA version 9.2 and DFM Concurrent Costing version 2.1.

"[Together, they identify] the major cost drivers associated with manufacturing and finishing parts. [It] helps engineering supply chains understand the cost structure of products and supports the development of designs that are easier and more economical to produce. The software takes a quantitative, multidisciplinary approach to cost assessment. A key benefit is the quick generation of an initial cost estimate at any stage of design in just a few simple steps." (Trailer / Body Builders, 2005)
"The software contains early cost models for various manufacturing processes, including sheet metalworking, machining, structural foam molding, plastic extrusion, injection molding, thermoforming, blow molding, cold and hot diecasting, hot forging, powder metal processing, sand casting, investment casting, printed circuit board processing, and automatic assembly. An interesting aspect of the automatic assembly element of the package is that it allows comparision of costs between automatic and manual assembly, which can be an important consideration for those considering off-shoring of production operations." (Anonymous, 2006)

Mileta Tomovic has developed expert systems on casting desing process and materials selection.

Besides, there are tools which leverage the development of expert systems. These tools are specifically designed for decision support systems unlike traditional programming languages or suites like C or Java which are intended to program any kind of applications. The "C Language Integrated Production System" (CLIPS) was born as a pilot project within NASA. It was chosen over other software developed by external companies, because it proved to be cheap and functional. CLIPS may be used for rule and/or object based [2]expert systems. For instance, it can handle both heuristics (also called rules or thumb) and procedural (line by line) programming. CLIPS is actually written in C which means that it can also be integrated with most programming languages (C, Java, FORTRAN, ADA, etc.) through subroutines, for example. It provides fact- and instance-lists (data storage), knowledge-bases (contains the rules) and an inference engine (control of rule execution).

Regarding to the development interface, CLIPS has pull-down menus, integrated editors, and multiple windows. It permits modular design and partitioning of a knowledge base. The system also provides support features like a debugger and capabilities to check for static and dynamic constraints of slot values and function arguments. Besides, it provides semantic analysis of rule patterns which determine if there are flaws in rule matching detection.

It is very important to mention that CLIPS is part of public domain now. This permits an open source and free access. It can be downloaded from:

http://www.ghg.net/clips/CLIPS.html

Some software companies also develop products to leverage the development of expert systems. For example, Dassault Systèmes provides "Knowledge Expert®" as a companion tool for CATIA® and DELMIA®. This tool allows the building and sharing of corporate knowledge in rule bases. It lets the knowledge to be deployed across the company to comply with design specifications. To do it, employees are able to create and manage generic rules and checks (for classes of objects) which are used to ensure that geometry comply with corporate standards. Users can define and manage rule sets to structure the

[2] "Object based" refers to software that can reuse full or partial programming blocks, i.e. modular components

corporate knowledge base. These bases can be imported too. Information-customizable reports in HTML, XML, or TXT are also available.

While CLIPS is intended for any kind of expert system (e.g. business, engineering, accounting, etc.), Knowledge Expert® is intended for design only. CLIPS is not embedded into any CAD tools, but Knowledge Expert® can only be used within Dassault Systèmes® suite. Another difference is that CLIPS is intended to be a development environment, and Knowledge Expert® is a companion of a design suite, therefore the latter is limited in functionalities, but is easier to use for design purposes.

2.4 DFX WITHIN THE PRODUCT LIFE-CYCLE

This section will describe how DFX fits into PLM. First, a general overview of the stages in the product life cycle will be presented, followed by a brief description on how the design stage interacts with the other phases in PLM. To conclude, the section will introduce some of the possible methodologies for design, and will finally present DFX concept.

According to Aca (Aca, 2004), the PLM cycle is composed of the following stages[3]:

- Product Development
- Process Development
- Facility Development
- Production and Sales
- Use and Maintenance
- Disposal

Product design and product development are not the same for some authors. Suh states that every designer follows these tasks:

“1. Know or understand their customers’ needs
2. Define the problem they must solve to satisfy the needs
3. Conceptualize the solution through synthesis
4. Perform analysis to optimize the proposed solution
5. Check the resulting design solution to see if it meets the original customer needs.” (Suh, 2001)

Suh defines design as “an interplay between what we want to achieve and how we want to achieve it” (Suh, 2001) and gives the following illustration:

[3] See Fig. 2.1.3.b

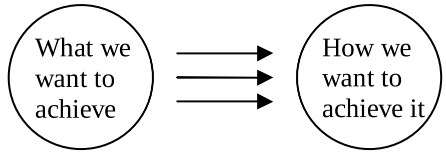


Figure 2.4-1 A definition of design (Suh, 2001)

In a similar way, Aspelund says that “design is a plan of action, created in response to a situation or problem that needs solving.” (Aspelund, 2006). In his opinion, the plan needs to be explained to a viewer in an understandable way. “Designing is about forming ideas, planning and explaining the execution of those ideas, and making choices based on the evolution of those ideas that will lead to an end result” (Aspelund, 2006). Aspelund identifies seven stages in the design process: Conceptualization, exploration/refinement, definition/modeling, communication and production (which also comprises prototyping).

It is important to note that design is an area-specific activity. It can be applied to engineering, arts, sciences and business activities.

On the other hand, Otto & Wood separate development from design so that development includes manufacturing plans (Otto & Wood, 2001). Beyond that, they consider the possibility of including the development of the distribution channels in product development. Conversely, design is included in the product development, and is a group of technical activities which include the translation of the product vision into technical specifications, the development of new concepts, and the engineering embodiment of the product. In turn, they present embodiment as the application of mathematical and science skills which can derive, for example, in the selection of the appropriate components for the product.

Aca (Aca, 2004) defines Product Development Process as the first stage of the Product Life Cycle. It starts with the product idea, and its final result is a functional prototype. For him, the four stages of this process are:

• *Conceptualization*, the idea is introduced before a commercial product can be designed. Such idea should lead to technical and economically viable applications. It is followed by the systematic search for selection and development of promising product ideas. The project scope and plan are defined here.

• *Basic Development,* this involves the gathering of information about the customer requirements and constraints to be embodied in the solution. The essential problems are identified through the establishment of function structures and the search for appropriate solution principles. A solution concept is performed to lay the basic solution path.

• *Advanced Development,* the arrangement, geometry and physical properties of all individual parts are established; the materials are specified; the technical and economic feasibility are rechecked; the sketches, BOM and any information related to the product are generated.

• *Launching,* any remaining issue is worked out and tested to check the functionality and foresee potential design modifications.

The main difference between the above definitions is in the final stage of the design/development definition. The reader is advised to consider design as an essential part of the product development process, and leave an open interpretation on the boundaries between them. Furthermore, prototyping will be considered as the final stage of product development.

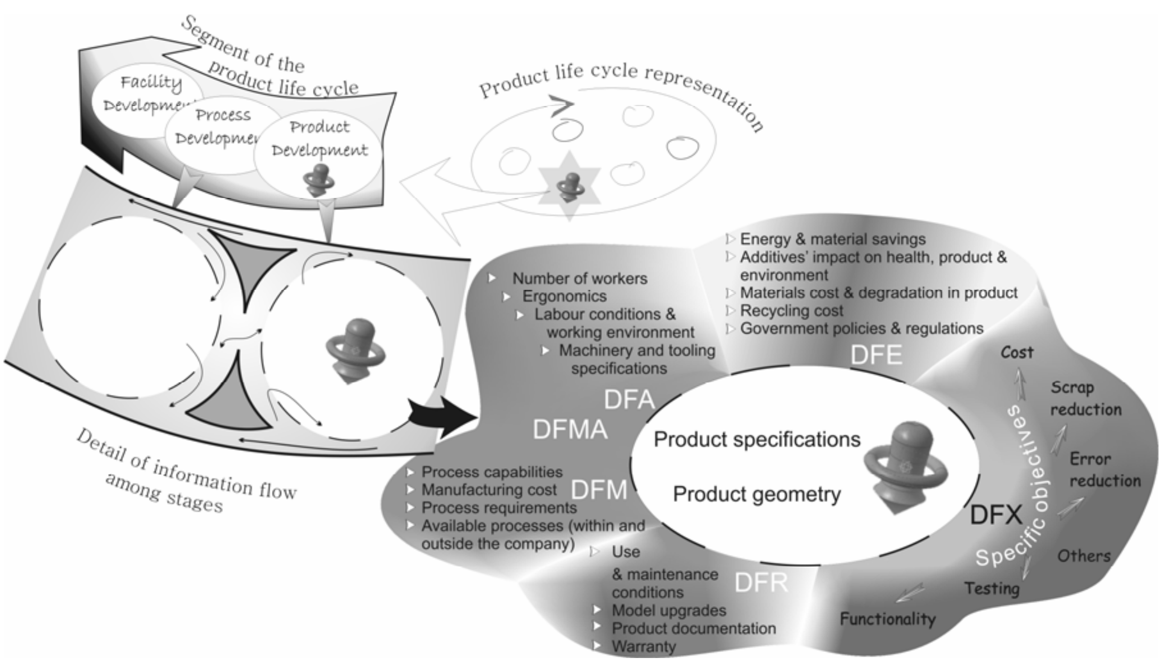


Figure 2.4-2 DFX within the Product Life Cycle.

In most cases, authors represent the life cycle of a product as having from three to ten stages (Grieves, 2006; Kovács, 2006; Aca, 2004; Bhamra, 2004). It is customarily considered as a loop, restarting after the recycling or disposal of the product. The convention is to consider the product design or development as the beginning of the cycle. The visual representations of life cycle usually include the stages connected by arrows or any other means to clarify the viewpoint of the author regarding each of the stages within the cycle. For that reason, these phases of the life cycle are customarily spatially separated in the representations. However, in the PLM approach, every stage is just another part of the whole life cycle, and they are actually interrelated.

Despite the fact that there is more interaction between specific stages, (e.g. the facility development has very little to do with the marketing department), the PLM approach boosts the flow of information from one stage to another. The stages are still independent from one another, but the information generated does not remain within them. Instead, it flows through the whole cycle by means of the PDM system.

In this way, the product design stage receives information from all the other stages. This structured data could come from the marketing, manufacturing, service or any other department in the company. All this information then becomes part of the product's final specifications and geometry. All of the above is represented in Figure 2.4-2.

The decisions taken during the product development stage will have repercussion on every other stage of the product life cycle. It is said that design is the cheapest of the costs included in the price of a product. Conversely, it is also accepted that about seventy percent of the costs are determined during the design stage (Boothroyd, Dewhurst & Knight, 2002).

Depending on the company's interests, the designer may be willing to incorporate a particular focus on the design. For example, if the company is mostly dedicated to perform assembly operations, then the designer has to optimize the product design for that process. This optimization will lead to savings in the final cost of the product.

Design for Assembly (DFA) is a method to ease the assembly of pieces. It has been the precedent to all the other Design for "X" (DFX) methodologies. It was first implemented in the 1960's. During the 1970's, Design for Manufacture (DFM) was also introduced into the design area (Boothroyd, Dewhurst & Knight, 2002; Huang, 1996). It is basically the design for ease of manufacture of every part that will form the final product. Its importance is so widespread that it can be subdivided into manual, automatic or robot DFA.

Despite some authors consider DFA as a part of DFM (Otto & Wood, 2001), most of the time they establish specific guidelines for it, and give it major relevance as part of DFM. Anyhow, DFA and DFM are so interrelated, that the term Design for Manufacture and Assembly (DFMA or DFM/A) is now accepted in the engineering and design areas. This subject deals with both manufacturing and assembly at the same time. However, there are companies that don't need the method from one of them (DFA or DFM) as much as they need the other. For instance, a casting company may not be interested in assembly operations, since they don't perform any.

Two of the other important methodologies that have become important in the industrial sector are Design for Environment (DFE; it is also known as Green Design or Ecodesign) and Design for Repair (DFR; better known as Design for Maintenance or Service). Companies were first driven to DFE by governmental policies, rules and fines. However, some have found that there are more benefits in implementing environment-friendly designs (Abele, Anderl & Birkhofer, 2005; Bahmra, 2004). For example, health issues are now reduced and some production costs may be lowered (Bahmra, 2004) (dry versus wet machining; the reduction of by-products and their required processes). In the case of DFR, companies (like the aeronautic, aerospace and naval industries) provide the service of maintenance to most of their own products, due to the specialization they require. Thus, maintenance is an important part of their revenues.

There are many other approaches to design. What is certain is that products are developed to fulfill a specific goal beyond its functionality or aesthetic appearance (Otto & Wood, 2001). Design for "X" (DFX) means to design a product towards a specific goal. Design for X includes a set of initiatives to reduce product's cost and improve its quality in the early stages of design (Huang, 1996). DFA[4], DFM[5], DFMA, DFE and DFR are just some of the most common types of methodologies. They all follow a set of rules, guidelines or procedures to accomplish their ends. Despite that it may be logical to apply more than a

[4] Design for: manual, automatic and robotic assembly are special cases of DFA

[5] Design for: casting, injection molding, welding, machining, brazing, etc. will be considered as special cases of DFM

single "X" to design, this is rarely done due to limited resources (Huang, 1996). The following is a set of guidelines proponed by Huang regarding when and where to apply certain DFX:

1. *"A consensus view is that DFX should be used as early as feasible. The earlier, the greater the potential.*
2. *DFX such as Design for Assembly and Design for Variety should be used to rationalize product assortments and structures before other types of DFX tools.*
3. *What the problem is and where it lies determine what DFX to use.*
4. *Exactly which specific DFX tool should be used is affected by a number of factors such as availability, applicability, vendor experience, etc."(Huang, 1996)*

In this thesis, the interests are on how to capture the DFX expertise, and incorporate it into the decision-making process.

2.5 Summary

There is a current deficiency of shared understanding and agreement on PLM, which makes it difficult to include all its elements in a single statement. PLM is a business approach focused on the management of product's data, process and development technologies and the people inherently involved with the product across the entire product lifecycle from its early conception to disposal. The main elements of PLM are: human resources, experience, education and training, support, change capacity, organization, process/practice and technology. Its major benefits of PLM are: increased revenues, decreased product cost and decreased product development cost.

The main role of PDM systems, within a PLM environment, is to provide support to the many activities of the lifecycle, such as design, the tracking of information in changing orders, the alternative designs management, and the product configuration control. PDM refers to digital systems performing the management of product data. A PDM system is defined as a tool which aids companies in managing all product-related data throughout the product lifecycle. PDM systems could not provide the required tools to design or perform any kind of analysis. Instead, they provide the platform in which every kind of user can access the information to share it or modify it. The main goal of PDM systems for companies is to be an efficient, secure and reliable provider of the product data for the ones who need it. The most important issue of PDM, relating to PLM, could be to maintain control and be flexible enough to allow changes as work is being performed.

An expert system is a computer system that emulates the decision-making ability of a human expert there are actually expert systems in diverse knowledge areas. Some of the ones developed in the product design area are: (a) Expert system for product manufacturability and cost evaluation, (b) Product audit tool, (c) ProPlanner and (d) Boothroyd & Dewhurst's DFMA software suite. There are tools designed to leverage the development of expert systems, such as: CLIPS and Knowledge Expert®.

Design is an area-specific activity. It can be applied to engineering, arts, sciences and business activities. Design can be considered as an essential part of the product development process. Design for "X" (DFX) means to design a product towards a specific goal. Design for X includes a set of initiatives to reduce product's cost and improve its quality in the early stages of design. DFA[6], DFM[7], DFMA, DFE and DFR are just some of the most common types of methodologies.

[6] Design for: manual, automatic and robotic assembly are special cases of DFA

[7] Design for: casting, injection molding, welding, machining, brazing, etc. will be considered as special cases of DFM

CHAPTER 3 A METHODOLOGY TO SUPPORT DFX PROCESS USING A PLM FRAMEWORK.

In the previous chapter, PLM, PDM, DFX and Expert System concepts were depicted. This chapter explains how those concepts fit together in order to achieve the same goal: to provide designers with the proper information and knowledge in order to improve the DFX process. In this chapter a methodology of manufacturing knowledge is proposed. The activities involved are explained in detail in order to execute and manage this methodology. The methodology is independent of the industrial sector of a company, and can be applied to any kind of industry.

This chapter consists of two sections. In section 3.1, a PLM framework to support a DFX process is shown. This framework consists of four actors: the PLM model, PDM tool, DFX process, and Expert System. An explanation of the actors, their roles, and the interactions between them, is given in this section. Section 3.2 shows a "Methodology for Manufacturing Knowledge Captured Using a PLM Framework." Finally, in section 3.3 a chapter summary is shown.

3.1 PLM Framework to support a DFX process

The present framework gives a general overview about how both Product Lifecycle Management and Expert Systems technologies accomplish the goal of improving the DFX process. The proposed way to do it is through information and knowledge management. As can be seen in the Figure 3.1-1, the PLM framework to support a DFX process has four entities: the PLM model, PDM systems, the Expert System and the DFX process. The PLM model is the first of the framework.

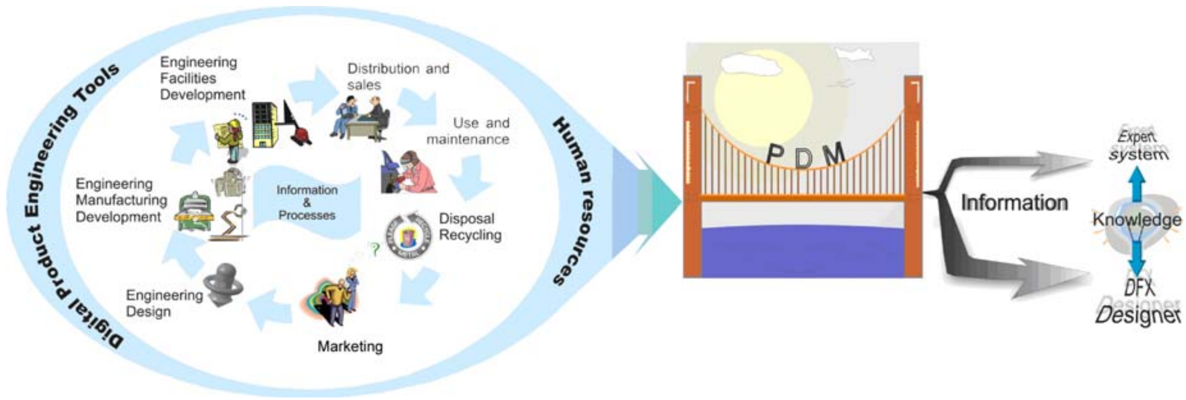


Figure 3.1-1 PLM framework to support a DFX process.

3.1.1 PLM Model

As can be seen in the literature review it is a common practice to show the PLM model as the product lifecycle stages linked by product information only. However, PLM Models not only include product management information across the product lifecycle, but also product processes, people involved in those processes and Digital product engineering tools supporting each product lifecycle stage (Grieves, M. 2005).

The PLM Model proposed in this thesis (View Figure 3.1-2) uses the arguments given above. PLM model has in the center, product information and product processes, which are kept in control trough the product lifecycle. Then, going outwards, we can find the product lifecycle, which starts with the marketing stage.

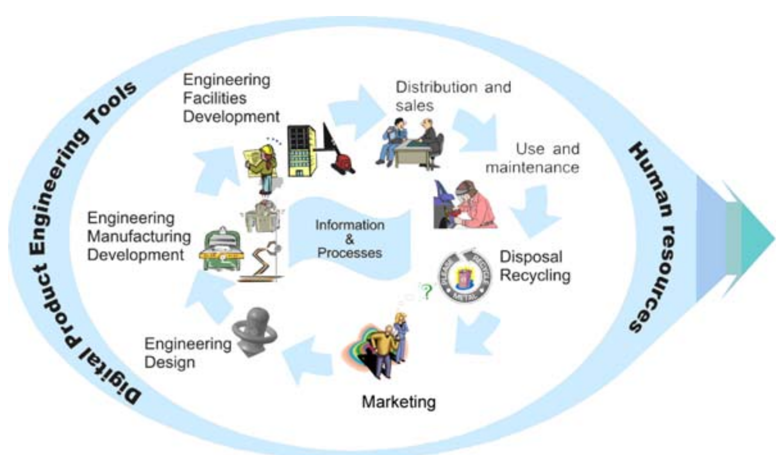


Figure 3.1-2 Product Lifecycle Management Model.

The marketing stage includes the necessity identification. This identification is done by the marketing department.

Engineering design includes: product idea, conceptual design, target specifications, design detailing and prototype. In this stage the customer's requirements are identified by concept engineering and prototyping.

The next phase of the model is manufacturing. The process selection comes after the product has been fully specified. The designs must be analyzed, and the operations to create the desired part have to be specified also.

Engineering facilities development includes manufacturer partner or supplier selection, manufacturing & quality control, equipment selection, human resources' ergonomic analysis, factory flow simulation, process plan, equipment set-up and both facilities development and set-up.

Distribution and sales are the following stages. Distribution includes packaging selection and the means of transportation to keep the product in good conditions. Marketing is included in the Sales stage. Distribution and sales use the product information to tell the customer what the functions and specifications of the product are in order to have it perform to those expected specifications.

The next stages are Use and Maintenance. After the product has been sold, the customer needs information to understand how it works. In case of malfunction or failure, service may be required. This stage of the product lifecycle also generates valuable about the product. How the product is performing during its usage is the most valuable information to determine if it was properly designed.

The last stage of the product's lifecycle (Disposal/Recycling) includes the process selection by which the product will be recycled or destroyed. Information about how the product was designed and its components configuration is necessary for effective and efficient recycling or disposal.

Finally, the PLM model is framed by human resources and digital product engineering tools. Human resources refer to the people involved with product process, while digital product engineering tools refer to CAD, PDM and CAM systems. Both Human resources and digital product engineering tools are the Information-Process manager drivers through the entire product lifecycle.

The PLM model is the entity providing all the product related information. Then, product related information is driven by a PDM system.

3.1.2 How does PLM Framework in order to support DFX process work?

After product related information is generated by the PLM model, that information is passed to the Product Data Management (PDM) system, which is the bridge between designers and the Expert System. Product related information includes product processes information, stored historical information and information contained in the digital product engineering tools as well. Some examples are CAD files, CFD data, change orders, NC codes, marketing results, user manuals. (See section 2.2.3 for more details about information driven by PDM systems).

Then, PDM system provides designers with the information needed to perform the DFX process, and provide the Expert System with information . However, the Expert System is not only provided by the PDM system, but also by designers in charge of the DFX process, who provide the experiences accumulated through that process. Then, Expert System takes all the information and knowledge and uses it as input in its system. It then structures it in the form of rules that allow the designer to makes decisions based on the experience of himself and/or his DFX partners. Doing that is the way the DFX process is achieved.

3.2 A Methodology to support DFX process using a PLM framework.

In the last section, a PLM framework was shown and the integration of its entities was depicted. This section, however, is about a methodology to capture manufacturing knowledge using a PLM framework. That methodology will define a way to take advantage of the PDM and Expert Systems into DFX process in order to improve it. The methodology was based on the DFX process framework shown below.

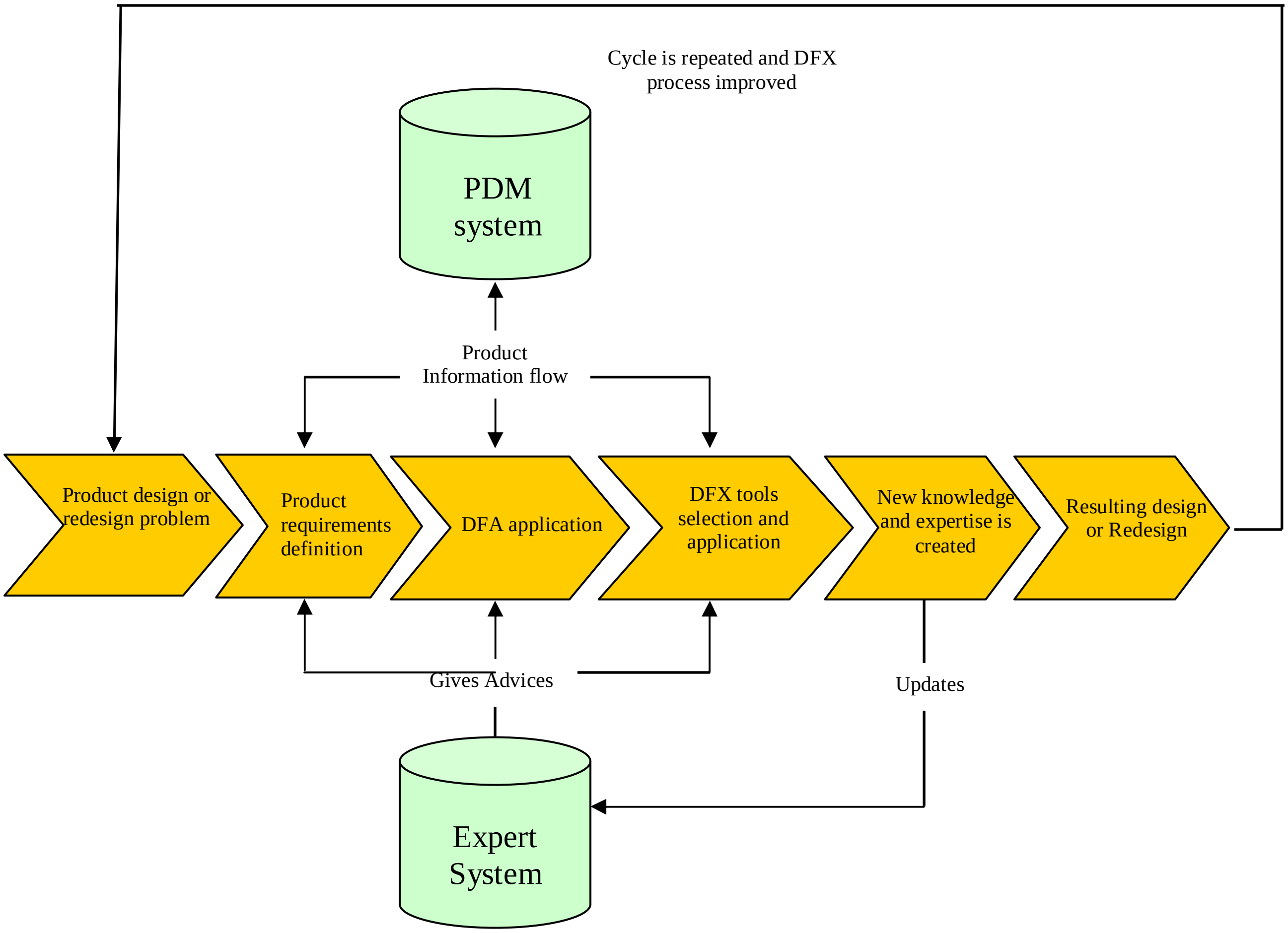


Figure 3.2-1 DFX process framework.

The DFX process framework starts when the company faces a product design or redesign problem. After that it is necessary to define the product requirements, for instance, objectives of the product, restrictions etc.; Then, DFX process continues with the Design For Assembly tool application in order to rationalize product assortments and structures before other types of DFX tools. Then, DFX tools selection begins according with what the problem is and where it lies. During Product requirements definition, DFA and DFX stages, designers are provided with the product information from the PDM system which is updated with information from the same designers. Somewhere else, during DFA and DFX tools application stages, designers are provided with rules from the Expert System in order to support their decisions. Once that DFA and DFX tools have been applied and during that process, the designers gain expertise and new knowledge, which is used to update the Expert system; Finally, the cycle is repeated and the expertise and new knowledge reused, resulting a DFX process improved.

3.2.1 Methodology definition

Based on the DFX process framework above, the methodology was designed in order to match and support each DFX process stage. The Methodology consists of four steps::

1. Obtaining customer's needs. This step supports the product requirement definition stage into the DFX process framework.
2. Obtaining product information. This step supports DFX process stages, DFA application and DFX tools selection.
3. Product data-information management through a PDM system. This step supports the integration of the PDM system with three DFX process framework stages, product requirements definition, DFA application and DFX tools selection-application as well.
4. Expert System application. This step supports the action of providing designers with advice in DFA and DFX tools selection-application stages as is shown in the DFX process framework. That advice comes from the expertise and knowledge created in the last DFX process and is updated during each DFX process cycle iteration.

The methodology steps shown above will be depicted in detail to continue.

3.2.2 Step 1: Getting customer's needs

Companies should determine what products features are in actual demand before expending large resources to develop a new or revised product. Therefore, it is important to permit a design team to hear the voice of the customers. However, this process is a difficult one, where several issues confound what the designer needs to know. Another problem is that customers typically only discuss failings of the products, what they do not like about their experience in using the product. It requires active prodding by the design team to uncover what is expected by the customer, that is, the latent needs that are not even mentioned directly by a customer (Otto, K. 2001).

Identifying customer needs is process in itself, *Methodology to DFX knowledge captures using a PLM framework* includes an identifying customer needs sub-methodology proposed by Ulrich, who presents a six-step process that is shown below (Ulrich, K. 2001).

1. Define the scope of the effort.
2. Gather raw data from customers.
3. Interpret the raw data in terms of customers needs.
4. Organize the needs into a hierarchy of primary, secondary, and (if necessary) tertiary needs.
5. Establish the relative importance of the needs.
6. Reflect on the results and the process.

3.2.3 Step 2: Getting product information

The first step in the methodology is to capture the product information that DFX processes need in order to be performed. That product information has been sorted into (1) Information about Design for Assembly and (2) Information of the X-lifecycle that has been selected by the designers. Each one of them will be depicted in the next three sections.

3.2.3.1 Getting Design for Assembly (DFA) information.

Design for assembly is information that should be used to rationalize product assortments and structures before other types of DFX tools. Due to that, it is important to get the necessary DFA information. (Huang, G. 1996)

DFA processes request the best information about the product or assembly, which include engineering drawings, exploded three-dimensional views, existing version and prototypes. Then, when the product information is obtained, the DFA process continues with the application of a methodology in order to take advance of the experience gained in this DFA process. The methodology followed in this thesis was first described by Boothroyd-Dewhurst, who included a set of charts and rules. The methodology itself, the charts and that rules, are the information that should be cached as well.

3.2.3.2 Getting X-Lifecycle information

After applying the DFA tool, the next DFX process step is to determine the DFX tools, which depend on what the problem is and where it lies (Huang, G.). Then, the x-lifecycle information depends of which DFX tools have been selected. It could include not only methodologies, rules and charts, but also information from international standards in quality, environment or manufacturing.

The table below shows an overview of many existing DFX tools and their place in the product lifecycle.

PLM stage	X	
Engineering		Ulrich & Eppinger, 2004
Manufacturing		Geoffrey, 2002
Development	Manufacture	Otto & Wood, 2001
		Ulrich & Eppinger, 2004
		Geoffrey, 2002
		Groover, 2002
		Otto & Wood, 2001
	Assembly	Wakil, 1998
		Geoffrey, 2002
	Manufacture and	Groover, 2002
	Assembly	Otto & Wood, 2001
		Geoffrey, 2002
	Automatic	Groover, 2002
	Assembly	Wakil, 1998
	Producibility	Geoffrey, 2002
		Geoffrey, 2002
	Robot assembly	Wakil, 1998
		Geoffrey, 2002
	Manual Assembly	Wakil, 1998
	Assembly Cost for	
	Printed Cicuit	
	Boards	Huang, 1996
	Effective Material	
Engineering Facilities	Storage and	
Development	Distribution	Huang, 1996
Distribution and sales	Marketability	Groover, 2002
	Product cost	Groover, 2002
	Competition	Huang, 1996
		Ulrich & Eppinger, 2004
		Anderson, 1990
Use and maintenance	Reliability	Otto & Wood, 2001
	Robustness	Ulrich & Eppinger, 2004
		Ulrich & Eppinger, 2004
	Serviceability	Huang, 1996
	Testability	Groover, 2002

	Maintenance	Anderson, 1990
	Repair	Anderson, 1990 Otto & Wood, 2001
	Disassembly	Huang, 1996
	Energy efficiency	Otto & Wood, 2001
	Dimensional control	Huang, 1996
	Inspectability	Huang, 1996
Disposal/Recycling	Environmental impact	Ulrich & Eppinger, 2004 Otto & Wood, 2001 Huang, 1996 Otto & Wood, 2001
	Recyclability	Huang, 1996
	Remanufacturing	Otto & Wood, 2001
	Minimize Material usage	Otto & Wood, 2001

Table 3.2-ADFX tools placed in life-cycle stages

3.2.4 Step 3: Product data-information management through a PDM system

Once the product information is collected, the next step is organizing that information and providing it to the designers. In this methodology, a PDM system is used in order to achieve this. However, before using the PDM system, it is necessary to define the company's product lifecycle as well as the actors involved in it.

*3.2.4.1*Defining company's product lifecycle

Defining a company's product lifecycle before applying a PDM system is useful in sorting the information collected and also provides a useful systematic overview that will guide designers through the DFX process. A general model of a product lifecycle accomplishes six stages: Product Development, Process Development, Facility Development, Production-Sales, Use-Maintenance and Disposal (Aca, J. 2004). However, each company has its own product lifecycle.

*3.2.4.2*Defining PLM actors

After defining the company's product lifecycle, the PLM actor's definition involves identifying the key people involved in each product lifecycle stage and with whom the product information must be shared. This task also includes identifying what information from each actor could be useful in the DFX process depending on the DFX tools selected.

3.2.4.3 Organizing information

Previously uploading the information in the PDM system is necessary to organize that information. The class diagram below shows an information organization system proposed in this methodology.

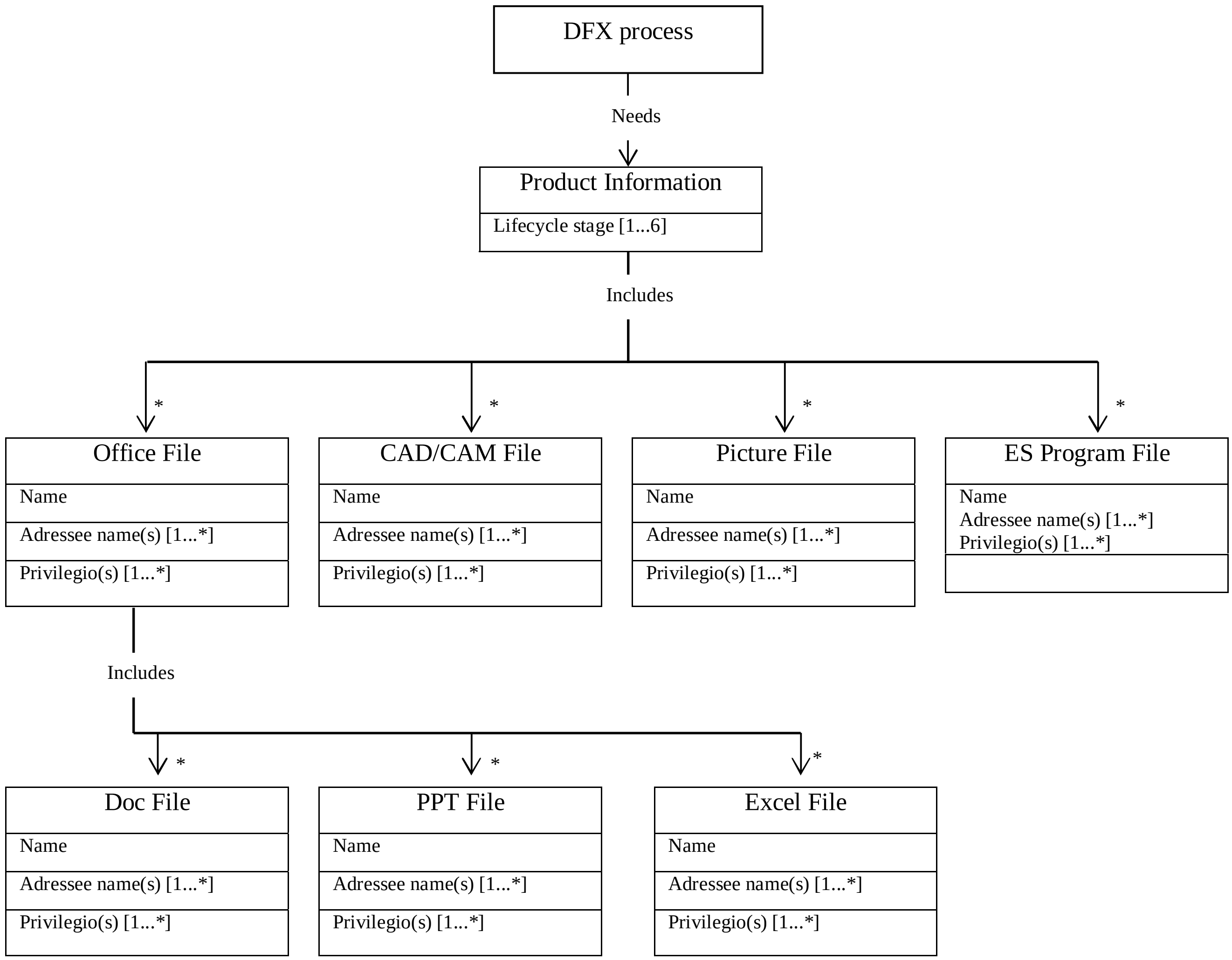


Figure 3.2-2 Organizing product information class diagram.

The class diagram proposes to organize the product information through each of the six product lifecycle stages. Then, each lifecycle stage includes four different classes of information, which are documents files, CAD/CAM files, Picture Files and Expert System Program files (the origin of this kind of file will be depicted in the section 3.2.4). Each of those classes must have the name of the file, the name of the person(s) that supplied the information and the name of the person(s) that need that information or in other words, the addresses.

3.2.4.4 PDM system application

After organizing the product information, the next task is to upload that information and share it with the appropiate actors. The PDM system application involves the creation of the web site trough which the actors will be able to access the product information. Then, it will be necessary to create the users needed by the previously defined actors. User creation includes the definition of profiles for each user, which can be as a reader only, reader-writer or administrator. After thatis the administrators will be able to upload each product information file and define which users should have access to read, write or manage that file.

3.2.5 Step 4: Expert System application

Once designers have finished the DFX process and during that process as well, they gain expertise and knowledge. That expertise and knowledge must be captured and reused in order to improve DFX process. This methodology proposes an Expert System as a vehicle to achieve that.

The Expert System application involves the following tasks: (a) collecting the expertise and knowledge from designers, (b) structuring that information into rules, (c) programming those rules into the Expert System and (d) fitting the Expert system into the PDM system in order to share the expertise and knowledge with the appropriate users.

3.2.5.1 Collecting the expertise and knowledge from designers

One method to extract directly the expertise from designers is the interview, while observation is a method to extract the expertise indirectly from the experts.

3.2.5.2 Structuring information in rules

The Expert systems' purpose is to support designers in decision-making, and providing them with rules is a way to achieve that. In order to define a rule it is necessary to establish the correlation between two variables. In other words, it is necessary to establish what will happen with the variable "X" when variable "Y" moves to a specific status.

3.2.5.3 Programming the rules into the Expert System

After defining the rules it is necessary to input them to the Expert System. In order to achieve thatit is necessary to make a program in the programming language used by the Expert System selected. However, C is the most popular programming language used by the expert systems currently in the market.

3.2.5.4 Fitting Expert system into the PDM system

Some PDM systems as Teamcenter Community and ENOVIA have a module for knowledge capture. However, they allow information collection only. Tor instance, they are capable of capturing the knowledge from a meeting through a word processor, but they are incapable that information and program it in a rule form. Due that it is necessary to use an external Expert System and also to fit that into the PDM system. This is accomplished by providing all designers with access to the Expert System software and uploading the programs in the PDM system as a file. In this way, users will be able to download and run the program needed in order to make the properly decisions.

3.3 Summary

This chapter is about a Methodology to capture manufacturing knowledge using a PLM framework. Previously, during the methodology explanation, a PLM framework to support a DFX process is depicted in order to give the readers an overview of the entities involved in integrating the methodology and the interaction between them as well.

The PLM framework to support a DFX process is made up of three related entities in order to achieve the DFX process through information and Knowledge Management. Those entities are the PLM model, PDM system and Expert Systems. The PLM Model generates the majority of the product related information needed by DFX designers. This information comes from each of the six product lifecycle stages, previously mentioned. That information is driven by the PDM system until designers and Expert System as well. Expert Systems capture this information and the experiences from designers and structure rules. Finally, designers use the rules provided by the Expert System and the product related information provided by the PDM system in order to make decisions properly.

A Methodology to support DFX process using a PLM framework is based on a DFX process framework, consisting of six stages: product design or redesign problem, getting product requirements, DFA application, DFX selection–application and new expertise-knowledge created. Those stages are interacting with the PDM and Expert Systems, which provide designers with the product information and rules to make decisions properly.

The Methodology to support DFX process using a PLM framework consist of three steps, (1) Obtaining product information, (2) product data-information management through a PDM system and (3) capturing DFX knowledge-expertise into an Expert System. The first stage includes getting customer needs, getting DFA information and getting X-lifecycle information; The second step includes defining a company's product lifecycle, defining PLM actors, organizing information and PDM system application. Finally, the third step includes collecting the expertise and knowledge from designers, structuring information rules, programming the rules into the expert system and fitting the expert system into the PDM system.

CHAPTER 4 CASE STUDY

4.1 Introduction

In this chapter a case study is developed in order to test the Methodology to support DFX process using a PLM framework.

This case of study was taken from the Purdue Solar Racing Project. This project involves the construction of the 7th generation of a solar racing car, which consists of the improvement of the current design (view Figure 4.1-1). This project started on September 2006, and will finish during spring 2009.

Those involved in the solar racing project are mostly students, but professors are also involved. The students and professors who developed this project come from a variety of different schools like Mechanical Engineering, Mechanical Engineering and Technology, Electrical Engineering, Industrial Engineering, Management, and Marketing. This multidisciplinary form of work is an enriching experience for the solar racing team.

Figure 4.1-1 Current PURDUE solar racing car (October 2006).

The current solar racing car consists of the following basic components: three wheels, 610 lbs of weight including the driver (chassis + suspension = 120 lbs), 550 solar cells (1200 watts). It reaches a top speed of 62 MPH, cruising Speed of 45 MPH and has a cost of $125,000 USD. The chassis was made of carbon fiber, and the suspension was made of aluminum.

The new vehicle is to be supplied with a new mechanical system. These mechanical changes will be on the chassis & roll cage, uprights, axles, hubs, brakes, trailing arm and steering. The case study developed in this thesis focuses exclusively on the Hub system redesign.

4.2 General description of the experiment

The scope of this experiment covers the hub system redesign. A DFX process framework (view section 3.2 for details) is to be followed and will be supported by the "Methodology to Support DFX Process Using a PLM Framework". For the purpose of this case study, the DFX selection-application stage will be ignored from the DFX process framework.

The structure of the experiment can be defined by the following DFX process framework stages: (1) Defining Product Requirements, (2) Design for Assembly Application and (3) Creating New Knowledge and Expertise. Each of these stages are matched up with a corresponding step of the "Methodology to Support DFX Process Using a PLM Framework.

In the "Defining Product Requirements" stage, the first step of the methodology is applied. The task involved is acquiring the customer's needs.

In the "Design for Assembly Application" stage, it is necessary for designers to collect and manage information regarding the product lifecycle. The second and third steps of the methodology are applied in order to support this stage. The second step involves getting the "Design for Assembly" information, and the third step involves defining the company's product lifecycle, defining PLM actors, organizing information, and finally the PDM application.

The final stage is the creation of new knowledge and expertise, which is supported by the fourth methodology step., This involves organizing the given knowledge and expertise for reuse in order to improve the DFX process. The tasks involved in the fourth methodology step are: collecting the expertise and knowledge from designers, structuring information in rules, programming the rules into the Expert System, and finally, fitting the Expert System into the PDM system.

4.3 Defining product requirements

This is the first stage to be discussed in this case study. The product requirements are provided mainly by customers. In this case of the study, the last solar racing car team was considered a customer since they have the practice and experience in building the last version of the solar racing car. They therefore know best what parts or systems must be improved or replaced.

In an interview with the “customers” the following requirements for the product were provided:

- Mechanical systems must be improved. Those systems include chassis & roll cage, uprights, axles, hubs, brakes, training arm, and steering.

4.4 Design for Assembly application

The main idea of this stage is the application of a DFA tool designed, by Boothroyd, to perform the DFA task. Before that, however, is necessary to collect as much useful product information as is available. In addition, the PDM application is to be executed in order to support this stage. The methodology steps developed to support the mentioned issues are the second and third, which are: Getting Design for Assembly (DFA) information, and Product Data-Information Management Through a PDM System.

4.4.1 Getting product information

The product information collected corresponds to the hub system only, due to the fact that it was the only section assigned to this case of the study. The product information collected consisted of CAD files, drawing files, CAM application files, report documents and pictures files. CAD files and drawings format were in Pro-E, and CAM application files were mainly finite element analysis files; Among the report documents, vehicle impact analysis and mechanical systems analysis were also included. Some of the information that was collected is shown below.

Hub picture

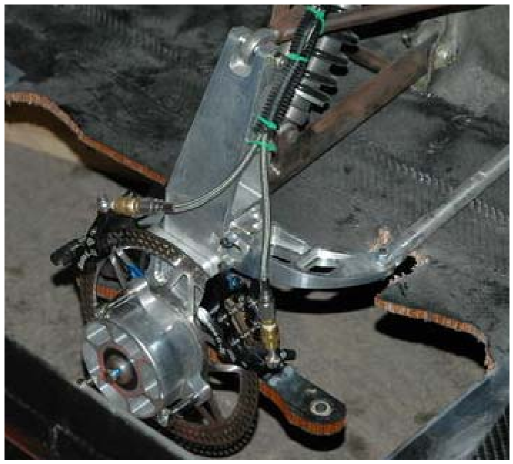


Figure 4.4-1 Hub system

Hub Drawings

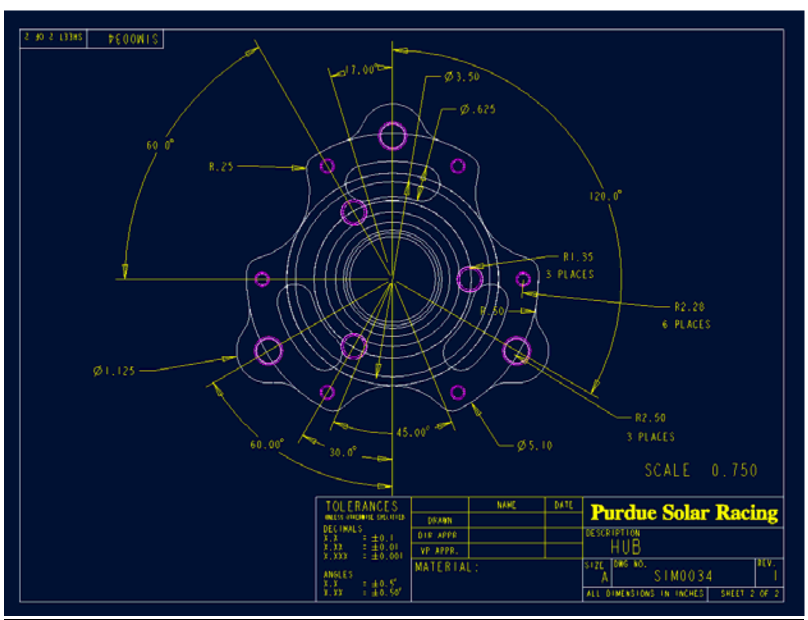


Figure 4.4-2 Hub Drawing (Top View)

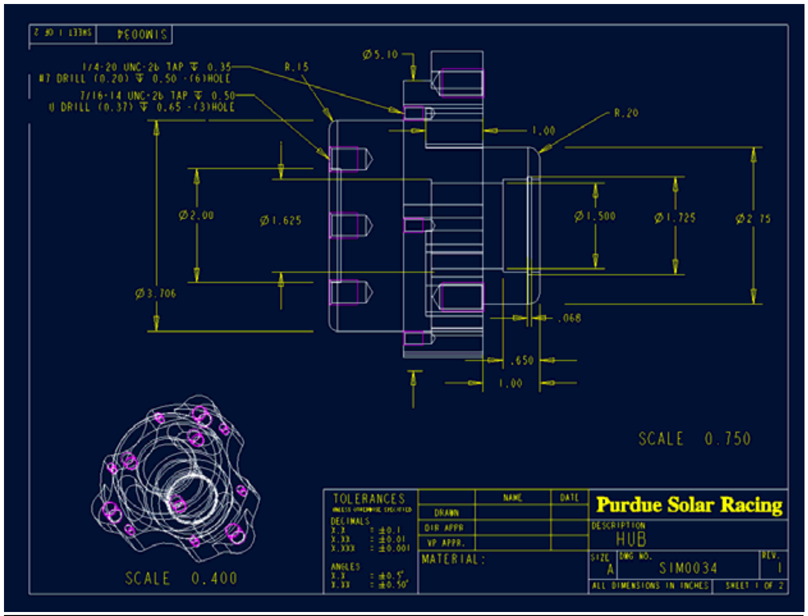


Figure 4.4-3 Hub Drawing (Right Front View)

4.4.2 Product data-information management through a PDM system

Once the product information is collected, the next step is to put it into the PDM system in order to manage it properly and present it to the designers in the best way possible. According to the methodology proposed, before the application of PDM there are some tasks that need to be performed which are: to define the Purdue solar lifecycle, to define the PLM actors, and to organize the product information collected.

4.4.2.1 Defining PURDUE solar racing car lifecycle

The solar racing car has a special aspect that hardly impacts its lifecycle. This is that the solar racing car was not constructed for mass production, and the current model will likely be the only one made. Other issues with little or no effect on the lifecycle include design, manufacturing, and maintenance. Factors that have more importances are those such as facility development and lost sales importance.

Solar racing car has six stages into its lifecycle (view Figure 4.4-4). First one is project plan, which contain all the projections for the future, tasks definition, resources definition, organizational plan, etc.; Second stage is product redesign, which include last part analysis and parts improvement; Third stage refers to manufacturing processes design or in some cases just to improve the past processes; fourth stage correspond to the marketing issues, where publicity and sponsors searching are performed; Next stage is maintenance, in this one, solar racing car is put it in use by the customer and then it naturally will need some kind of maintenance due failures or simple use; Finally, when solar racing car won't be able to work it must be disposal and/or recycle.

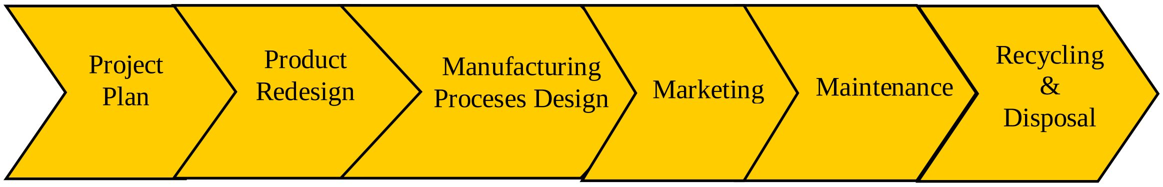


Figure 4.4-4 Solar racing car lifecycle.

4.4.2.2 Defining PLM actors

Once the solar racing car´s lifecycle has been defined, it is necessary to define who the actors are in each stage. This is in order to analyze what kind of information is generated by each one, as well as decide which information must be shared them. For instance, product designers might need some material properties information, while the marketing department is just concerned with the final shape of the solar racing car in order to create publicity.

	Stages	Actor	Role
Solar racing car lifecycle	Project plan	Brian kester (ME)	Team leader
		Ryan Smith (ME)	Senior Design project Manager & Chief Engineer
		Hannah Phares(ME)	Project Manager
	Product redesign	Jeff Tippmann (AE)	Rim FEA
		Julian Mast (ME)	Hub designer
		Alan Dukeshire (ME)	Axle designer
		Kent Butz (ME)	Brake system designer
		Christy Miecholson (ME)	Brake system designer
		Edgar Raygoza (IE)	Design for manufacturability
	Manufacturing process design	Edgar Raygoza (IE)	Design for manufacturability
	Marketing	-	
	Maintenance	Edgar Raygoza (IE)	Design for manufacturability

	Recycle & disposal	Edgar Raygoza (IE)	Design for manufacturability

Table 4.4 Actors into solar racing car lifecycle.

4.4.2.3 Organizing information

The information collected was organized according to the "Organizing Product Information Class" diagram proposed in the methodology. As the tool to be development in this case of study is DFA, the needed product information is from the product development stage.

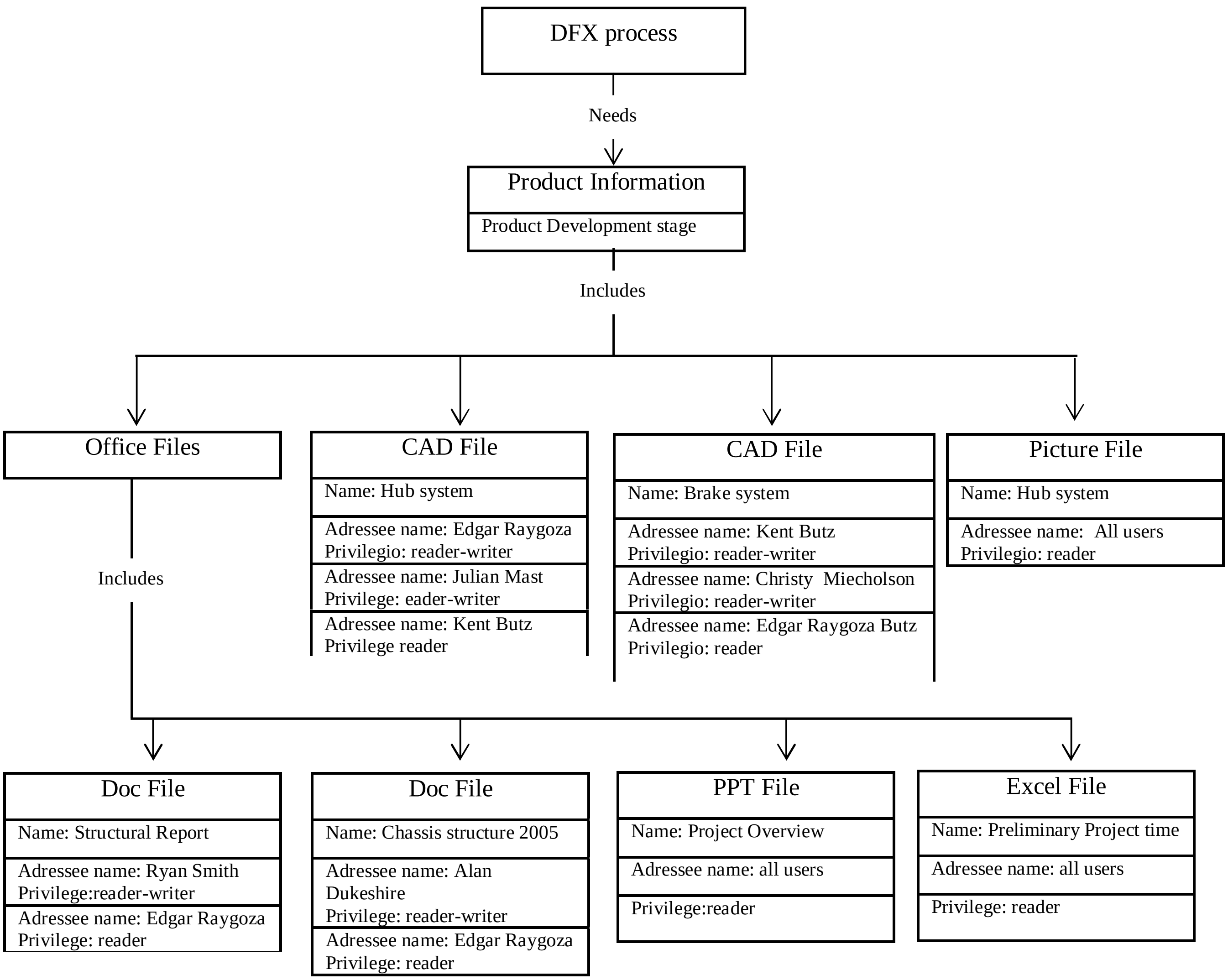


Fig.4.4-5 Organizing hub system information class diagram.

4.4.2.4 PDM system application

In this case of the study, Teamcenter® Community will be the commercial software holding the PDM system, it doesn't allow product data-information management only, but also add a set of extra functionalities. Using Teamcenter Community, you also can:

- Upload multiple files, 2D and 3D data, or perform seamless editing on Office documents.
- Conference with others to collaborate on 2D files and 3D assemblies, documents, and data.
- Manage Visual Issues throughout the product lifecycle.
- Use the 2D/3D viewer to interact with your visualization data.
- Capture knowledge during meetings or on your site recording actions and modifications.
- Capture ideas, then rank them and convert them to requirements.
- Use the Enhanced Document Library to cut, copy, and paste documents and folders; upload items, integrate visualization data from conferences, and check document history.

The Teamcenter community feature used in this case of the study is how manage the product information files with the users through the entire solar racing car lifecycle. Then, in order to star using Teamcenter community, was necessary to create the Teamcenter Community Site where users can be able to access. A print scream of The Teamcenter Community site created and provided at the users is shown below

https://pace2.ecn.purdue.edu/cot/plm/student_learning/PSRC/default.aspx

Fig. 4.4-6 Teamcenter Community site for the solar racing car project.

After to create the Teamcenter community site is necessary to create and customize the users. Teamcenter community offers four kinds of users, which are Reader, contributor, web designer, and administrator. The privilege of each one are explained below.

A. Reader- Has read-only access to the web site.
B. Contributor- Can adds content to existing document libraries and lists.
C. Web Designer- Can creates lists and document libraries and customizes pages in the web site.
D. Administrator- Has full control of the web site.

For this specific case of the study all the users have been defined as contributors because all of them are supposed to create files that must be share with all the other members. After to define the users privileges, is the time to define the files privileges, which are the same that the users. Then, we are able to upload those files with their own privileges also.

4.4.3 Boothroyd DFA tool application into PDM environment

After to apply the Bootroyd methodology it is necessary to define the most economic assembly method for the particular project.

Boothroyd proposes six main assembly methods. They have three categories, assembly, special purpose transfer machine assembly and robot assembly. The six methods into their respective categories are shown below.

Manual Assembly
Bench or transfer- line assembly using only simple tools.

Special-purpose transfer machine assembly
Assemblies are transferred by an indexing transfer device (rotary or in line).
Assemblies are transferred by a free-transfer device (non- synchronous).

Robot assembly
One general-purpose robot arm operates at a single work station.
Two general-purpose robot arms work hand-in-hand at a single station.
A multi-station free-transfer machine with general-purpose robot arms.

The most economic assembly method can be determinate by three aspects, the first one is the annual production volume which is the average number of assemblies of all styles produced during the equipment payback period; second issue is the number of parts in the assembly, which is the average number of parts or subassemblies to be assembled on assembly system; the last one is the total number of parts, which is the total number of parts or sub-assemblies from which various product styles can be assembled. Considering all the aspects mentioned above, the most economic assembly method for the hub is manual assembly method.

The methodology to manual assembly method involves the next steps:

1. To get the information about the product or assembly.
2. Take the assembly apart (or image how this might be done).
3. Fulfill the design for assembly worksheet.
4. Begin re-assembling the product.
5. To estimate manual assembly time and manual assembly cost.
6. Finally, the manual assembly design efficiency is obtained by entering the figures generated from the worksheet into the equation: EM = 3XNM/TM.

The sub-assembly system consists of six parts, which are rim, hub, washer, pipe, bearing, break disc and screws. The hub system assembly exploded is shown below.

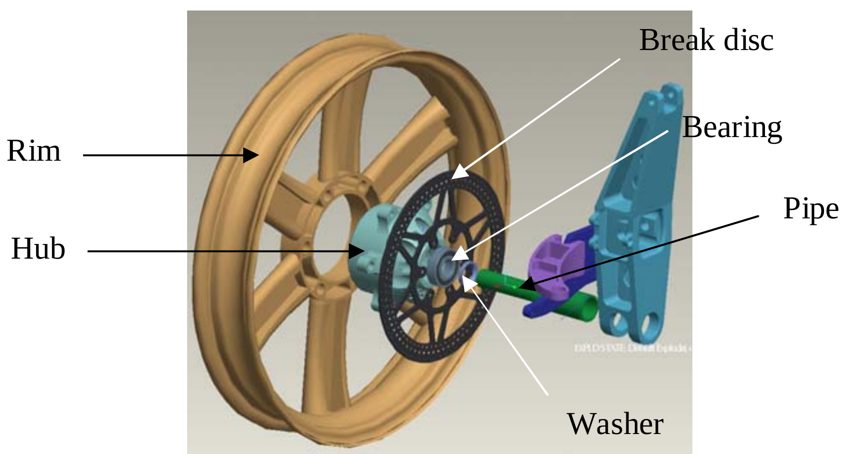


Fig. 4.4.3a Hub system assembly exploded

The worksheet fulfilled with the information of the assembly is shown below.

1	2	3	4	5	6	7	8	9	Name of Assembly
Part I.D. No.	Number of times the operation is carried out consecutively	Two-digit manual handling time per part	Manual handling time per part	Two-digit manual insertion code	Manual insertion time per part	Operation time, seconds (2) x [(4) + (6)]	Operation cost, cents 0.4 x (7)	Figures for estimation of theoretical	**HUB SYSTEM**
1	1	00	1.13	00	1.5	2.63	1.052	1	Rim
2	1	38	3.34	08	6.5	9.84	3.936	0	Hub
3	1	38	3.34	08	6.5	9.84	3.936	1	Break disc
4	1	10	1.5	00	1.5	3	1.2	1	Bearing
5	1	10	1.5	00	1.5	3	1.2	1	Pipe
6	1	10	1.5	00	1.5	3	1.2	1	Washer
7	12	11	1.8	38	6	7.8	3.12	0	Screw
						39.11	15.644	5	Manual design efficiency = 3x NM/TM = **0.38**
						TM	CM	NM	

Fig. 4.4.3.b worksheet for Hub system sub-assembly

After to analyze the assembly with the support of the worksheet above was decided not to reduce the number of parts in the assembly because of constrains in manufacturing. However, the hub was redesigned in order to make it lighter, the new hub design is shown in the figure below.

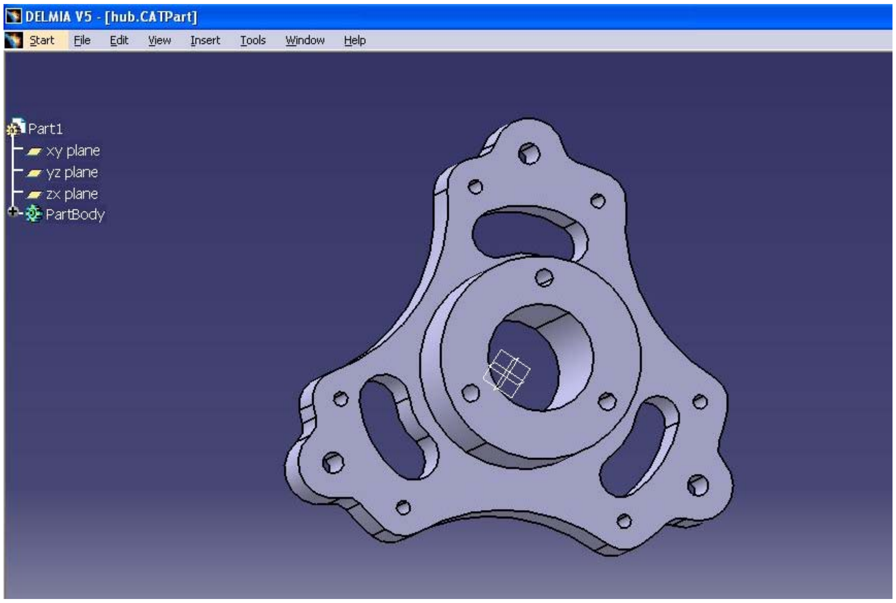


Fig. 4.4.3.c New hub design

4.5 Creating new knowledge and expertise

The final stage is the creation of new knowledge and expertise, and the third step of the methodology support this stage in order to capture those knowledge and expertise for then reuse it and improve the DFX process. The tasks involved in the third methodology step are collecting the expertise and knowledge from designers, structuring information in rules, programming the rules into the Expert System and finally, fitting Expert system into the PDM system. The expert system used in this case study was CLIP.

4.5.1 Collecting knowledge

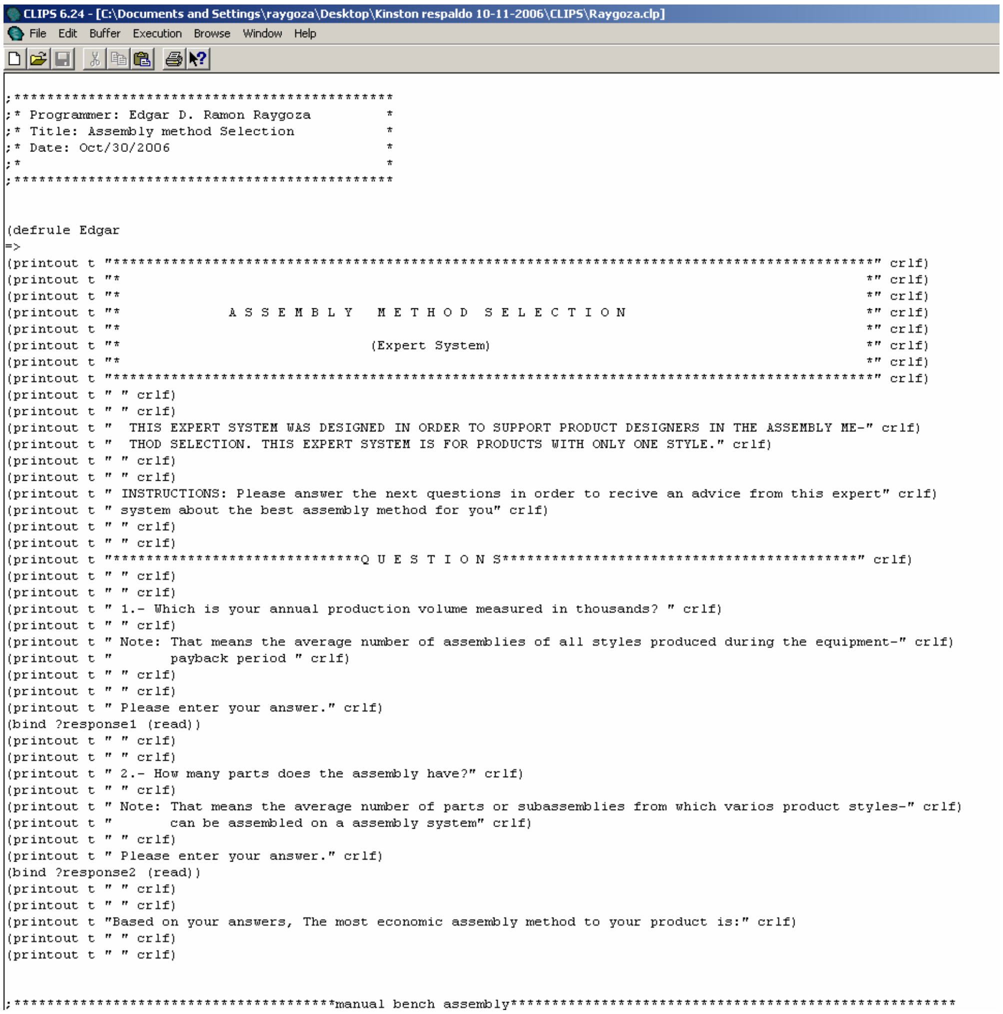
The knowledge captured in this case study was about how to select the most economic assembly method, which was the first stage in Bootroyd DFA tool application.

4.5.2 Making rules

After collecting knowledge is necessary to structure it in a rule way in order to be able to programming into the Expert System software. To make a rule is necessary identify the dependent and independent variables for then relate them. The independent variables defined were, (1) annual production volume measured in thousands, (2) number of parts in the assembly and (3) total number of parts. While the dependent variables defined were each one of the six assembly methods: (1) Special-purpose indexing, (2) Sp.-purp. Free-transfer, (3) Single-St. one robot arm, (4) Single St. two robot arms, (5) multi-station with robots and (6) manual bench assembly. The way in which those variables were related is summarized in the chart below, where VA means annual production measured in thousands, while NA means number of parts in the assembly.

4.5.3 Programing rules into the Expert System software

CLIPS software has its own programming language. However, it has also designed for full integration with other languages such as C and ADA. A print scream of the codec programmed in CLIPS is shown in the next pictures.




```
;***********************************************
;* Programmer: Edgar D. Ramon Raygoza          *
;* Title: Assembly method Selection            *
;* Date: Oct/30/2006                           *
;*                                             *
;***********************************************


(defrule Edgar
=>
(printout t "*****************************************************************************************" crlf)
(printout t "*                                                                                       *" crlf)
(printout t "*                                                                                       *" crlf)
(printout t "*             A S S E M B L Y   M E T H O D  S E L E C T I O N                          *" crlf)
(printout t "*                                                                                       *" crlf)
(printout t "*                                       (Expert System)                                 *" crlf)
(printout t "*                                                                                       *" crlf)
(printout t "*****************************************************************************************" crlf)
(printout t " " crlf)
(printout t " " crlf)
(printout t "  THIS EXPERT SYSTEM WAS DESIGNED IN ORDER TO SUPPORT PRODUCT DESIGNERS IN THE ASSEMBLY ME-" crlf)
(printout t "  THOD SELECTION. THIS EXPERT SYSTEM IS FOR PRODUCTS WITH ONLY ONE STYLE." crlf)
(printout t " " crlf)
(printout t " " crlf)
(printout t " INSTRUCTIONS: Please answer the next questions in order to recive an advice from this expert" crlf)
(printout t " system about the best assembly method for you" crlf)
(printout t " " crlf)
(printout t " " crlf)
(printout t "*******************************Q U E S T I O N S********************************************" crlf)
(printout t " " crlf)
(printout t " " crlf)
(printout t " 1.- Which is your annual production volume measured in thousands? " crlf)
(printout t " " crlf)
(printout t " Note: That means the average number of assemblies of all styles produced during the equipment-" crlf)
(printout t "       payback period " crlf)
(printout t " " crlf)
(printout t " " crlf)
(printout t " Please enter your answer." crlf)
(bind ?response1 (read))
(printout t " " crlf)
(printout t " " crlf)
(printout t " 2.- How many parts does the assembly have?" crlf)
(printout t " " crlf)
(printout t " Note: That means the average number of parts or subassemblies from which varios product styles-" crlf)
(printout t "       can be assembled on a assembly system" crlf)
(printout t " " crlf)
(printout t " Please enter your answer." crlf)
(bind ?response2 (read))
(printout t " " crlf)
(printout t " " crlf)
(printout t "Based on your answers, The most economic assembly method to your product is:" crlf)
(printout t " " crlf)
(printout t " " crlf)


;***************************************manual bench assembly*******************************************************
```

Figure 4.5-1a CLIPS code

```
(if (<= ?response1 850)
  then
  (if (<= ?response2 3)
      then
          (printout t " MANUAL BENCH ASSEMBLY. It means bench or transfer-line assembly using only simple tools" crlf)
          (printout t " " crlf)
          (printout t " " crlf)
          (printout t "***** THANKS YOU FOR USING THIS EXPERT SYSTEM*****")
          (printout t " " crlf)
          (printout t " " crlf)))

(if (<= ?response1 600)
  then
  (if (<= ?response2 4)
      then
          (printout t " MANUAL BENCH ASSEMBLY. It means bench or transfer-line assembly using only simple tools" crlf)
          (printout t " " crlf)
          (printout t " " crlf)
          (printout t "***** THANKS YOU FOR USING THIS EXPERT SYSTEM*****")
          (printout t " " crlf)
          (printout t " " crlf)))

(if (<= ?response1 400)
  then
  (if (> ?response2 3)
      then
         (if (<= ?response2 6)
          then
              (printout t " MANUAL BENCH ASSEMBLY. It means bench or transfer-line assembly using only simple tools" crlf)
              (printout t " " crlf)
              (printout t " " crlf)
              (printout t "***** THANKS YOU FOR USING THIS EXPERT SYSTEM*****")
              (printout t " " crlf)
              (printout t " " crlf))))

(if (<= ?response1 850)
  then
  (if (> ?response2 5)
      then
         (if (<= ?response2 8)
           then
              (printout t " MANUAL BENCH ASSEMBLY. It means bench or transfer-line assembly using only simple tools" crlf)
              (printout t " " crlf)
              (printout t " " crlf)
              (printout t "***** THANKS YOU FOR USING THIS EXPERT SYSTEM*****")
              (printout t " " crlf)
              (printout t " " crlf))))

(if (<= ?response1 700)
```

Figure 4.5-2b CLIPS code

After to run the program done, the Expert System advices the manual assembly such as the most economic assembly method. The print scream of those results is shown below.

Figure 4.5-3 CLIPS program running

4.5.4 Fitting Expert System into PDM system

Due that CLIPS is external software with no interface with the PDM system, the only way to fit it is upload it as a file. However, each designer must install CLIPS software in their computers in order to be able to use the Expert System file when will be necessary.

4.6 Results

The results of the methodology were measurement through a comparison with the last solar racing car project. The most important benefits of the application of this methodology were

On the time and cost reduction for the hub design. These reductions were produced mainly by less time in searching information, less time spent in meetings, reduction in mistakes made during modelling process, and prototypes cost reduction.

Less time by searching information and knowledge was achieved with the use of the PDM system which allowed organizing and sharing all the information related with the hub through all the designers, in addition, the expert system allowed reusing the experience gained. Less spent time by meetings was due to the use of Teamcenter community platform which allowed establishing a collaborative environment between the designers. Time Reduction in reworks due at mistakes during modelling process was achieved with the use of the PLM tools (CAD) and correct information available in the PDM and expert systems. Finally, prototypes cost reduction was possible through the use of the digital manufacturing tools that allowed. All the depicted points are summarized in the table below.

	Last version	Current version
Spent time by searching information and knowledge	96 hour/month	25 hours/month
Spent time by meetings	16 hours/month	2 hours/month
Spent time in reworks due at mistakes made during modelling process	41 hours/month	8 hours/month
Prototype cost	USD$780.00	0

Table 4.6 Results of the PLM application

4.7 Summary

This chapter showed a case study taken from the PURDUE solar racing car project. This case study was about DFA application tool on the Hub system, which needed to be redesigned. In order to achieve that, the “Methodology to support DFX process using a PLM framework” presented in chapter three was tested. The DFX process stages followed and which methodology steps was matched on, were: (1) defining product requirements, (2) Design for assembly application and (3) creating new knowledge and expertise.

CHAPTER 5 RESULTS, CONCLUSIONS & FURTHER WORK

5.1 Results

The thesis results include:

- The reviewing of the PLM definitions, elements, characteristics, model and tools.
- The reviewing of the DFX concept and determination of the knowledge needed from each product lifecycle.
- The reviewing of the Expert System concept and construction principles. The programming of an ES to select the most economic assembly method. The ES was developing on CLIPS, which is commercial ES software.
- The reviewing of the PDM concept and characteristic. The application of Teamcenter community to share information.
- The definition of a methodology to integrate PDM and ES tools to support DFX process.

Finally, this thesis was developed in a collaborative environment between ITESM, MTY campus and PURDUE University. The results of that collaborative environment were:

- Stronger relationship between the research centers of those institutions, which are “Innovation Center for Design and technology”, on ITESM side, and “PLM Center of Excellence” on PURDUE University side.
- Enriched literature review due to the synergy between both institutions’ libraries, software tools, and shared material.

5.2 Conclusions

The PLM is a relatively new concept, which is known mainly by its tools such as CAD, CAM, CAE and PDM. Its main application is on product and processes design. However, most PLM applications are used separately and forget the central aim of the PLM philosophy, which is the integration of whole areas of the companies. That integration can be achieved through the PDM system, which is the heart of a PLM launching. The most important processes in a PLM launching are the substitution of resources, materials and time by information, the virtualization of physical object, and the use of computer technology. The main benefits of PLM that can be seen in a simple modelling-virtualization project are a shortening of product-launching times and cost reduction on materials and resources.

The research on DFX shows that there are many types of possible Xs. As it has been said, design depends on the company's approach. Therefore, this is also true for DFX. For this reason, there exist many sets of guidelines for the processes or products from different companies. As a consequence, a vast amount of Xs have been created. This thesis presents the available material in the formal literature, regardless of whether there are additional sources in other companies targeting different Xs.

If this continues, the amount of available guidelines for DFX could go out of control. For example, given any two companies manufacturing clothes, one of them could embrace "Design for Durability" while the other could select "Design for Strength". In this hypothetical case, the two guidelines may be slightly different, but one could easily substitute the other. Each company may never know about the existence of the other option, so there would be two new Xs with the same basic goal. Therefore, the effort and time of making a new set of guidelines would be lost.

The Expert System is a Knowledge Management tool that by means of computer technologies stores and shares the expertise in the many areas of the science. There are many applications of Expert Systems in the engineering field, but not one specific to support the whole DFX process. The majority of the commercial expert systems are not able to update automatically the information stored in them. In addition to this, there is a lack of integration of the Expert System with the PLM tools.

5.3 Further Studies

Regarding PLM, one important study is the definition of metrics to evaluate the results of a PLM launching.

Regarding DFX, there is a need to make sub-classifications, because some authors refer to area-specific processes as Xs. Take the following example: Design for: Casting, Extrusion, etc. All of these are manufacturing processes, and could be included in DFM or DFMA as special cases. For instance, DFCM could represent Design for Casting Manufacturing which immediately gives the notion of sharing many of the general DFM guidelines with other processes (e.g., welding, machining, etc.), but with the addition of process-specific rules.

Regarding Expert Systems, the further studies are: how to integrate Expert System software into PLM tools. Finding the best way to capture designers' knowledge and making a dynamic system capable of automatically updating the information stored in it.

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