Mileta M. Tomovic
Shaoping Wang
Editors

Product Realization

A Comprehensive Approach

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Preface

Comprehensive product realization, or Product Lifecycle Management (PLM), is a holistic approach to sustainable product development from market analysis, concept definition, design and analysis, production, customer service, all the way to the product's recycle. It is defined by a set of technological tools and a change in business practices that will provide effective feedback mechanism to support continuous and timely improvements in product development. It is a methodology for the use of tools and technology enabled by a digital collaborative environment, with the goal to improve competitiveness through the effective sharing and use and reuse of information.

PLM is highly applied area which has significant impact on industry and provides numerous benefits to the adopters of technology and business practices, including: (i) increase in revenue through shorter time to market, (ii) decrease in product costs through knowledge reuse, and (iii) decrease in product development costs through effective feedback mechanisms. Some of the commonly used strategic metrics to measure PLM's return on investment indicate significant benefits of using PLM. According to IBM PLM On Demand Business report, companies 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. Today when global competition is forcing industry to reduce the cost of product development and manufacture, and increase product options through mass customization, PLM is proving to be an enabling technology that can gives manufacturers a competitive advantage.

The applications of PLM are expanding rapidly. According to CIMdata Inc., the overall PLM market is expected to exceed $20 billion in 2008. The Next Generation Manufacturing Report funded by the NSF, published by Jordan and Michel, 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."

Although highly applied PLM has numerous theoretical challenges that need to be addressed and solved in order to take full advantage of the comprehensive approach to product development. The major challenges are related to areas at the boundaries between various well defined technical fields, as well as to human aspects of implementation of the complex interdisciplinary and globally diverse organizational structures.

The book presents some of the latest scientific findings and ideas along with technical developments in the area of Product Lifecycle Management and covers broad range of interdisciplinary topics ranging from measuring the impact of PLM, social issues of PLM, product design optimization, PLM and virtualization of product information, and multidisciplinary optimization. The authors wish to thank all contributors for their contribution to the general body of knowledge in this emerging interdisciplinary field, and for granting the editors permission to use their material.

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Product Life Cycle and Assessment Parameters

Jože Duhovnik

Abstract The paper presents a review of some important articles about the product life cycle. The phases of the entire cycle are specifically defined, from product development to its use and elimination. On the basis of this phase definition, a concept of unified assessments is elaborated, which essentially defines the characteristics of both the product and the external influences on its life cycle. The main phases are presented, as well as the use of specific fields that essentially supplement the assessment of a product's suitability during individual product life cycle phases. The design parameters are used and supplemented with constraints during the product conquering phase. Specifically, product parameters during the phase of product use are presented as the key elements of assessment. Finally, the product elimination parameters are also used for assessment. Costs are included as well; these are specific to each product phase and need to be discussed separately. All the three product phases form the basis of a comprehensive assessment. The division to three separate product life cycle phases and definition of parameters for validating the product's characteristics constitute a significant contribution to a fuller understanding of the product life cycle process.

Keywords PLC · PDM · Lifecycle Assessment · Product Validation · Product Perfection

1 Introduction

The term "Product Life Cycle" (PLC) denotes the product's life in general. This refers to products which constitute technical systems. Technical systems are for example mechanical assemblies, electronic devices, information systems or biotechnical systems. In principle, technical systems are intended for the fulfillment of a certain technical process function [6]. Each technical process – as a

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cybernetic model – has transformation of material, information and energy. A technical process can exist only if certain resources are available. In a similar manner as technical processes are analyzed, the IDEF0 foundations are given for process description [7]. A certain technical system placed in nature usually serves a particular purpose. After the analysis of natural and technical processes, one can establish whether a technical process is a good substitute to a natural process [3]. The more a technical process can substitute a natural one, the better the technical system substituting this natural process.

Figure 1 shows that the levels of processes and systems are the same when compared in two environments: nature and technology. The crucial question here is one of transition from a natural process to a technical one. A natural process must be recognized as accurately as possible in order to recognize a natural system (or its functioning) in sufficient detail. It is crucial to execute the process of transition from a natural to a technical process as thoroughly as possible. But this can be achieved only if a comparison is made of the two systems: the natural one and the technical one. During such a comparison, one seeks to achieve the highest possible level of perfection of the technical system.

A requirement is usually set that the result of assessment of the level of perfection of the technical system should be its level of perfection. Therefore, this level will be sought in the technical part of the assessment. This method of searching and assessment proved good with the axiomatic design method [13], with which an optimal solution for a certain design parameter can be found. During product development, however, not just a few parameters are taken into account–a greater number is needed, including the constraints, which are those

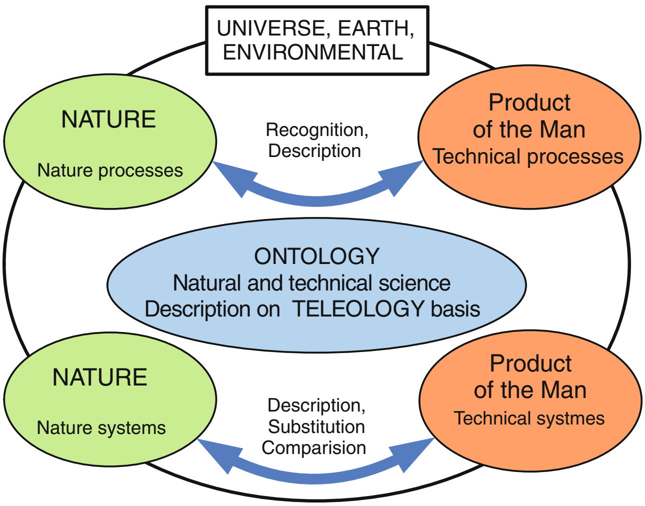

Fig. 1 Connection between nature and technology vs. interaction of processes and systems

that enable an optimum solution in a given environment. It is the optimality of the solution that usually constitutes the most critical element of new product development. Optimality as a condition takes into account certain given boundary conditions, which are normally related to the environment in which the product will be used, throughout its scope. Specifically, boundary conditions are related to the technical and technological situation, as well as the directions of development in a certain environment. For this reason, balancing between a real natural system on one hand and a real technical system on the other is the basic, constantly recurring question for each new product.

A product is not excluded from nature, it is connected with it in every case. Many literature resources [4], [5], [8], [16] etc. have recently been recognizing the basic product cycle in nature. Some authors distinguish between individual life cycles with respect to product type [16] etc., while others seek a generalized model based on material foundations, processes, manufacture, sales, recycling and disposal [4], [5] and others.

After process analyses (design, manufacturing etc.), the understanding of product life cycle was positioned within a closed cycle of material, information and energy flow. Recently, the very last portion of the product life cycle, at which point the product has reached the end of its use and essentially constitutes only the material, has been increasingly studied. The development of new materials is mainly aimed only at generating them, without considering their disposal after use [17]. The level of knowledge about nature is low and the process of product elimination is analyzed only to a small extent, therefore one can expect large problems when dealing with recycling and disposal of products. During development and designing of technical systems there is still insufficient emphasis on the optimization of parameters of the third phase of the product life cycle. It is no coincidence that the analysis of the last product's phase is difficult; the reason for this also lies in the fact that the product's analysis during the first phase of its life cycle is inadequate. Therefore, in the case of many products, the problem of recycling is still addressed only at the end, and not during their conceptual design, unfortunately. Researchers Xirochakis and Dimitris [17] and [18] have specifically drawn our attention to this problem.

When knowledge of the entire PLC and of the essential variables for analyzing the fulfillment of individual product functions becomes more comprehensive we can expect to be able to systematically monitor the product life cycle. The objective of this paper is to first provide a review of the structure of activities taking place during a product life cycle and then to define individual variables for high-quality product assessment through its individual phases. To make assessment as unbiased as possible, a general method is derived below for a quantitative evaluation of the results. A special chapter presents a generalized diagram for changing individual variables throughout the product life cycle. A generalized LPP-T (Level of Product Perfection-Time) diagram will be given for technical assessment; its logarithmic scale for the time variable significantly simplifies the understanding of the product life cycle.

The characteristic constraints of the proposed presentation of the product life cycle will be discussed in the conclusion.

2 Description of Individual PLC Phases

Any product, which is intended for the execution of a specific technical process, is defined in the conceptual design phase and during analysis, including testing. Processing of new products from idea to realization is called the Development & Design Process (D&DP). With respect to different levels of the design process (from designing anew (i.e. from scratch) to adaptive design) [2], we sometimes use the term Research & Development process (R&D) for designing a new, but this includes only the developmental part of the process, in which special and new product functions are researched and developed still in the form of a rough prototype, and not a product undergoing manufacture. Such a process is usually used for mass production (automobiles, pharmaceuticals, electronics). During this period, a product is formed according to the basic requirements, which are usually specified as a design task or a list of product specifications. In some areas, some analysis like a RMS (Reconfigurable Manufacturing System) present some method, which could be used for some particular evaluation in the first step and finally used for development of the product. [1]. All methods of the D&DP include an incorporated demand that the specification of requirements be as clear as possible [6], [10], [12], [13], [14], [15] and others. On the basis of the requirements, one can define assessment of the solutions or develop a mathematical relationship for each product; this mathematical relationship is defined on the basis of the characteristic parameters as the “design parameter” [13]. Thus some kind of axioms, which are product-specific, can be developed on the basis of a design task. It is especially important to emphasize that this method is impoverished, so to speak, because it does not take the constraints directly into account; some researchers [11] do not even consider it as method for development of new products. Because of the specificities of the D&DP, during which the product is created and materialized, one can simply speak of product conquering.

According to various authors, the phase of product conquering usually includes the following: an idea (which is related to the given situation based on the natural environment), product development, engineering analysis, designing, prototype, production, product manufacture and testing. The descriptions of all these processes may vary somewhat with the author, but the comparison of individual processes definitely reveals roughly matching phases, as was explained in Fig. 2. In the presentations of some authors discussing the product life cycle, the number of phases is usually reduced to three: idea, conceptual design and product manufacture. The phase of product conquering can be treated as a continual iterative process [3]. The essential element at the iterative procedure of product conquering are activities taking place in the designers’ room (a team with one expert from a particular field, or

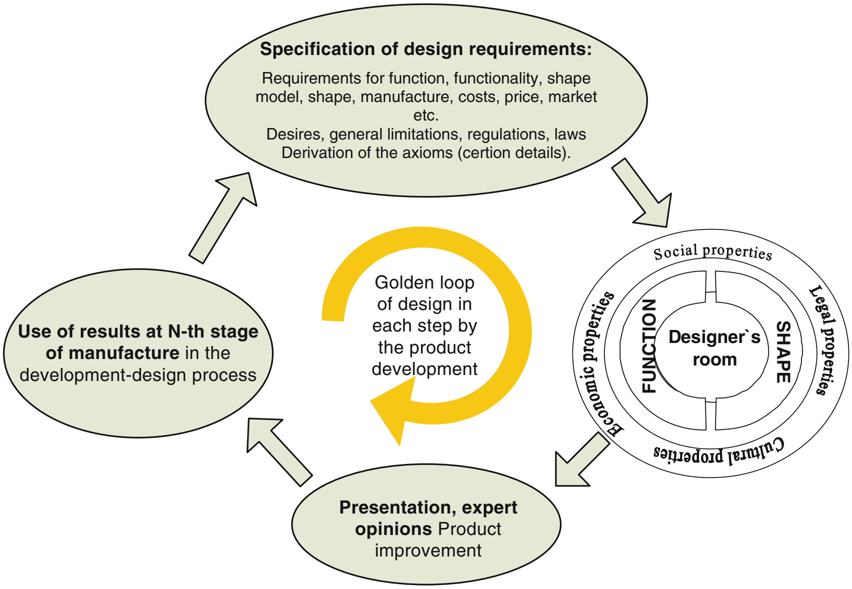

Fig. 2 Product conquering phase. Continuously iterative process with Golden loop [3]

several such experts). The flow of information from specifications to the presentation and use always revolves within the "golden" loops [3], and the objective of this process is to reach the product's golden mean of sorts (i.e. a harmonious product, perfectly adjusted to its purpose in a specific environment).

Important part in the design "golden loop" is specification of design requirements. On the list of design requirements is not just technical data, but also commercial, financial, production, user profile and ecological. All those requirements are as a starting position for searching the better answer, which we are aspect from the designer. Designer in that case is a man or team at all. According our knowledge all those requirements are normally specified but later in the PLC are forgot and generate once. We proposed in our PDM and PLM systems that the basic requirements should be used through all PLC. During the PLC the new knowledge of the product was generate or described continuously. This knowledge we just added on the list of requirements. One or part of requirements should be change during the development process. In that case we changed it. In the search process was happened that some new axioms, new function or new data was done. We should understood that fact on the dynamical way. So we added the list of specification.

All data on the specification list is a goal for the designers. Usually the particular result on some development stage or phase the goal was not fully satisfied. The differences between the goal and real result we unified with the

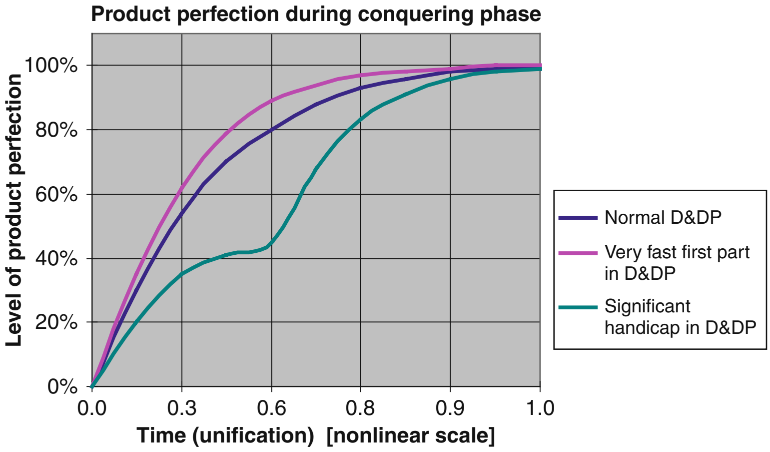

Fig. 3 Phase of product conquering during the PLC, taking into account the assessment of the product's level of perfection

percentage range. If the difference is too small we used more sensitive scale by presentation.

During the phase of product conquering, several different approaches can be undertaken, but irrespective of the approach, the team's quality always plays the crucial role (Fig. 3). The diagram shows three ways of product conquering. Series 1 shows normal flow of the product conquering process and Series 2 an accelerated course. In Series 3, the process of product conquering is initially slower, but later, with a planned inclusion of a team that is better in terms of knowledge and equipment, it is possible to prove that one is achieving the same results within the required time.

Any product that is manufactured is intended to be used. Therefore, it is important what happens to a product during its use. In addition to sales (distribution, start-up and initial use during the warranty period), the following activities also take place: maintenance, reconstruction and perhaps even partial recycling of consumable materials. At the same time that the product is placed on the market, manufacture needs to be changed) in order to be harmonized with sales in terms of quantity, quality and scheduling. The initial product assessment criteria now change as well. The technical criteria are the most important ones for creating good products, but business criteria are crucial for good sales. Usually environmental aspect as by into nature not included into the production and sale strategy, mainly because the manufacturer, sales man or final customer do not pay attention, whether the product is environmentally tolerable or not. For that reason we used additional criterion for ecological assessment of products. Therefore, it is possible to use business parameters for assessment during the process of product's use. It is no coincidence that the concept of redistribution of manufacture originated from business parameters [11] is a possible way of reducing costs. During a product's use, the basic parameter is cost, both on the side of manufacture and on the side of the buyer. On the side of manufacture, costs reduction is associated with greater profitability. On the side of the buyer, lower costs are achieved via cheaper product use. In such evaluation, costs appear as a generalized concept. In addition to costs, the product's competitive position in the market also has to be reviewed in this period, since one of the main assessment parameters is the fulfillment of customer expectations regarding the product's competitiveness. When we searched for a suitable parameter, a decision was made to use the product's level of perfection. The level of perfection does not include only the technical characteristics or the level of technical perfection; it is complementary to the criterion of competitiveness.

The phase of product use consists of two parts (Fig. 4), which need to be balanced. The first is comprised of production, planning, purchasing, manufacturing, assembly, testing of the main product parameters, packaging and warehousing. The second one comprises distribution, start-up, initial use during the warranty period, current maintenance, investment maintenance and recycling of consumable materials. The division of a product to two separate life lines, which are interwoven with the use of concurrent engineering, but conducted in sequence along the main timeline, is just one option for a clearer analysis of the product life cycle in both the technical and business senses.

The product life cycle must be concluded within a natural environment, so that product components remain part of nature. The completion of product life

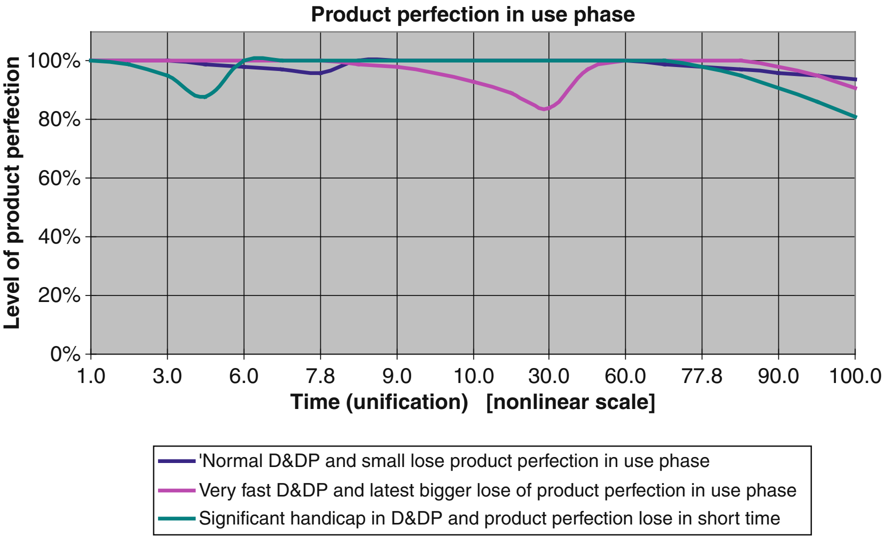

Fig. 4 Phase of product use. Several parallel flows are shown different influence from product conquering phase

cycle is enabled by various processes (End Of Life, EOL). The quickest way to eliminate a product is to destroy it. However, this is accompanied by various additional influences, since destruction in itself does not imply permanent returning of materials to nature; it merely means destruction of a product. Other processes used in the EOL cycle also enable partial or total return of materials to the natural cycle.

We are therefore dealing with the principles of product reuse and recycling, which enable its partial prolonged use or prolongation of the life cycle of individual modules by separating its parts. With the reuse principle, each individual module is understood as a partial or main function of an individual product component. At the level of the product's material structure, the principles of recycling are applied, which make it possible for materials to be reused as basic materials, changed materials or as filler. Some part of the product normally remains and is technically or technologically useless, therefore it is usually disposed of. It is important to understand that this process is manageable as well and should not be left to chance. At the EOL, the product's level of perfection falls to zero. An important criterion for deciding on process type are costs, but these should not be estimated only from process costs; they should comprise total costs, including those of persistence of the product's remainders in a certain environment, e.g. in nature.

The product elimination phase (Fig. 5) is crucial for understanding the overall product life cycle. Processes taking place in this phase are destruction,

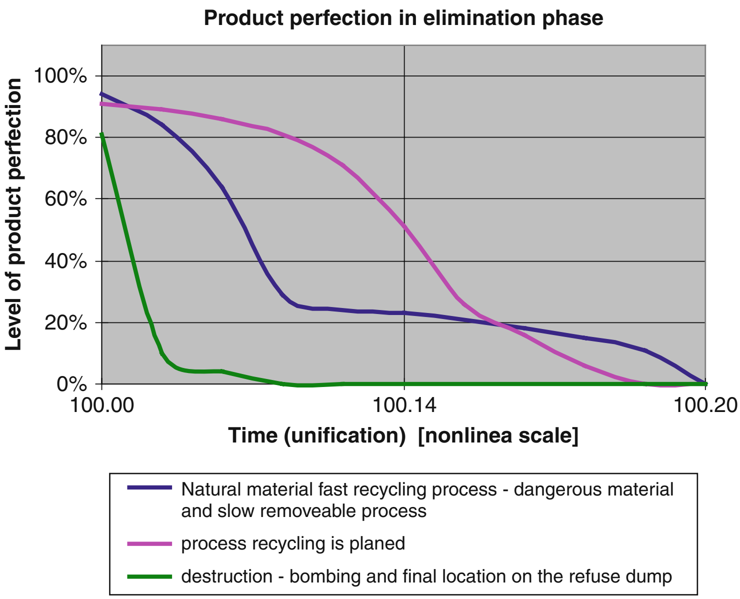

Fig. 5 Phase of product elimination

reuse, recycling and disposal. Here as well there are three separate lines of processing, but these usually run separately, without any special connections between them. Processing depends on the decision regarding the product elimination procedure, which is normally determined – both in terms of time and process – already in the phase of product use. The decision on the EOL process is ordinarily related to its costs. Any additional parameters that appear during assessment of the suitability of an individual process can be used either as a supplement to or substantiation of the decision. This also indicates a relatively low level of knowledge about this part of the process and its importance in places where the concentration of products is so high that nature can no longer accept them, either in the form of product non-use (random disposal) or as its destruction (destruction, no elimination).

In the Fig. 5 we have three different types in EOL phase:

Type 1: Elimination and longer disposal of product remains at appropriate sites. Natural material made chance for fast recycling process in the beginning. Dangerous material request special technology and made slow removable process.

Type 2: Prediction of a appropriate product elimination and disposal process. Strategy or scenario of EOL is planed and can be shorter as it can.

Type 3: Product destruction (blasting) and depositing without sorting. Some typical EOL when blasting was used. Example: situation by war where bombing was used. Another example: some particular activities by ecological and technical no regain consciousness people.

Finally, the variation of the product's level of perfection throughout the three phases of the product life cycle can be examined in Fig. 6. In the figure are present three typical curves for product perfection during the product life cycle.

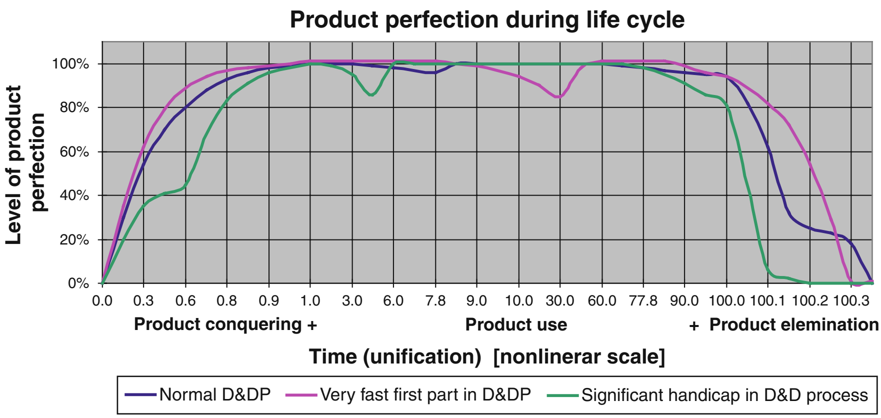

Fig. 6 Product life cycle through all its phases

Those examples are used by experts system for planning and controlling the D&D process which has important influence on the product use and product elimination phase. We can predict some typical deviation in those two phases according the activities in the D&D process.

3 Determination of Variables in Individual Phases and Product Validation

Three typical phases of the PLC, i.e. three characteristic periods in the life of a product were identified in the previous chapter. It is interesting that these three periods can be compared with biological processes in nature (birth, life and death). There are different criteria for validating the product's success, i.e. its suitability for its environment in each period of the PLC.

The product developed or search without any criteria which are defined clearly especially for our new idea about the product. Designer must create all criteria by himself and for that reason the creation of right criteria is a major task in the first stage of development phase. Definition of criteria can be as an axiom or some definition or limitations which are based on designer's knowledge. Usually definition or some parameter limitations are based on ontology. If designer has more knowledge from "soft" science their criteria are more undefined ("softly"). If designer has more knowledge on the natural-technological and engineering science his criteria are more defined on the numerical or physics basis. Generally all criteria depend of the designer's knowledge about the nature.

During the development phase criteria should be deeply defined or changes. By the design phase criteria are usually more precisely defined. When we discuss about criteria we understood that finally we find out some parameters. In generally the parameters have value inside the interval, which is defined by designers. Parameters with one value should be used by adoption design. It is strictly prohibited by the design a new or innovative design. The field of criteria is very important and designers must specify them.

A few criteria per phase that are crucial for assessment were already mentioned in the previous chapter. Figure 7 shows the influence of the said criteria in all phases of the PLC. The values of these criteria are classified into groups below:

A. Product conquering phase

VPP,C	Product's technical level of perfection	50–70%
VC,C	Manufacturing costs during product conquering	20–10%
VP,C	Profitability	30–20%
VO,C	Other	0–20%

B. Product use phase

VPP,U	Product's level of perfection	20–30%
VC,U	Production costs	40–50%

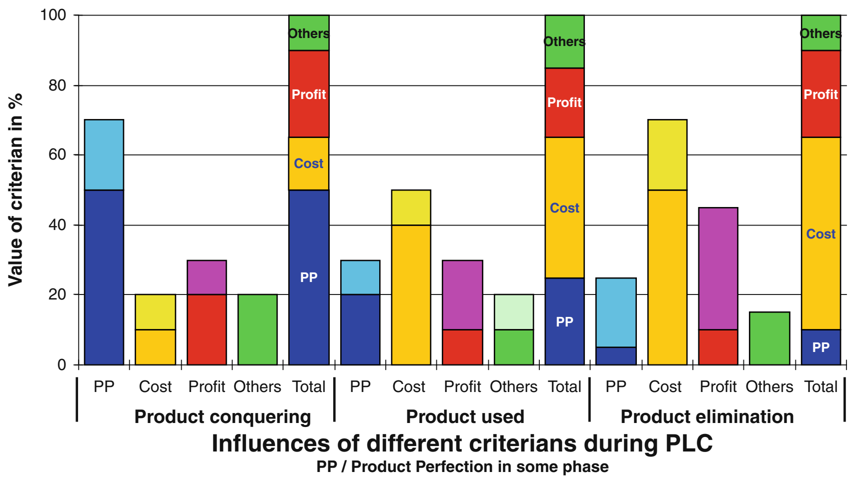

Fig. 7 Influence of individual criteria during individual phases of PLC

VP,U	Profitability	30–10%
VO,U	Other	10–20%

C. Product elimination phase

VPP,E	Product's level of perfection	5–25%
VC,E	Elimination costs	50–70%
VP,E	Product's profitability during PLC	45–10%
VO,E	Other	0–15%

The presented criteria can be discussed within three basic categories: technical level of perfection, costs and profitability. The category "Other" usually also includes supply, i.e. accessibility in real time. During the product conquering phase, real time represents the customer's expectations (market in a broader sense), during the product use phase, which is also the customer or the market, and the same applies to the phase of elimination. The impact of individual criteria varies due to different work tasks and different expectations in individual PLC phases.

The author believes that because of variable impact of individual criteria over the entire PLC one can easily understand some entirely opposing expectations of the participants in individual phases. Technically oriented professionals insist on the technical level of perfection, while economically oriented ones are against high costs or even want no costs for new products. Financial professionals desire reliability of financial operations, i.e. a suitable, and not extreme, degree of profitability. Balancing between all of the extremes is possible if the goal, i.e. to have a new product on the market, is clear.

The magnitude of influences during individual phases needs to be determined separately for each product. Limit values stated in the diagram are merely recommendations. Their general range cannot be determined with a sufficient accuracy, but the list and extent of influences are intended for general and initial assessment.

In addition to these criteria, which serve as the basis for assessment of the suitability of a new product, the product must also be assessed according to other criteria. Features (categories) important for manufacture, sales, distribution, use and the environment need to be taken into account as well.

On the basis of a review of important categories, a decision was made on the following ones, which in our opinion comprise the main influences throughout the three phases of the PLC. The technical category denotes exclusivity concerning engineering resources.

The category of production takes into account the entire manufacturing complex in product materialization. The commercial and financial categories refer to components of business operation. Users are listed in schematic way because their decisions regarding the product have a significant impact on its continued production. The category of nature is termed so in order to generalize the influence of the environment.

By more detailed analysis we used individual criteria. Individual criteria are more detail assessment, which give in the D&D process or better in whole life cycle of product good and right view about the total quality of the product.

Below are present and roughly divided assessments of individual criteria, each comprising the relevant specifications:

- **Technical criterion**

  Φ_{tec} = TECH (*function, shape, functionality, form, technology use, etc.*)

  Categories as a function, shape, functionality, form, technology use, etc. are we defined closely to the products. For different categories we used a parameter, which present technical criteria for product who is developed.

- **Commercial criterion**

  Φ_{com} = COM (*market, purchase, delivery, goods exchange, etc.*)

  Categories as a market, purchase, delivery, goods exchange, etc. present environment, which has influence of man and their society. Categories present commercial parameters which are reflected to product from environmental use.

- **Finance criterion**

  Φ_{fin} = FIN (*profit, investment, security, bilateral & multilateral exchange, etc.*)

  Categories as a profit, investment, security, bilateral and multilateral exchange, etc. present international finance and banking systems, which depend from country to country and international geographical and political situation.

- **Production criterion**

Φ_{pro} = PROD (*cost, logistics, human resources, employment, social security, etc.*)

Categories as a cost, logistics, human resources, employment, social security define production capabilities on the different location. Manufacturing possibilities are included in $\Phi_t$function.

- **User criterion**

Φ_{use} = USE (*better machine, better quality; easy operation, minimum maintenance, fast delivery, etc.*)

By use we have important user assessment, which include many different categories like a: better machine, easy operation, better quality, robust use, minimum maintenance, etc. Definitions of those categories are coming from virtual users, which are simulated in development and design phase. In that case we usually used some expert system by some particular market and users.

- **Eco (Nature) criterion**

Φ_{eco} = ECO (*environmental safety, no environmental impact, more reuse, easier recycling, less disposal, security, etc.*)

Categories, which present eco system are today more important. They are: environmental safety, no environmental impact, more reuse, easier recycling, less disposal, security. By the assessment at these categories plays an important role the local (country) legal system.

All those criteria can be used for a general assessment by product validation. The parameters, which are used by some criterion, were generated on the requirements basis. List of requirements was used as a list of parameters, which was defined in the early stage of D&D process. All parameters, as a description of function, technical specification, description of law, financial data etc. we can put in the validation process. The reason for that is an assumption that the product is not depended of some particular fields. The product is one part in the nature (Fig. 1) and his validation should be compare to it.

It is evident that the above categories are not directly related to the criteria. Many categories also have different influences on the criteria. This means that the assertion about a direct, solid association between individual categories and the criteria is incorrect. For each individual category, it is necessary to separately define the parameters and their values. It is especially important to have a separate definition of the parameters for each product's location on the earth (in the world (the universe in general)). The function values for individual categories also vary with time, as the system is dynamic and not static. A general equation applying to individual products was written, independent of the distribution of the influence of individual categories on the criteria. Influence of whole criteria can be summarized in function (1), which we can denominate as a product validation function.

$$\Phi(x),(t) = \frac{\sum_{j=1}^{k}\left[w(j), x^{*}\Phi(x)\underline{j}, t\right]}{\sum_{j=1}^{k}\left[w(j), x^{*}\Phi(x)\underline{j}, \max\right]} \tag{1}$$

$x = x$ (*tec, com, fin, pro, use, eco*)	index of different criteria, like a technical, commercial, financial, production, use and ecological
j	index for particular parameter inside the different criteria
$\Phi\ (x),(t)$	product validation function present the product assessment for typical criteria defined in time t, where we made assessment
$\Phi\ (x)j,(t)$	product validation function for typical category and particular parameter (indexing with j) defined in time t, where we made assessment
$\Phi\ (x)j,max$	maximum value of product validation function for typical category and particular parameter (indexing with j) defined in time interval from t_o till t, where the assessment was made
$w\ (j),x$	weight function for each particular parameter and each different criteria

If we like follow dynamic changes by some criteria and validated it we used particular equation which is developed from (1). Validation function for technical criteria is follow:

$$\Phi(tec),(t) = \frac{\sum_{j=1}^{k}\left[w(j), tec * \Phi(tec)\underline{j}, t\right]}{\sum_{j=1}^{k}\left[w(j), tec * \Phi(tec)\underline{j}, \max\right]} \tag{2}$$

j	index for particular parameter inside the different criteria
$\Phi\ (tec),(t)$	product validation function on technical basis, present the product assessment for technical criteria defined in time t, where we made assessment
$\Phi\ (tec)j,(t)$	product validation function on technical basis for typical category and particular parameter (indexing with j) defined in time t, where we made assessment
$\Phi\ (tec)j,max$	maximum value of product validation function on technical basis for typical category and particular parameter (indexing with j) defined in time interval from t_o till t, where the assessment was made
$w\ (j),tec$	weight function for each particular parameter and each different criteria

It is essential to be able made relation and influences of individual categories during the assessment, so that in spite of different categories one can obtain their relative influence on the final assessment (Fig. 8). It is vital to always obtain values between 0 and 1 for each assessment category. If a product is monitored over time t, from its development and use to elimination, an interesting variation of the product's assessment is obtained. On the basis of changes in the trend of assessment for individual categories, one can adopt decisions or institute measures over the entire PLC.

If one wishes to evaluate a product according to criteria from individual categories and over a certain time period (t) during the PLC, a detailed graphical presentation should be made for this time interval. As a rule, assessment becomes valuable only when the product enters a more mature phase (over 60% of the time required for its development). Assessment during earlier phases may even be disturbing and stressful for the developmental-design and manufacturing teams. On the other hand, a product can be assessed especially thoroughly at the time of its direct use, which is part of the next phase. On the basis of the product's first entry into the environment, one obtains characteristic trends of product assessment per criterion (Figs. 9a, 9b and 9c).

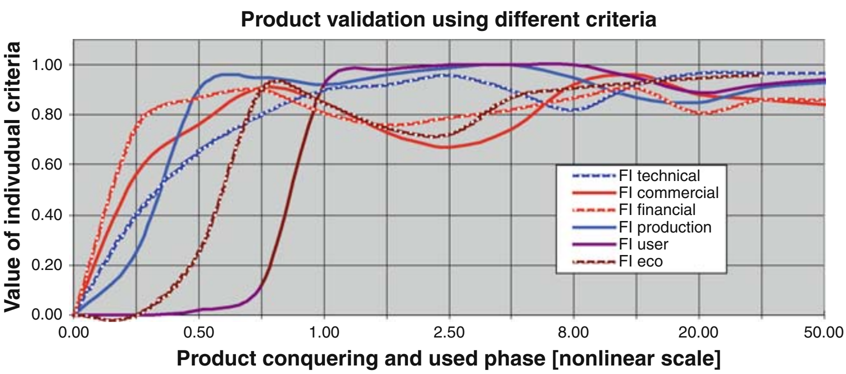

Fig. 8 Variation of product assessments (various criteria) during the PLC

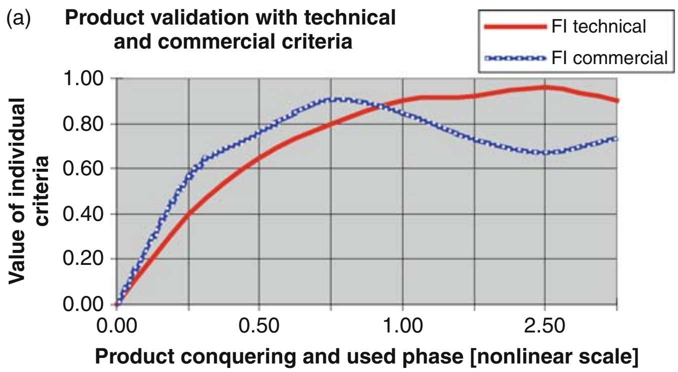

Fig. 9a Product validation with technical and commercial criteria

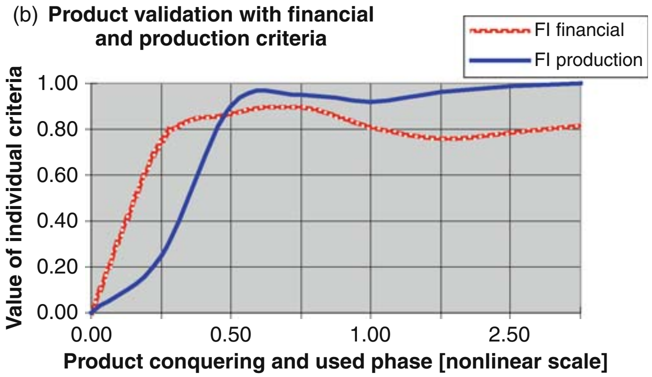

Fig. 9b Product validation with financial and production criteria

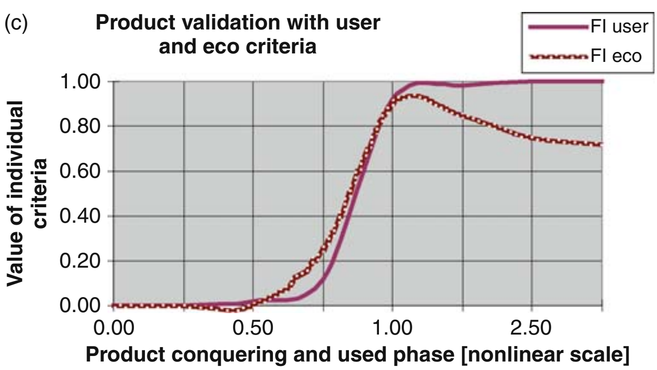

Fig. 9c Product validation with user and ecological criteria

4 Trends of Assessment According to Individual Criteria

When assessing individual parameters in a certain category (tec,com,fin,pro, use,eco), one attempts to define the comparability of assessments in absolute terms and as accurately as possible, particularly their variations. Therefore, data capture at predefined time intervals is very important. Irrespective of temporal variations, though, one must also monitor the product's location in the universe. Sometimes, comparable locations can appear for individual products, even though the difference in details between individual locations is very large.

Insufficient sensitivity of product assessment at various locations (sometimes called remote viewing) is manifested as excessive oscillations of the achieved results. As a rule, such locations must be identified, and the assessment parameters must be analyzed separately and monitored in order to be able to isolate and analyze them separately in the event of changes.

Assessment can be performed on the basis of hard or soft data. Hard data, for example, include physical data (capacity, power etc.), financial data (price, costs, interest etc.). Soft data are for example technical data (industrial design, technological capabilities etc.), user competence (better work capabilities, good after-sales services, etc.). For each parameter, an attempt is made during the assessment process to determine its value as soon as possible on the basis of hard data, not by capturing soft values. It is understandable that the problem has several layers, therefore some assertions by individual authors found in literature regarding hard data for assessment parameters which are in principle soft, are very questionable. As a rule, such data can be formed only on the basis of global capture of values and their special transformation into data. Since this is sensitive information, global commercial complexes must protect them as business secrets. Our team has simulated a few cases of products, with five different locations of product conquering, use and elimination, and the results were very interesting.

When reviewing suitable mathematical formulations for evaluating the sensitivity of assessment, an attempt was made to select the kind of function that would be more sensitive at small differences and less at greater ones. This method was chosen on the basis of experience in assessing the technical characteristics of products according to the VDI 2222 reference. At absolute values in the low range of assessments, linear determination of differences still enables a rough determination of the successful solution. In the event of smaller differences, i.e. with very similar technical solutions, however, the absolute values are so small that they usually do not enable high-quality evaluation. Therefore, a differentiated assessment method was chosen and defined with the term "*First Step to Better Product*" (*FSBP*).

$$FSBP = [1 - \Phi(x), (t)]^{SEN} \tag{3}$$

$\Phi(x), (t)$ product validation function by typical criteria named x, defined in time t, where we made assessment, see equation No.1

Sensibilness of the FSBP function is mostly defined with potential coefficient named *SEN,* which is defined with equation

$$SEN = \sqrt{1 - \left(\Phi(x), (t_1, t_2)_{\min}\right)} \tag{4}$$

$\Phi(x), (t_1, t_2)_{\min}$ minimal value by the product validation function by typical criteria named x in the investigation time interval, from t_1 to t_2

So obtained FSBP values enable a better differentiation and easier decisions even for values around 1.0. It should be emphasized, though, that other important information besides the assessment includes minimal values, as well as the time interval itself.

In Fig. 10 we presented FSBP curve for technical and commercial parameters. The interval in PLC is from 0.50 to 4.0. That interval is usually very sensitive for product perfection value. Include the final phase at product conquering phase and first phase or starting period in product used phase. Assessment in that phase made also good treatment value for product value on the market and environment at all.

In generally we find out that such analysis give better and clear value for self control process. The parameters are generated for product itself. If the chosen

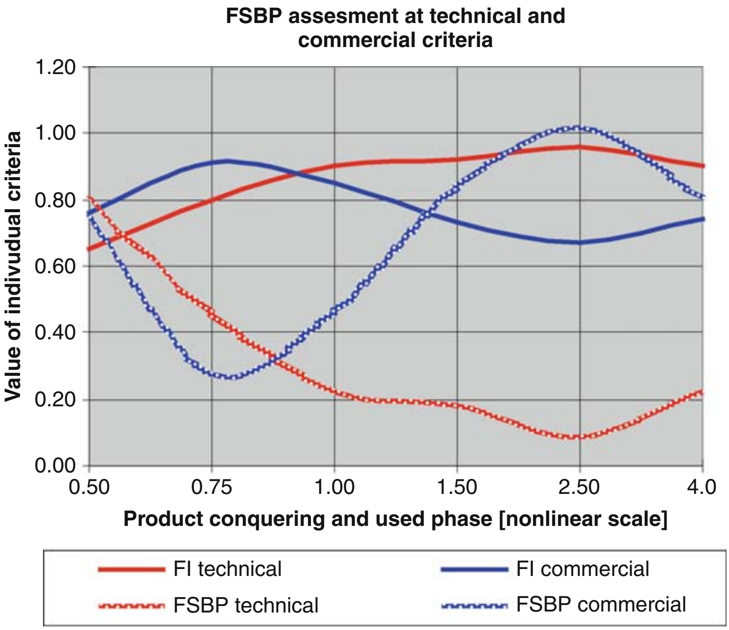

Fig. 10 FSBP curve at technical and commercial assessment compare to the product perfection function in the watching interval from 0.50 till 4.00.

parameters are right or appropriate the D&D team can recognize during the process. If they find out that the parameters are not appropriate at all they can be added too. In that case the additional parameters must be used from starting point of assessment process. The new parameters could not be used for assessment from some time or for some time in PLC interval.

5 Conclusion

The paper presents three characteristic product phases. This means that product planning needs to be performed over the entire PLC. The current knowledge of product planning or economic resources planning is focused only on manufacture, therefore an expansion of such an information system to PLC conquering can be problematic. Certain processes occurring in the phases of product use and elimination are therefore analyzed in lesser detail or very specifically for individual product types.

For easier product conquering over its entire life cycle, six basic criteria have been defined (tec,com,fin,pro,use,eco). By each of these criteria, we used some categories for detail analyses. Categories should be defined with some parameters, which are presented like a value or described. PLC started with D&D process, where we defined list of specification. The specification list is not static but should be changed during the development of the product, generally during the PLC. Maximum of the request is a goal of the products requirements. In reality we try the best that the goal can be achieved. Differences between the goal and our real results we like used as an assessment value. In the paper was proposed unification measure with the percentage scale.

We also introduce the product validation function which can be used as a timely assessment of the product during the PLC. For some particular reason we can also individual criteria use as a (tec,com,fin,pro,use,eco).

Generally speaking we define the requirement for the selection of assessment parameters. Product assessment was then performed at certain time intervals, with the same starting points. When the variation of the assessment function for all six parameters was reviewed (tec,com,fin,pro,use,eco), it was found that it is possible to enforce the extrapolation principle for the variations expected in the following time intervals. An estimate of the scatter of expected results was also used. Timely intervention enables correct and more successful directing of trends already at time t, when the last assessment of product is performed. Among five products, interventions were made in two on the basis of assessment by directing activities towards additional progress. Progress was first enforced in the phase of product conquering (product development) and for the second time in the phase of its use (after-sale services). For various reasons, detailed data on product types cannot be provided here.

The method was applied in the standard PDM (three cases) and “PLM” (two cases) systems. We added standard software with the data base of specification list, which was followed all PLC. Through the PLC we made product validation function and the designers, researchers, salesman, controlling department and marketing man follow their activities. Some particular action was done according the trend analysis.

The method enables the analysis of those important categories that are relevant for the product, not only in technical terms, but also generally, including economic and user influences, but not neglecting the assessment of the product's environmental impact, i.e. its effects on nature.

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Collaborative Optimization and Application of Active Suspension

Hao Wang, Shaoping Wang, and Mileta M. Tomovic

Abstract This paper addresses the current state of collaborative optimization (CO) and its application to active suspension system. CO is a bi-level optimization architecture, which preserves the autonomy to individual disciplines. Through this decomposition, CO can solve the loose-composite problem. When it comes to strong-composite cases, CO will have difficulty in convergence because of the form of system-level constraint in its structure. In order to change this nonlinear phenomenon, we use Response Surface Model (RSM) to modify the interdisciplinary discrepancy. Central Composite Design method is used to select the experiment point to construct the RSM.

Keywords Collaborative Optimization · Compatibility constraint · Approximation approach · Agent model · Response Surface Model (RSM) · Design of Experiment (DOE)

Nomenclature

x_{sl}	Design variables in system level
x_{sl}^*	Optimal values for system level
x_i	The i th subsystem design variables
x_i^*	Optimal values for subsystem level
ε	Dynamic factor in interdisciplinary compatibility
$l_u l_d l_k l_p$	Length of upper and lower wishbone, kingpin and knuckle
$d_u d_d d_k d_p$	Diameter of upper and lower wishbone, kingpin and knuckle
σ_u, σ_d	Yield stress of upper and lower wishbone
σ_k	Yield stress of kingpin and knuckle (considered as a whole)
λ	Angle of tire plane
Δl	Horizontal slip of the tire
$\sigma_{\max}$	Maximum value among $\sigma_u, \sigma_d, \sigma_k$

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Constant in analysis

ρ	Density of the rod, gain = 7.8×10^3 kg/m^3
$[\sigma]$	Yield stress for steel, gain = 70 MPa
E	Modulus of Elasticity, gain = 200 GPa
ν	Poisson's ratio, gain = 0.3
K_1	Stiffness factor of sprung, gain = 1.3×10^4 N/m
C_1	Damping factor of sprung, gain = 1000
M_1	Sprung mass (quarter car model), gain = 330 kg
F_1	Preload force of sprung, gain = 3236.2 N
K_2	Stiffness factor of unsprung, gain = 1.7×10^5 N/m
C_2	Damping factor of unsprung, gain = 0
M_2	Unsprung mass (car model), gain = 25 kg
F_2	Preload force of sprung quarter, gain = 3481.4 N

1 Introduction

Multidisciplinary design optimization (MDO) is a field of engineering that uses optimization methods to solve design problems incorporating a number of disciplines. Especially to the complex system, its performance is related to many disciplines. Whereas the traditional design of complex system always concerns some disciplines while it ignores others, it may lead to design conflict among different disciplines (Fig. 1).

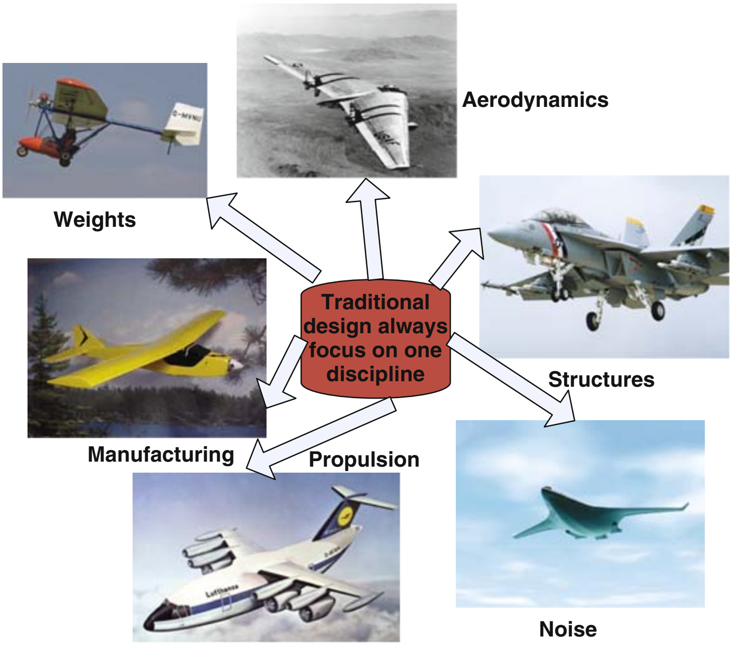

Fig. 1 Traditional design always focus on one discipline

Details of the CO method have been developed by several researchers, primarily in the last 20 years, although closely-related work is described in publications as early as 1977 (Peterson et al. 1977). CO is a promising decomposition algorithm introduced by Braun (Braun et al. 1996) and further developed by Sobiesky (Sobiesky 1998) to solve the general (non-convex) MDO problem. There are many applications in the aviation industry. Budianto (Budianto, 2004) presents a study of collaborative optimization as a systematic, multivariable method for the conceptual design of satellite constellations. Perez (Perez 2006) presented an integrated control-configured aircraft design-sizing framework. It overcomes the challenges that the flight dynamics and control integration present when included with the traditional disciplines in an aircraft sizing process. During these applications, there are two ways in subsystem level analysis: CAE analysis and approximation method. Because of the difficulty and time cost of the computation, some of the application used approximation method instead of direct CAE analysis. Sangook Jun (Jun et al. 2004) used CO to design the aircraft wing. Genetic algorithm is widely used for the system level optimization while the gradient-based method as a subspace optimization algorithm. The response surfaces are exploited to realize CO in subspace in some research work. Hence, the human interface is crucially important to enable engineers to control the design process (Enblom 2006). It is necessary to establish a platform that enables data transmission between different commercial uni-discipline software and realize the MDO. Xu Lin (Lin 2006) proposed a platform that integrated aerodynamic, propulsion and structure disciplines to design a missile based on MDO framework iSIGHT. S.-X. Chen developed an email-based communication technology of global coordinative optimization of distributed structural system (Chen 2005). The application of CO in the automobile field is rare. WU Bao-gui proposed a CO integration platform that did successfully test the whole vehicle virtual model in crash, aerodynamic and NVH (Noise, Vibration and Harshness) disciplines (Wu et al. 2007). MDO through CO method and multidisciplinary integrated simulation is a new attempt in active suspension design.

CO is a good method in MDO because its structure is like real division of work in industry. However, CO is still a relatively immature decomposition method because its compatibility constraint in system level adds much nonlinear characters to the optimization. This problem is still not solved completely as little experience in true industrial environments is available. But some efforts have been made to change this disadvantage of CO algorithm. Approximation approach is one of the successful methods among the improvements. Approximation approach is part of agent based model method and Design of Experiment (DOE) is another part of it. In this paper we use Response Surface Model (RSM) which is one of the approximation approaches widely used in MDO to solve a two-discipline optimization problem on active suspension system.

The remainder of this article is organized as follows: Section 2 introduces the CO methodology and its character. Section 3 provides agent model to solve the discrepancies of the disciplines. Section 4 describes the application on active suspension system which concurrent design is used and two CAE model sharing the same CAD model has been proposed to improve the design efficiency. Section 5 is the conclusion of whole paper.

2 Collaborative Optimization

Before discussion of CO, brief introduction and comparison of four key MDO decomposition frameworks are summarized from 2006 European-U.S. MDO Colloquium (de Weck et al. 2007) (Table 1).

2.1 CO Methodology

With recent advances in the field of MDO, it is possible to transfer the traditional vertical design process into horizontal process, enabling concurrent analysis and design. Among many MDO methods, CO shown below (Fig. 2) is recognized as suitable method to design and optimize multidisciplinary coupling problems.

CO method consists of two-level optimization architecture. The subsystem must satisfy all of their disciplinary constraints. To achieve its design task with given target variables from the system, the subsystem can choose their local variables freely. However, when there is not enough degree of freedom in choosing local variables, the subspaces are also allowed to change their target copies with minimum departure from their target variables. The task of the system is to adjust the target variables so that all subspaces can achieve their own task, while minimizing the system-level objective. When using this method, it is very similar to the real work. Every department and expert of different disciplines can do their own design and optimization separately (Perez 2006).

Table 1 Overview of MDO decomposition frameworks

	Method			
Characteristic	BLISS	CO	ATC	CSSO
System-level Analysis Required?	No	No	No	Yes
Subspace Sensitivity Analysis Required?	No	No	No	Yes
Number of Levels	Two	Two	Multiple	Two
Partitioned by:	Discipline Analysis	Discipline Analysis	Object/ Component	Discipline Analysis
Subspace optimization influenced by targets?	Yes	Yes	Yes	No
Autonomous Subspace Optimization?	Yes	Yes	Yes	Yes

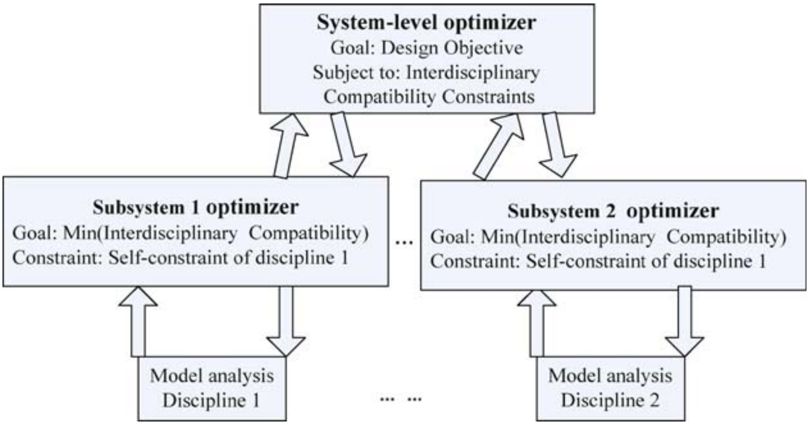

Fig. 2 Collaborative optimization method

At the system level (SL), the collaborative optimization objective is stated as:

$$\min f(x_{sl}) \text{Subject to} J_i^*(x_{sli}, x_i^*) = \sum_{j=1}^{m} (x_{slij} - x_{ij}^*)^2 \leq \varepsilon, i = 1, \ldots\ldots, n \quad (1)$$

where $f(x_{sl})$ represents the system level objective function which is also the design objective function. J_i^* represents the compatibility constraint for the i th subsystem (of the total n subsystems) optimization problem and x_i are the i th subsystem design variables whose dimension is m. Variables with a superscript asterisk indicate optimal values for the subsystem level optimization. Note that the system level constraint assures simultaneous coordination of the coupled disciplinary values.

The lower-level objective function is formulated such that it minimizes the interdisciplinary discrepancy while meeting local disciplinary constraints. At the disciplinary level, the i th subsystem optimization is stated as

$$\min J_i(x_{sli}^*, x_i) = \sum_{j=1}^{m} (x_{slij}^* - x_{ij})^2 \text{ subject to } g_i(x_i) \leq 0 \quad (2)$$

where g_i is the specific disciplinary constraint; variables with a superscript asterisk indicate optimal values for the system level optimization.

Considering the condition of three variables and two disciplines as an example, the process of CO is illustrated in Fig. 3 (Kobayashi et al. 2005). In the figure below, three coordinate axis represent the values of design variables – X, Y and Z. The two surfaces α and β represent the constraint of two disciplines. Our goal is to find out the minimum value of object function ω. From Fig. 3(a), we can clearly find the optimal point is point 0 that located on the intersection of two constraint surfaces. Point 1 represents a set of system-level design variables that are given as the initial value. Then it will go to subsystem level. In order to

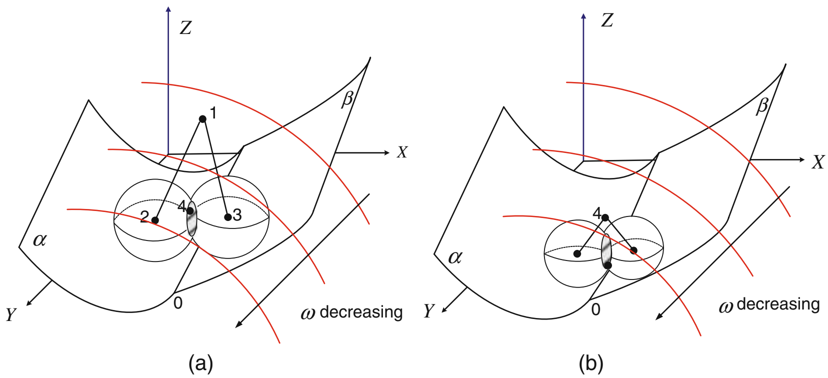

Fig. 3 Process of CO

satisfy the constraint, we need to find the closest point to point 1 on the two surfaces according to geometrical meaning of the equation (2). The result of this step is point 2 and 3. Then in system level, the geometry meaning of the constraint is two spheres. The optimal point is among the intersection of these two spheres. We can get point 4 here that is closer to the optimal solution. Then go on the iteration to get closer to and arrive at point 0 (Fig. 3(b)).

2.2 Advantages of CO

Major characteristics of CO are its bi-level and distributed structure. CO has computational and organizational advantages, and these advantages can be maximized when used for a large-scale design optimization consisting of a large number of design variables and disciplines (Jun et al. 2004).

Collaborative optimization is formulated to remove direct communication among disciplines, so as to guarantee disciplinary autonomy. Computationally, decrease of direct communication among disciplines enables a reduction of computational cost, especially in large-scale problems that require large amount of data exchange at each iteration. Furthermore, each discipline's analysis tools can be directly integrated with a specific optimization algorithm without much modification. Organizationally, the collaborative optimization architecture provides a natural fit to the current disciplinary expertise structure found in most design organizations and used by most project teams.

2.3 Weaknesses of CO

2.3.1 Problems from the Experiments

I. Kroo and V. Manning's experiments have suggested that the price that must be paid for the advantages of decomposition is a somewhat increased computational time (Kroo and Manni 2000). CO often leads to inefficient convergence, especially when gradient-based method is used for system level optimization. In this case of gradient-based method use, CO also strongly depends on the initial condition for convergence (Jun et al. 2004). A few difficulties caused by certain features of its architecture have been also reported. The architecture, with discipline-level optimizations nested in a system level optimization, leads to considerably increased computational time. In addition, numerical difficulties such as the problem of slow convergence or unexpected nonlinearity of the compatibility constraint in the system level optimization are known weaknesses of CO (Jang 2005).

2.3.2 Reasons of the Problems of CO

The use of quadratic forms for the system level compatibility constraints means that near the solution changes in system targets have little effect on the constraint values. Specifically, the gradient approaches zero, leading to difficulties for many optimizers, especially those that rely on linear approximations to these functions. The implications of the singular Jacobi are discussed in (Alexandrov and Lewis 2000) using an SQP method at the system level. For a simple test case, convergence of the system problem was not achieved. This failure is attributed, not to a failure of the optimizer, but to the specific CO formulation (Jang 2005). That is because the system-level problem fails to satisfy the standard first-order necessary conditions (Karush-Kuhn-Tucker or KKT conditions (Fiacco and McCormick 1990)).

3 Agent Based Model Approximation

From the above analysis, we know that the bi-level and distributed structure allows CO to easily decompose MDO problem but also causes some unavoidable convergence difficulty in computation. Some alternate choices for the form of subspace objectives, system constrains, and optimizers are discussed in (DeMiguel, and Murray 2000).

Several ideas for modification have been explored which focus on alternating choices for the form of interdisciplinary discrepancy. These modifications can be categorized as following:

1. Loose system constraint method. The constraint in system level is equal constraint which is ideal but very hard to satisfy. Robert Braun (Braun et al., 1996) knows this problem from the beginning and proposed that we should change the equal constraint to inequality$J_i^*(x_{sli}, x_i^*) \leq s$. The writer has used this method to test a simple MDO problem and found that the DONLP, LSGRG2 and SLP method all failed in the optimization because they are emanative and could not find the optimal solution. For the value of S, it cannot be so small because there will be a difference between x_{sli} and x_i^*

so it can meet the subsystem level but cannot meet the system level. The S cannot be big either because it is hard to meet this constraint in system level optimization. Li Xiang improved this method by using a dynamic factor $\varepsilon = (\lambda * \|X_1^* - X_2^*\|)^2, \lambda \in (0.5, 1)$in inequality constraint instead of stationary factor (Xiang 2004).

2. Penalty function method. Angel-Victor DeMiguel and Walter Murray proposed a new CO formulation called Modified Collaborative Optimization (MCO) which uses penalty function instead of the quadratic penalty function used by Braun (DeMiguel, and Murray 2000).
3. The use of response surfaces to model the system constraints. I.P. Sobieskin and I.M. Kroo had expounded two kinds of method used in CO and refinement was performed using ideas from trust region methods (Sobieski and Kroo 2000).

While in this paper we use response surfaces (RS) to modify the system constrains. RS method is an approximation approach which is widely used in MDO field.

3.1 Response Surface Method (RSM)

Response surface methodology (RSM) is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes. In general, suppose that the system involving a response y that depends on the controllable input variables x. The relationship is $y = f(x)$. Because the form of the true response function f is unknown, we must approximate it. Usually, a low-order polynomial in some relatively small region of the independent variable space is appropriate. The 4th order or Quartic model is represented by a polynomial of the following form:

$$F(x) = a_0 + \sum_{i=1}^{N} b_i x_i + \sum_{i=1}^{N} c_{ii} x_i^2 + \sum_{1}^{N} c_{ij} x_i x_j + \sum_{i=1}^{N} d_i x_i^2 + + \sum_{i=1}^{N} e_i x_i^4 \quad (3)$$

where

N is the number of the model inputs
X_i is the set of model inputs X_i
a, b, c, d, e are the polynomial coefficients, the total number of coefficients is $(N+1)(N+2)/2+2\,N$.

3.2 Design of Experiment (DOE)

Experimental design, in which a prescribed set of experiments or trials (system analyses) is performed, can be used to study the effects of design parameters on the design states so that intelligent design decisions can be made. Primary considerations in experimental design are as follows:

1. Number of experiments that can be performed (given cost and time constraints).
2. Values for the parameters in each experiment.
3. Proper interpretation of the results.

During every subsystem-level optimization we need to construct the response surface function according to some experiment point. In our RSM process, we use Central Composite Design (CCD). CCD is a statistically based technique in which a 2-level full-factorial experiment is augmented with a center point and two additional points for each factor (called “star points”). Thus, five levels are defined for each factor, and to study n factors using CCD requires $2^n + 2n + 1$ design point evaluations. Figure 4 shows the CCD points for three factors.

The center and star points are added to acquire knowledge from regions of the design space inside and outside the 2-level full-factorial points, allowing for an estimation of higher order effects (curvature). The star point(s) are determined by defining a parameter which relates these points to the full-factorial points by

$$\begin{aligned} S_{\text{upper}} &= b + (u - b) \times a \\ S_{\text{slow}} &= b - (b - l) \times a \end{aligned} \tag{4}$$

where

b = baseline design
l = lower factorial point
u = upper factorial point, $l < b < u$.

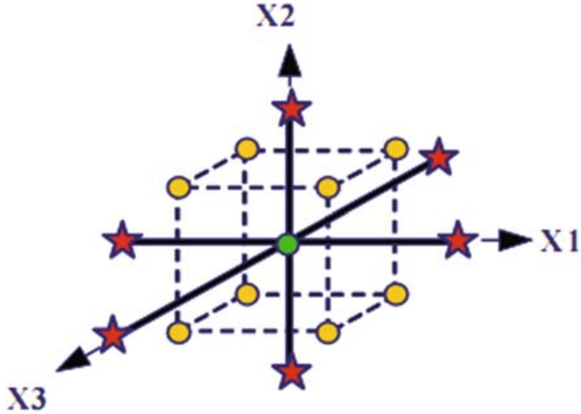

Fig. 4 Central Composite Design points for three factors

Although CCD requires a significant number of design point evaluations, it is a popular technique for compiling data for Response Surface Modeling due to the expanse of design space covered, and the higher order information obtained (iSIGHT user reference guide 2000).

3.3 RSM and Whole Computation Flow

The whole computation process is described as follows:

1. According to CCD experiment method we mentioned before we select a group of system level design variables vector X_{sik}^{*}, $k = 1, 2, 3\ldots.(N+1)(N+2)/2+2\,N$, where N is the number of the input variables.
2. Performs the subsystem-level optimization in every discipline and get the optimal result of the objective function J_{ik}^{*}, $i = 1, 2, 3\ldots.n$, $k = 1, 2, 3\ldots.(N+1)(N+2)/2+2\,N$, where n is the number of the disciplines and N is the number of the input variables.
3. Construct the RSM function between subsystem optimal objective functions and system optimal design variables according to J_{ik}^{*} and X_{sik}^{*} :

$$J_{ik}^{*} = a_0 + \sum_{i=1}^{N} b_i x_i + \sum_{i=1}^{N} c_{ii} x_i^2 + \sum_{1}^{N} c_{ij} x_i x_j + \sum_{i=1}^{N} d_i x_i^2 + + \sum_{i=1}^{N} e_i x_i^4$$

4. According to formula 1 we can get the system level optimization problem is:

$$\begin{aligned} &\text{Min} \quad f(x_{sl}) \\ &\text{Subject to} \\ &J_{ik}^{*} = a_0 + \sum_{i=1}^{N} b_i x_i + \sum_{i=1}^{N} c_{ii} x_i^2 + \sum_{1}^{N} c_{ij} x_i x_j + \sum_{i=1}^{N} d_i x_i^2 + + \sum_{i=1}^{N} e_i x_i^4 = 0 \end{aligned} \tag{5}$$

5. Performs the system level optimization and get the new design variables vectorX_{si}^{*}

Aforementioned process executes literately until the whole system converged.

4 Application on Active Suspension

In performing this analysis, it is assumed that the mass of the members is negligible compared to that of the applied loading. Friction and compliance at the joints are also assumed negligible.

4.1 Subsystem-level Design and Analysis

4.1.1 Dynamic Subsystem

The Fig. 5 above shows the double wishbone suspension structure. The length of upper and lower wishbone is l_u and l_d. l_k and l_p represent the length of the kingpin and knuckle. The height of the wheel is h. We need to measure the angle of wheel plane λ and horizontal slip of the wheel Δl. When the wheel beating from top to bottom, we just need to design the length of every rod and make a correct layout. Then we can make the changes λ of Δl and in the scope of the limit.

Now we will deduce the relationship between λ,Δl and wheel structure.

When the wheel beat from top to bottom, the upper and lower wishbone will rotate around rotation center. The angle of rotation is a very complex and nonlinear function so we cannot get them easily. We will use $\alpha(l_u, l_d, l_k)$ and $\beta(l_u, l_d, l_k)$ to express them. We define that the projective length on the ground of OA, AD, DE, BC are l'_d,l'_k, l'_p and h'. According to the geometrical relationship from the Fig. above, we can easily deduce following formula:

$$\begin{aligned} l'_d &= l_d \cos\alpha\,(l_u, l_d, l_k) \\ l'_k &= \frac{1}{2} l_k \cos\alpha\,(l_u, l_d, l_k) \\ l'_p &= l_p \cos\lambda \\ h' &= \frac{1}{2} h\,\sin\lambda \end{aligned} \tag{6}$$

$$\begin{aligned} \Delta l =& (l_d + l_p) - (l'_d - l'_k + l'_p + h') = (l_d + l_p) \\ & - \left(l_d \cos\alpha(l_u, l_d, l_k) - \frac{1}{2} l_k \cos\alpha\,(l_u, l_d, l_k) + l_p \cos\lambda + \frac{1}{2} h \sin\lambda\right) \end{aligned}$$

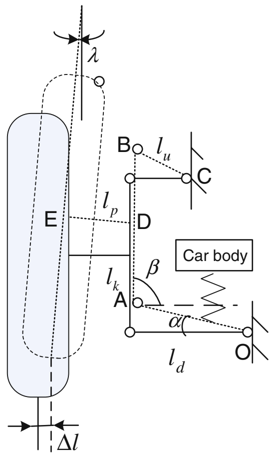

Fig. 5 Dynamic analysis of a two double wishbone active suspension

From the formula above, we can consider that Δl is related to l_u,l_d,l_k and l_p. The height of tire h is also in the function but we do not consider it as a design variable. The slip displacement of wheel Δl should be not more than 5 mm, that is $\Delta l \leq 5$ mm. This is the allowable displacement of elastic deformation.

4.1.2 Structure Subsystem

To the structure discipline, load is the active force provided by hydraulic cylinder (Fig. 6(a)) (Happian-Smith 2002). Assume F_w is the wheel load and F_s is the maximum active force we calculated in Section 2 through multidisciplinary collaborative simulation.

When the free body diagram of the wheel and knuckle is considered (Fig. 6(b)), the directions of F_w and F_B are known and together establish the point of concurrencyP_1, for the three forces that act on the body. If the magnitude of F_w is known, the magnitudes of F_A and F_B can be determined from the triangle of forces through:$\frac{F_w}{l_k} = \frac{F_k}{l_u} = \frac{F_A}{\sqrt{l_u^2+l_k^2}}$ (Fig. 6(c)). For the free body diagram of AO (Fig. 6(d)), the point of concurrency is at P_2 and with F_A, F_s and $\theta(l_u, l_k)$known, F_o can be found from the second triangle of forces (Fig. 6(e)).

To the lower wishbone OA, the load and geometry parameter is shown in Fig. 6(d). According to the model, we can get the formula from the mechanism handbook (Joseph et al. 2004). The cross-section G is the dangerous one because it is located at the maximum bending moment (absolute).

$$F_A = \frac{F_s a^2}{2l_d^3}(3l_d - a)/\cos\theta(l_u, l_k)$$

$$M_{\max} = \frac{F_s a^2}{2l_d^3}(3l_d^2 + a^2 - 4al_d)/\cos\theta(l_u, l_k) \tag{7}$$

$$\sigma_d = \frac{M_{\max}}{W_z} \leq [\sigma_d]$$

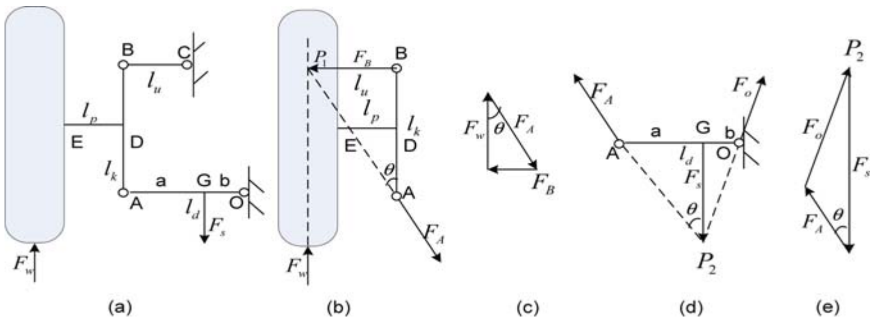

Fig. 6 Forces analysis of a double wishbone active suspension

where $W_z = \frac{I_z}{y_{\max}}$ represents the flexural coefficient of the cross-section; $I_z$denotes the moment of inertia to the neutral axis that is related to the geometry of the cross-section; $y_{\max}$ represents the maximum displacement from the point of stress tensor to the neutral axis. To the plastic deformation for ductile material such as metal, we use Von Mises yield criterion. The von Mises yield criterion, as a function of the principal stresses, is defined as:

$$\sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}} \leq [\sigma] \tag{8}$$

In the formula, σ_1 ,σ_2,σ_3, $[\sigma]$ are fist, second, third principal stress and yield stress. The cross-section G can be considered that only the first principal stress works. The constraint is that maximum stress tensor is smaller than the yield one$1-\frac{\sigma_d(l_d,l_u,l_k,a,d_d)}{[\sigma_d]}>0$.

To the upper wishbone CB, we can make the analysis similar to OA:

$$\begin{aligned}
F_B &= F_A \tan\theta = \frac{Fa^2}{2l_d^3}(3l_d-a)\sin\theta(l_u,l_k)/\cos^2\theta(l_u,l_k) \\
M_{\max} &= \frac{Fa^2 l_u}{2l_d^3}(3l_d-a)\sin\theta(l_u,l_k)/\cos^2\theta(l_u,l_k) \\
\sigma_u &= \frac{M_{\max}}{W_z} \leq [\sigma_u]
\end{aligned} \tag{9}$$

The moment of inertia is similar to the expression above. We can consider that the stress tensor of CB is related to design variables l_d, l_u, l_k, a, d_u. The constraint is that maximum stress tensor is smaller than the yield one$1-\frac{\sigma_u(l_d,l_u,l_k,a,d_u)}{[\sigma_u]}>0$.

Considering kingpin and knuckle as a whole, we can also get the constraint is $\sigma_k(l_k,l_p,d_k,d_p) \leq [\sigma_k]$.

Through the analysis above, we can use CO method to solve the structure and dynamic coupling problems. The analysis result is summarized in Fig. 7.

4.2 Implement of the Design and Optimization

One of the most challenging aspects of multidisciplinary design and optimization is the sharing of disciplinary data between the various analysis codes. MDO frameworks iSIGHT is chosen to build up the MDO model. The model constructed in Pro/ENGINEER can be used in Patran and ADAMS. Through

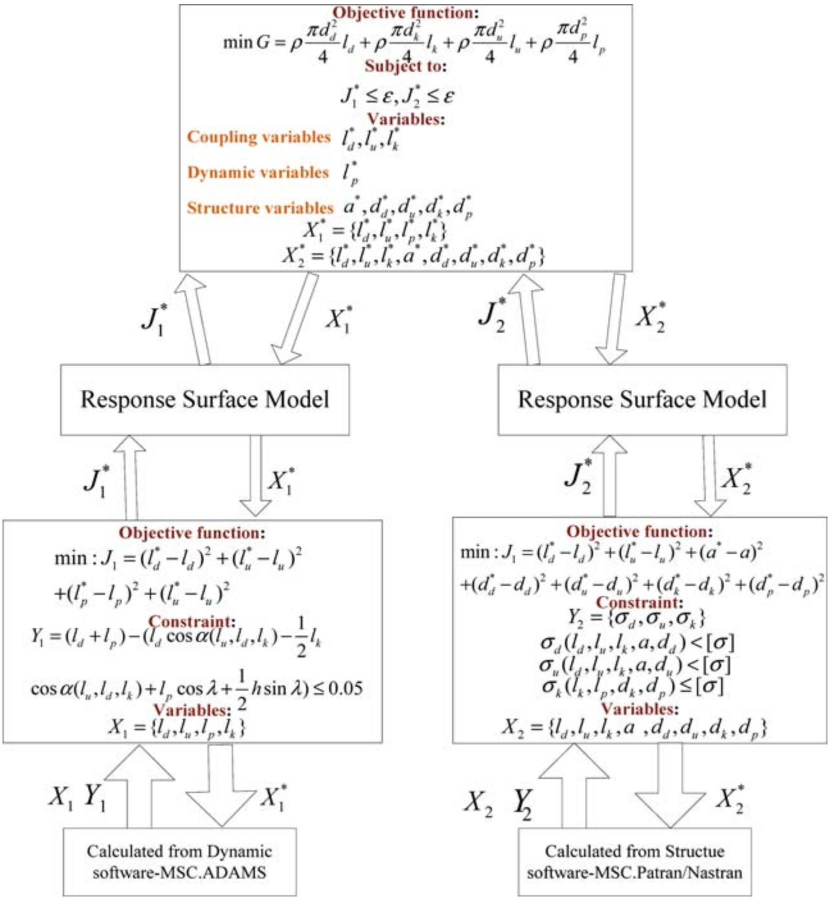

Fig. 7 Expression of coupling problems of structure and dynamic discipline in CO

this kind of sharing model, the speed of design and optimization can be improved significantly. In optimal cycle, we cannot run the CAD/CAE software every time by Graphics User Interface (GUI). Instead of it, we execute command files that automatically record every operation step, save the command flow at the first time, and modify them according to our need. The data transmission among every step is shown in Fig. 8.

4.3 Result

Before the optimal process, we need to normalize the unit of every parameter before we calculate the discrepancies of the disciplines. In the suspension

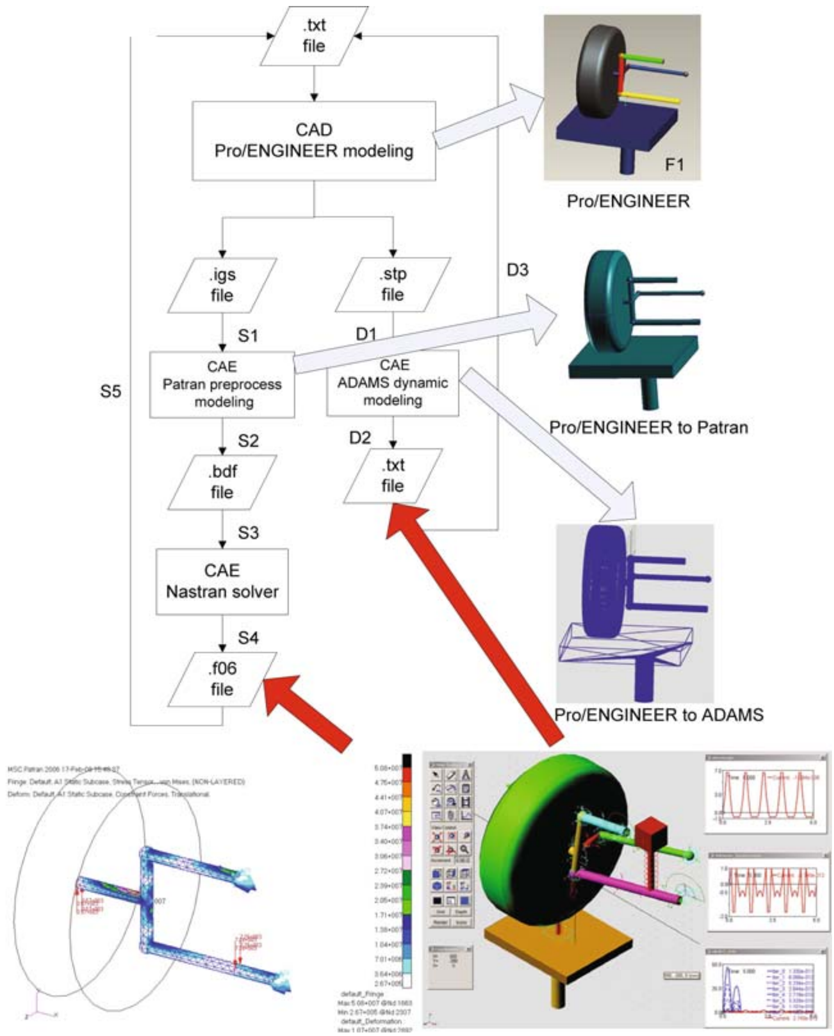

Fig. 8 Automatic data transmission in iteration

system, we use linear normalization to change the value to the domain from 0 to 1. The calculation rule is as follows: $X_n = \frac{X - X_{\min}}{X_{\max} - X_{\min}} (X_n \in [0, 1])$

The initial and final value are XandX_n. The normalization is preceded in the step S5 and D3.With the collaborative design and hierarchy optimization, we can get the optimal values listed in Table 2:

With the CO method, we can get the mass of the suspension deceased by 22.52%. The dynamic and structure performance of the system are greatly improved.

Table 2 Result of the optimization

Nomenclature	Initial value	Min value	Max value	Result	Unit
l_u	35	26	38	36.26	cm
l_d	50	40	58	41.65	cm
l_k	32	28	40	31.28	cm
l_p	26	20	30	24.50	cm
d_u	40	30	50	38.05	mm
d_d	40	30	50	41.60	mm
d_k	40	35	45	34.80	mm
d_p	40	35	45	40.40	mm
a	40	35	50	33.60	cm
λ	12.5			1.8	mm
$\sigma_{\max}$	97			50.8	MPa
G	14.3033			11.0826	kg

5 Conclusion

This paper summarizes the advantages and weakness when using CO method to solve MDO problems. Bi-level structure and nonlinear system level constraint makes CO hard to converge and even fail to find the optimal solution. Three kinds of modifications of CO have been summarized and compared.

4-order response surface model was used in this paper to the application of active suspension. The presented result showed that the CO coupling process worked. The analysis and optimization models were simple enough to develop the desired methodology without involving high computational load. If the design variables become more and then we need more experiments and time because it requires $O(n^2)$ function evaluations.

In the future, the complexity of models in each discipline will be increased to analyze realistic active suspension models. Furthermore, a stronger coupling will be developed by including the control effects of the hydraulic components in hydraulic and control disciplines. Finally, several decomposition will be implemented on the active suspension design process and products that are more comprehensive can be undertaken.

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Back to the Future: Product Lifecycle Management and the Virtualization of Product Information

Michael Grieves

Abstract Product Lifecycle Management (PLM) is new as both a term and an acronym, with their usage occurring only in this new century. Since PLM is new, it is necessary to have an understanding of how it is defined. PLM is based on the substitution of product information for wasted physical resources and using that information for the entire lifecycle of the product. One of the attractions of PLM is that it is a return to a concept as old as the concept of a product. That concept is a product-centric view of the product from creation to disposal. However, mass production and division of labor had made that concept unworkable. The ability to virtualize products allows a return to a product-centric view. The Information Mirror Model (IMM) is a conceptual framework that describes how this product-centric view will be operationalized and used through the four stages of the product's life: create, build, support, and dispose.

Keywords PLM · Product Information · IMM · Product-Centric View · Back to the future

1 Introduction

Product Lifecycle Management (PLM) appears to be a new and different approach to product information. As a defined term and acronym, Product Lifecycle Management and PLM are new. However, on closer examination, PLM is really a "back-to-the future" concept.

PLM trades information for physical resources, specifically wasted time, energy, and material. This is not a new concept. Humans have attempted to do this for as long as they have had the capacity to reason and remember. However, this ability to reason and remember was on an individual effort and limited by the capabilities of the human brain. It only worked on a small scale.

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However limited this ability, humans did concern themselves with the lifecycles of their artifacts or, as I will refer to them, their products. Humans created products. They built those products. They maintained those products in good working order. When those products outlived their useful life, humans disposed of them.

Because for the most part, humans relied on mental representations that they maintained within their own memory, this model worked under limited conditions. The products were simple. The numbers of products were small. The products remained in close physical proximity to the product producers.

Product proximity was necessary. Information is an intrinsic characteristic of a product. Length, width, weight, and composition, to name some of information characteristics that products contain, are embedded within a product. Humans could and did extract that information in order to be more efficient in using physical resources. However, except for the memory of humans and their notes and sketches, information about the product did not exist independent of the physical product itself.

The ability to strip and record this embedded product information took a long time to develop, but did get increasingly better. Standards of measurement and instruments to perform such measurements, blueprints, and detailed product descriptions represented product information that was embedded into the product. However, it was only with computers and communication technology development in the last half of the 20th century that product information could not only be fully described but also could be dynamically manipulated regardless of proximity to the actual product.

This opened up the possibility of linking a physical product with the information about that product. This stripping, modeling, and linking of product information on computers "virtualizes" the physical product. The Information Mirror Model ("IMM") is conceptually related to mental representations of humans. However, it is richer, more extensive, more precise, and can be shared.

The global nature of the Internet makes this virtualized model available to anyone independent of their geographical location and proximity to the physical product itself. This linking of the physical product with its virtual equivalent throughout the life of the product with the purpose of minimizing the waste of physical resources is the basis for Product Lifecycle Management or PLM.

2 Defining PLM

Product Lifecycle Management and its acronym are literally 21st century creations. If a search by ABI Inform for industry or academic articles about PLM as Product Lifecycle Management before the year 2000 is done, the results are that there are no articles found. While as discussed elsewhere (Grieves 2006), PLM came about as other technologies and concepts, such as Computer-Aided Design (CAD), Computer-Integrated Manufacturing (CIM), and Product Data Management (PDM) were integrated into a product-centric view of product information over the life of the product.

While there was some usage of the term by software vendors and information system analysts at the beginning of the century, one of the first periodicals to attempt to define Product Lifecycle Management (PLM) was *CIO Magazine*. The article, “There’s a New App in Town” (Stackpole 2003), was a seminal article about PLM. It was the first time an executive-oriented magazine featured Product Lifecycle Management as a topic that the executive suite should be interested in.

The definition in its present form was developed for my first book on Product Lifecycle Management (Grieves 2006), although elements appeared in a previous paper (Grieves 2005). There are some other definitions of Product Lifecycle Management that differ, and some that differ very radically, from the definition that I will present here. However, I would argue that the practitioners in the field would generally agree that this definition captures what most people familiar with Product Lifecycle Management would consider when thinking about PLM.

The definition for PLM is as follows:

> Product Lifecycle Management (PLM) 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 lean thinking.

While there are many interesting implications of this definition, the focus of this chapter will be on the why an integrated information approach has relevance to the four phases of a product’s life, namely the create, build, support, and dispose phases, and what a model for such an approach would look like.

3 Information as a Substitute for Wasted Time, Energy, and Material

Any discussion of virtualization needs to start with the rationale for doing so. It has only been fairly recently that economists have recognized the economic value and difference of information as compared to other resources (Warsh 2006). The concept of trading atoms for bits has been proposed before (Negroponte 1995). However, the rationale for doing so has not always been made clear. It often appears that going “digital” is goal in itself. However, there should be a better rationale than that.

For PLM, it is in the definitional phrase stated above, “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 lean thinking.” Lean thinking is the idea that we minimize the use of physical resources in the four cycles of the product’s life: create, build, support, and dispose.

We do this by using information about the product or what we will call the “virtualized product” to reduce the use of wasted time, energy, and material. We cannot eliminate all usage of time, energy, and material. PLM is about physical products that are atom-based. Material has to be moved, shaped, assembled, repaired, and disposed of. However, we can attempt to minimize the amount of resources to do those tasks. The resources above that minimum are by definition waste.

There are many, many examples that illustrate the waste of resources that occurs during the product's lifecycle: redesigning parts that already exist; manufacturing parts that do not fit together at assembly; ordering repair parts that are not the right part which is discovered only when the product has been disassembled; digging parts out of a landfill because they are toxic and should have been disposed of differently.

Time, energy, material, and information are not directly comparable. Three of them, time, energy, and material, are quantifiable, but have different units of measurement. However, we do have a mechanism to equate them. That mechanism is the costing function. We can apply the cost of each unit of measure times the quantity of measurement to arrive at a common unit of comparison, cost in dollars.

Information is more difficult to deal with. Unlike time, energy, and material, information is not a rival good. The cost of information is not in its application since the use of information does not diminish it. However, there is a cost in collecting, organizing, and transmitting information. For purposes of this analysis, the costs of the resources and computer and communications equipment to do this collecting, organizing, and transmitting over the life of a specific task can serve as a proxy for the costs of information.

Figure 1 is illustrative of this substitution of information for wasted time, energy, and material. In this figure, the two bars represent the costs of any designated task involved with a product's lifecycle. The task could be the designing of a part that has certain functionality. It could be the manufacture and assembly of that part. It could be the repair of that part when it ceases to function correctly.

The bottom parts of the two bars are identical. They represent the most efficient use of time, energy, and material to perform the task in question. For

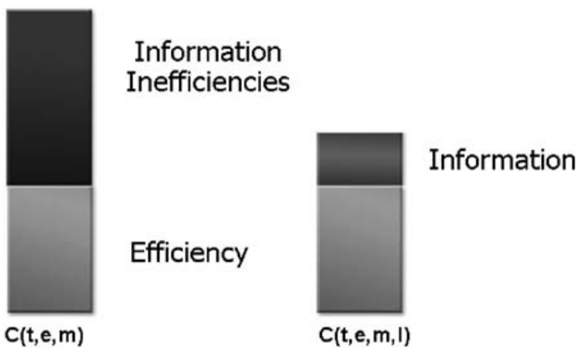

Fig. 1 Information as Time, Energy, Material Substitute

designing the part, the bottom part of the bar represents the minimum amount of resources it would take to create a part that met the functional requirements if one had the ability to evaluate all possible approaches. For the manufacturing and support tasks, the same analysis would apply – evaluating all possible approaches and choosing the one (or ones if there were multiple, equal solutions) that minimized the use time, energy, and material.

The top part of the left bar represents the costs of resources that are used in excess of the minimum. It represents the resources used in designing the part and testing it only to find that it does not quite meet the requirements, necessitating redesign and retesting. It represents rework in manufacturing the part so that two components fit properly together. It represents having to dissemble and reassemble the part in for repair because wiring was not connected in the proper sequence.

The top part of the right bar represents the cost of information that replaces the wasted resources of the task. It is engineering information that predicts that a design will meet specific requirements. It is a manufacturing simulation that produces a process so that rework is not required. It is a step-by-step repair procedure that eliminates the need for disassembly and reassembly.

For purposes of illustration, the cost of information reflected in the right bar is less than the cost of wasted time, energy, and material. For simple tasks, a trial-and-error approach may be less costly than collecting, organizing, and transferring information. However, for complex tasks and repeatable tasks, it is fairly self evident that the relationship of information being less costly than wasting time, energy, and material holds true. Learning or experience curves, "lean" manufacturing (Womack, Jones, et al. 1990), and the Toyota Production System (Liker 2004) are all based on trading information for wasted time, energy, and material.

It is also important to note that this is an idealized representation. For complex tasks, there is no way to know the task method(s) that uses the minimum amount of resources. Information will only be a replacement for some of the wasted time, energy, and material. There still may be some wasted resources.

The lifecycle of a product is made up of a number of tasks. When looking at the trade-off of information for wasted time, energy, and material, the sum of the tradeoffs must be done over the life of the product. If the cost of the resource for a task is given by C(x), with x being Information (I), wasted Time (T_w), wasted Energy (E_w), wasted Material (M_w), then for this substitution of Information to make economical sense, the sum of the information needs to be less than the sum of the wasted time, energy, and material ($C(I) < \Sigma C(T_w, E_w, M_w)$ over all these tasks.

It is also important to note that different views of the product lifecycle will yield different results. If product producers only consider the tasks necessary to create and build the product, their calculation of costs may differ considerably than if costs of supporting and disposing the product are taken into consideration. The trend due to legal and regulatory pressures is for product producers to take a broader view of their responsibility.

4 Back-to-the-Future

Product Lifecycle Management is a new phrase and PLM is a new acronym. However a product-centric view of the four phases of a product's lifecycle, i.e. build, create, support, and dispose, is not a new concept. One of the intrinsic appeals of PLM and a source of confidence in its effectiveness is that the concept has worked in the past. PLM is in fact an old concept that has gained new life due to advances in information technology.

The idea that a product manufacturer concerns itself with the four phases of a product is as old as product manufacturers themselves. The realization that information could be substituted for wasted time, energy, and material would have been known to even the most primitive manufacturers of products. The product producers who did engage in this substitution would have prospered more than those that did not. The resources that these increasingly efficient producers did not waste could go into to more productive efforts.

In addition to this understanding, product producers of the past would have been concerned with the entire lifecycle of their products. Product producers were part of relatively small communities and had long relationships with their products and the users of their products.

By way of example, it is reasonable to assume the manufacturers of chariots were practitioners of PLM. These ancient craftsmen would have designed their chariots with an end purpose in mind: transportation, battles, or races to name some.

The chariot craftsmen would have manufactured the chariots. They hewed the lumber to build the frames, weaved the basketry for the passenger compartment, formed wood into V shapes for wheel spokes and lashed wooden segments with rawhide to form the tires, and beat metal into shape to form the amour.

These same craftsmen would have supported the product when it was in use. They would have fabricated new parts when old parts broke. They might have improved certain aspects of the chariot, such as the placement of amour, after seeing how the chariot performed in battle. They would have changed out parts to make the chariot suitable for new terrain.

It certainly may have been that product producers would have remained very involved in the support of their products. Standards of measurements and the measurement tools required for interchangeable parts were not developed until the mid 1800s. Before then, each product was unique. The individual best capable of supporting the product was the producer of the product.

In the disposal phase, these craftsmen would have attempted to salvage all the parts that could be reused on other chariots. They would have scavenged all the metal parts for either reuse or melting down and repurposing for other armament, such as spear tips. While there is no historical record of used chariot lots, it certainly is not unreasonable to postulate that chariot manufacturers facilitated the transfer of chariots from old (or dead) warriors to young warriors coming of age.

The coming of the Industrial Age and the ability to mass produce diminished the focus and the ability of product producers to concern themselves with the entire lifecycle of a product. As pointed out by Adam Smith (Smith and Jenkins 1948) in his pin factory example, division of labor was a method of reducing the resources required to produce a given quantity of products.

While this division of labor increased productivity due in part to a substitution of information for time, energy, and material, there was a loss in information about the product as a whole. Product information became siloed in functional areas such as engineering or manufacturing. However, as products became more complex to create, build, and support, the requirement to have a product-centric view of product information became more compelling. However, until computer and communications technologies developed sufficiently, it simply was not possible.

5 Information Mirror Model

The ability to return to a product-centric perspective requires the ability to access and manipulate product information as a construct separate from the product itself. As discussed in the introduction, product information is embedded within the physical product itself. While humans have had the capability to extract this information, previous technologies for capturing, manipulating, and transferring this information could only deal with abstracted and limited subsets of this information.

However, in order to maintain the division of labor and distinct functional areas that have allowed for increases in productivity, we need an informational model of the product that is both rich and shareable. The mental model of an individual who would be involved with a product from birth to death no longer suffices. Modern, complex products require many individuals to be involved with the information about a product throughout its life. However, if these individuals are to do so effectively, they need to have all the information of the product available without the requirement of being in proximity to the physical product throughout its life.

In a product-centric approach, the requirements for physical-to-information mapping exist at all phases of the lifecycle, although the direction of the flow of information may differ. In the creation phase, mental designs need to be fully described and tested for feasibility. In the manufacturing phase, the steps that minimize resource usage needed to turn these designs into physical products need to be developed and the actual physical configurations ("as-built") need to be captured. In the support phase, the as-built information needs to available so the product can be maintained to its designed level of functionality ("as-maintained"), ideally before it fails. In the disposal phase, the design intent to provide for safe, recyclable disposal is known and can be carried out.

It is only until recently that computers and communications technologies could deal with the vast amount of data needed for robust representations. Additionally, prior to computers, manipulation of this information in a dynamic fashion could only be done internally in human minds and then only in a limited fashion. The simple rotation in three-dimensional space of a mental model would be considered a feat that only a limited number of people would be capable of performing.

We are reaching a point in time where the technical capability of computers and communications makes possible the rich representations of products. In addition to rendering the geometric shapes with great fidelity in three dimensions, we are developing the capability of simulating physical characteristics of these products with increasingly better and better fidelity and precision. Simulating complex characteristics such as the crash testing of automobiles or showing the flow of air on an entire airplane is now possible.

What will be required to fully realize PLM is a model that represents products and informational constructs. What I have proposed is to "virtualize" physical products and maintain that linkage throughout the life of the product. This virtualized product can then be used to substitute for wasted time, energy, and material. The intent with the virtualized product is to use bits wherever possible in place of atoms. This model was developed to simply describe the connection between products and their associated information. It was first called the Mirror Spaces Model (Grieves 2005). The name was subsequently changed to the Information Mirror Model (Grieves 2006). However, the substance of the model itself remained relatively unchanged, although refinements and clarifications were made.

The model consists of three elements: Real Space, Virtual Space(s), and a linking mechanism, referred to as Data and Information connecting Real Space and Virtual Space(s). As described in Fig. 2, this is a model that uses elements that are embedded into our very way of thinking. However, when used as a model for managing information, it changes some very fundamental ways product data is captured, organized and used. Specifically it "de-silos" product information, such that data is not organized by its function, but by the emergent or instantiated physical object with which it is associated. Doing so brings us "back to the future" in terms of our interaction with product information.

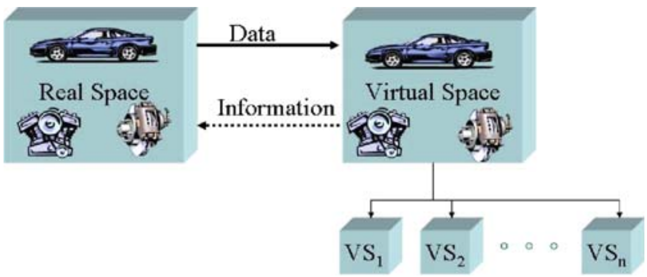

Fig. 2 Information Mirroring Model

5.1 Real Space

As humans living in real space, we are ontologically compelled to think in terms of physical spaces. For real objects, it is obvious that a space-based model is natural. As much as we attempt to conceptualize and abstract the world around us, we are inextricably bound to our view of the world that comes to us via our senses. It is embedded in our very language (Lakoff and Johnson 1980). We experience our world in terms of spaces having physical dimensions that govern our understandings. No amount of abstraction can separate us from our connection to physical space and our perception of that space (Latour 1999).

We constantly think in spatial terms even when the concepts are not spatial concepts, such as up/down, above/below, here/there, and over/under (Lakoff and Johnson 1999). Common examples abound. "I am feeling up today." "The foreman is over the assembly line workers." "My thinking here is..." We think in spatial terms even when thinking about abstract, non-spatial concepts, sometimes unconscious that we are doing this and at other times very deliberately (Grieves 2000).

5.2 Virtual Spaces

As humans, we have been able to create virtual spaces in our minds as far back as there is history. While imperfect and transient, we have the ability to create virtual spaces and control what happens in those spaces. This is the process we know as imagining (Casey 1976). We can build representations of the real world and change these representations either as things change in the real world, or as we postulate things could change.

Drawing in the dirt was probably our first mechanism to share our virtual space. However, langue was and is our main mechanism to share these private virtual spaces. Rearranging atoms (dirt, clay, papyrus, ink and paper) gave both our drawings and writings permanence, albeit in static form and with some forms less permanent than others. The advent of computers allowed for dynamic spaces that could be shared on a local basis by all connected to that particular computer system.

The advent of computers also created a virtual space that possessed independent processing capabilities and therefore could be dynamic. Communications technology allowed this virtual space to be shared by individuals in geographically diverse locations. The Internet took communications to the level of ubiquity where anyone anywhere in the world could access and interact with the shared virtual space.

The constraints or limitations with earlier computer systems were such that their representations of the real world were constrained by the state of computing technology to only a very limited amount of information about real world objects. This necessitated substantial abstraction to only the coarsest characteristics. For example, early computerized information about a part consisted of its part number and limited amount of characteristics such as dimensions, color, weight, etc.

In addition, manipulations were limited by processing power. Even if real world objects could be described sufficiently, the processing power to do anything useful was unavailable. For example, in the 1970s, the mathematical calculations required to rotate even a simple geometric representation required dedicating a multi-million dollar mainframe computer.

Thanks to Moore's law and its corollaries in computer storage and communication bandwidth, these limitations have reached the threshold where computing systems can accommodate a desired functionality with respect both to mirroring the description of complex objects and to manipulating them. Mathematical descriptions of parts' geometries are such that they can directly drive manufacturing machinery to create functional parts without human intervention. In addition, these complex objects can be combined to form even more complex objects with the correct spatial orientations within the context of their use. This was and is a shared space where an object could be created and manipulated. Multiple people could agree on its interpretation because they all see and understand the same thing.

However, it was not until the global diffusion of the Internet that easily shared, universally accessible virtual spaces were made possible. Prior to the Internet and World Wide Web becoming readily accessible, the ability to link multiple individuals into this shared space, especially if separated geographically, was technically challenging and very expensive. Connections to this shared space took planning and dedicated communications resources. The Internet enabled nearly anyone with access to a computer and communication line to access these shared spaces.

Per the IMM, this shared space implies a singularity of information. Unlike real space, it is almost costless to reproduce and manipulate copies of data objects. While a powerful advantage of virtual spaces, multiple copies can also be a source of waste and inefficiency. In engineering design, multiple copies can lead to wasted work being done on old versions of the object. In support, it can lead to multiple copies of the product that reflect different components that can only be resolved by expensive physical inspection.

Where there is a corresponding physical object, the issue of singularity of information is obvious: the virtual space mirrors the physical space. The issue does arise where there is no physical equivalent as in the create phase. In fact, an advantage of PLM is to forego the costs of developing physical prototypes and do as much work in designing and testing digitally and virtually. In this case, the people dealing in the creation phase need to treat their virtual object as if it did have a single, physical equivalent. This representation has been called the "controlling" virtual object (Grieves 2006, p. 78). Failure to observe this convention can easily result in incompatible work being done on different versions of what should be the same virtual object. The result is wasted resources in diagnosing the situation and substantial recovery and rework.

Where real space has only a single, unique existence, virtual spaces can be duplicated. As indicated in Fig. 2, these subspaces ($VS_1 \ldots VS_n$) can be used recreate the shared virtual space in order perform individual work on products. Different configurations and simulations of those configurations can be performed in these private subspaces without affecting the shared space.

While a subspace may be identical to the shared space, any activity taking place is independent of the shared space. The results of any work done in these subspaces can be moved to shared space and become a controlling virtual object only under the conditions specified by the owner of the shared virtual space.

The simulations afforded by these subspaces allow for much more experimenting and testing than can be done in real space. As computers become more powerful, more testing will be done via virtual subspaces. While physical testing, such as crash testing, will continue to take place, it will be done not as testing but as validation of the virtual tests that have taken place in virtual space.

5.3 Linking Mechanisms

Once virtual spaces are able to be built, accessed, and manipulated, the key to IMM and consequently to PLM is the ability to link the virtual space to its real space or physical counterpart. This is what will allow PLM to have real utility. It is the ability to access the virtual representation of an item and know that it substantially mirrors the state of the real world object.

To make full use of virtual spaces, linking mechanisms are required in both directions. Data must be collected and transmitted from real space to virtual space where it is organized into information. That information must be accessible and available in real space. In both cases, this currently is a human-intensive activity. With the exception of process control systems, the interface between the real and virtual spaces has primarily been humans coding and entering data and requesting information via tactile devices, such as keyboards, touch screens, mice, graphical tablets, etc.

This means that the create phase has advanced and will continue to advance rapidly. The creation of a physical product requires that the designer first create a virtual product. The technologies that exist, while not of "Minority Report" science fiction quality, do a sufficient job of capturing designs originating in real space and will continue to improve. Displaying those designs back to the designers and their colleagues in full scale (Power Walls) and in 3-D statically and even dynamically (caves and interactive caves) also exist and are advancing. Creating physical objects directly from this information via various technologies such as stereolithography and laser/powder metal forming is feasible and advancing.

In the manufacturing phase, capturing the data on the creation of physical products ("as-builts") and building mirrored virtual products is occurring slowly. The three components required to do this are: a) physical measurement and capture equipment such as Coordinate Measuring Machines (CMM's) and sensor equipped machinery; b) data collection and consolidation software; c) Manufacturing Execution Systems (MES) to organize and store the virtual product. As manufacturers become aware of the ability to use this information for such purposes as virtual quality control, the capabilities and technologies will advance more rapidly.

The support phase is still in its infancy. Product manufacturers are becoming increasingly aware of the need to instrument their products and use that data to remain linked to the product after the product has left the factory door. As manufacturers recognize that this creates new revenue opportunities and as instrumentation and associated communication technology advances, this area will grow rapidly.

The disposal phase has been ignored for the most part. However, the ability to dispose and recycle appropriately requires that the virtual product with its information about how it was designed to be recycled and disposed be available. It is only a matter of time until regulatory and legal pressures make this a priority.

For IMM to reach its full potential, the linkage between the object in virtual space and its counterpart will have to be robust, accurate, and timely. This area of linkage is where substantial investments and advancements in technology are currently taking place. On the data collection side, the advancements are occurring in areas such as RFID, mechatronics, sensors, and video recognition. On the information presentation side, advancement areas include search engines, virtual reality technologies (e.g. VR goggles, caves, holographic and haptic equipment, etc.). For both areas, wireless communications technologies are a key enabler.

6 Summary

Product Lifecycle Management as a term and PLM as an acronym are 21st century constructs. PLM is a product-centric perspective of the information about a product throughout the four phases of its life: create, build, support, and dispose. The premise underlying PLM is that less expensive information can replace more expensive wasted time, energy, and material.

The intrinsic appeal of PLM is that, although new in its current construction, it is a back-to-the-future approach to product information. When products were simpler and localized, information about the product could reside in mental models of the individuals who created, built, supported, and disposed of the products. These individuals could use the information they had about the products to replace wasted time, energy, and material. As products became more complex, more voluminous, and less localized, these mental models were incapable of maintaining the information required. Division of labor was the method needed to efficiently support such a change in product production. However, this meant information became siloed and a product-centric perspective was lost.

It required the capabilities of the modern computers with their current capacities in computing capability, data storage, and communications bandwidth to return to a product-centric model. The requirements to fully "virtualize" products and maintain information throughout the life of the product required 21st century technology.

The model presented here, the Information Mirror Model (IMM), is an ideal representation of what a virtualized product will entail. The ability to maintain a virtual product that reflects the state of the real product and vice-versa will allow individuals to trade this virtual information for physical resources, namely time, energy, and material. While this is an idealized model, the trend of applications in the PLM area is supporting the direction of this model.

While PLM is a back-to-the-future concept, the technologies of today are qualitatively incomparable with what the chariot producers of eons ago had at their disposable, namely their mental models and minimal drawings. Correspondingly the potential trade-off of PLM information for wasted time, energy, and material is also incomparable with greater savings as the technologies enabling the Information Mirroring Model continue on their improvement trajectories.

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Measuring the Impact of Product Lifecycle Management: Process Plan, Waste Reduction and Innovations Conceptual Frameworks, and Logic Model for Developing Metrics

Cynthia Tomovic, Abram Walton, Lisa Ncube, Michael Grieves, Ben Birtles, and Brandon Bednar

Abstract Companies implement Product Lifecycle Management (PLM) as a means to reduce costs associated with wasted time, energy, and material with the expectation that captured resources can be reallocated to product and process improvements and innovations, potentially resulting in new revenue streams. As organizations prepare to implement PLM, it is critical that they understand their expectations of PLM and that they track the impact of PLM relative to achieving their organizational goals. A PLM Process Plan, PLM Waste Reduction and Innovation Conceptual Frameworks, and PLM Logic Model for Developing Metrics are suggested as a guide to organizations tasked with determining the impact of their PLM initiative.

Keywords Product lifecycle management · Performance measurement · Metrics

1 Introduction

Product Lifecycle Management (PLM) is a holistic business strategy built on lean-thinking principles. Whereas lean-thinking focuses on reducing organizational wastes associated with time, energy, and materials, PLM focuses on capturing wasted resources and reallocating them in support of product and process improvements and innovations, potentially resulting in new revenue streams. While numerous studies have been conducted on measuring an organization's level of waste reduction, literature on how to accurately measure the revenue generation capacity associated with PLM is relatively new (Grieves 2006; Stark 2004; UGS 2007; Symmonds 2005).

The vision of PLM is to transform the way companies manage the product lifecycle phases including initial ideation, concept design, product design, manufacturing design, production, and delivery to the customer, in-service support,

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and retirement from use (Miller 2005). Today more than ever before, if companies are to sustain a competitive advantage, they must exploit their innovative capabilities or develop such capabilities to address the disruptive effects of emerging technologies, customization demands, new market entrants, shorter product life cycles, geopolitical instability, and market globalization (Muller et al. 2005).

As PLM transforms the way companies do business, it is important that companies understand how well they are doing, that is, whether or not PLM is making a difference in their operations and to their bottom line. In recent years there has been a major change in how business performance is measured. While traditional performance measures include net income, operating income, revenue, and while these measures will always be relevant and important in determining profitability and successes of an organization, the role played by project theory in developing, operating and evaluating projects is being recognized (Barchan 1999).

Projects in general, but PLM projects in particular, tend to be complex projects consisting of many different interlocking components. The failure to pay attention to all phases of product lifecycle, particularly the end of the lifecycle when sales dip and administrative costs soar, can result in a negative impact on business performance (Marien 2006).

After having invested millions of dollars in technological infrastructure, training and support, senior level executives are anxious to see reliable data supporting their investments in PLM. Moreover, without knowing the bottom line impact of PLM on cost-savings and revenue-generation, executives are unable to accurately estimate the level of risk associated with future PLM investments. The primary focus of this chapter is to suggest a PLM Process Plan, PLM Waste Reduction and Innovation Conceptual Frameworks, and a PLM Logic Model for Developing Metrics to guide organizations as they define the process and the metrics used to measure how effectively they are 'PLMing'.

2 PLM Process Plan

Businesses need to develop and follow a PLM Process Plan (Fig. 1). For every company, there must be clear and compelling reasons to engage in PLM. It is critical that companies consult their own strategic plan and question how PLM can help them achieve their particular goals. In essence, businesses should first conduct a benefits appraisal. By focusing on the goals and potential benefits, companies will less likely focus on technology alone and instead come to see PLM as a total system involving people, processes/practices, and technology. Even in the early stages of considering PLM, it is important that companies begin to think about what metrics to embrace; so that they can later measure actual benefits achieved from the PLM related solutions deployed (CIMdata 2002). Once having consulted the strategic plan and determined on which goals

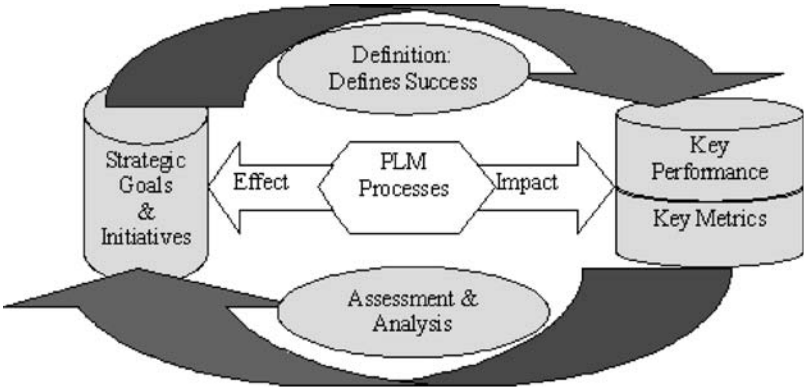

Fig. 1 PLM Process Plan

to focus, and once defined appropriate metrics, including baselines and targets for each metric, the next step is to define the methodology to collect the data. Finally, procedures should be defined as to how data should be fed back into the system to ensure that the PLM solution is delivering expected benefits, thus, contributing to the cycle of continuous improvements as it relates to the PLM initiative (Deming 1993).

3 PLM Basics – Capturing Wastes and Reallocating for Innovations

Literature suggests (Grieves 2006; CIMdata 2002) that approximately eighty percent of the overall cost of a product is based in engineering. Consequently, most executives focus their PLM efforts on the plan/design, and manufacturing phases of PLM. While these efforts do not represent the entire cycle of PLM, those who are successful in their implementation of these PLM components are being heavily rewarded with increased market share, profit margins, brand recognition and the like. Nonetheless, in order to continue their support and investment in PLM, executives are asked to justify expenses associated with PLM and its potential. Alternatively, as is often the case, executives make the case that without PLM, they stand to go out of business. In either case, once the decision to invest in PLM is made, executives struggle with how to effectively and successfully orchestrate such a large corporate-wide initiative, and how to demonstrate its impact.

One of the most news-worthy examples of the success and pitfalls of PLM involves the number one and number two airplane manufacturers in the world. Boeing and Airbus each embarked on their own multi-billion dollar venture, to revolutionize air travel. Boeing, with its Dreamliner and major improvement in operating efficiency and ultimate passenger experience, and Airbus with its A380 and unprecedented passenger capacity loads, were in a first to market race, and each had hopes of capturing the other's market share. Due to version control issues, Airbus ended up billions of dollars and years behind their target (Duvall and Bartholomew 2007). Boeing, on the other hand, escaped this pitfall by having maintained tighter version control.

As many other engineering and manufacturing based companies are learning to traverse the world of PLM implementation, they are finding that there are vast opportunities for PLM initiatives. With American companies facing issues such as global warming, rising fuel costs, and increased global competition, pioneering companies are finding innovative ways to address and capitalize on these new challenges. Engineers from around the globe who pool their information to design better products are engaged in 'follow-the-sun' strategies, e.g. finding innovative ways to reduce vehicle emissions, reduce vehicle weights, increase gas mileage, all while increasing brand recognition and passenger safety (Kriz 2007).

Since implementing PLM, GM has saved thousands of hours and reallocated their savings to improving product safety. Today, GM will simulate 175 crash tests for every 1 full-vehicle crash test (Brown 2007). Not only are companies simulating more prototypes and tests, but the simulations are vastly more complicated than those prior to PLM technologies. Simulated computer models could solve 1,000 equations simultaneously, prior to PLM, while today they can solve over 30 million equations (Brown 2007). This level of complexity allows engineers to analyze crash results in frames of 100th of a second.

These types of innovations coupled with a corporation's willingness to invest in PLM and undertake the more challenging opportunities are proving to be lucrative and environmentally friendly. In an effort to reduce their impact on global warming by decreasing new vehicle emissions, Toyota and BMW designed cars with fewer emissions which received the attention of many new customers and improved their market share. John DeCicco suggests that efforts such as these are "a clear example of innovative designs paying off for the bottom line and the environment" (Thomas 2007, p. 1).

3.1 PLM Waste Reduction Conceptual Framework

PLM users require product knowledge at each particular product phase and access to product information throughout the entire product lifecycle. Sections 3.1.1 through 3.1.3 describes the PLM elements (Grieves 2006) on which the proposed PLM Waste Reduction Conceptual Framework is based (Fig. 2).

Waste Reduction Components	**PLM Elements**		
	People	Process Practices	Technology
Time			
Energy			
Materials			

Fig. 2 PLM waste reduction conceptual framework

3.1.1 People

A commitment to supporting people by educating them is essential to effective information flow. As with any change implemented at the organizational level, willingness to guide people through the transitional period can mean the difference between success and failure (Bridges 2003). With significant resources already invested in a technological infrastructure it would be foolish not to help employees change their current paradigm with regard to both how to access and how to communicate within a system of information.

Within a traditional organization, established lines of communication seldom follow a product or service through the product lifecycle. Departments tend to act independently of one another, handing off a completed module at the end of a department's value-adding process. Establishing clear lines of communication between departments and facilitating real time communications clearly affects peoples' behavior and will necessitate a change if increases in productivity are to be realized.

Supporting a culture where information is shared instead of being guarded during a product's lifecycle is paramount to PLM success (Bridges 2003). An organization can capitalize on identifying potential errors when they exist in virtual space instead of scraping products due to errors at the manufacturing phase. Recognizing errors earlier in the process requires employees to develop a greater sense of trust. It also requires that each department be involved in the entire lifecycle of a product.

Ways in which to think about the potential impact of PLM on waste reduction with regard to time, energy, and materials across people might include: time – *time to complete product cycle*; expect a reduction in product cycle time as upstream changes can be communicated immediately to persons downstream such that changes can be accommodated without delay; energy – *energy used to support meetings*; expect a reduction in energy required to support people in face to face meetings as they begin to work in virtual space; materials – *number of times raw material is delivered correctly to each person in the manufacturing process,* expect an increase in the number of correct times raw materials are correctly distributed to each person in the manufacturing process as the pull-system can be simulated and adjusted based on actual sales figures versus historical data.

3.1.2 Processes and Practices

A focus on processes and information flow must be established in tandem with the creation of an information system if PLM is going to be successfully implemented. Best practices often are created through the natural norming practices of organizations. Prior to the advent of PLM, communication between departments may or may not have been codified. Upon review and standardization, such communication practices may be defined as acceptable processes.

A simple yet useful distinction between processes and practices are that processes are input and routine driven, while practices are output or results driven. With processes, the output or result is the results of applying the specified routines or processes to the defined inputs. With practices, the desired result or output is attempted to be obtained by selecting inputs and routines from the universe of all possible inputs and routines.

The information requirements for processes and practices differ considerably. With processes, the information needed is only that input that is called for by the routines or processes. With practices, all information that is relevant, and maybe even information that appears irrelevant, needs to be made available so that the practitioner can explore as many potential situations as possible to yield the desired results.

With the advent of a PLM system, members can work together in real time on digital models. A change in design can be immediately communicated to engineering, who in turn can adjust component requirements, which is communicated to purchasing and budgeting. Since these changes are happening concurrently, the representative of each department can focus on their tasks as they relate to the entire product. Due to the transparency of the PLM process, employees will be less likely to inadvertently duplicate one another's work (CIMdata 2003a, b).

Accessibility to internet databases becomes more important as virtual design and testing become a part of accepted business practices. With an adequate computing system and access to the internet, team members no longer need to be in close physical proximity (Friedman 2006). The ability to collaborate from a distance reduces costs in gathering a product team in one location and allows organizational leaders more flexibility when making decisions involving staffing and team composition (CIMdata 2006).

Ways in which to think about the potential impact of PLM on waste reduction with regard to time, energy, and materials across processes/practices might include: time – *number of times designs are reused*, expect a reduction in time as engineers build and store a digital catalogue of parts which may be reused in future product designs; energy – *amount of energy required to sustain a manufacturing line*, expect a reduction in energy used to run a manufacturing line as alternative subassembly arrangements may be virtually created and consulted with regard to energy use in advance of building the actual manufacturing process; materials– *amount of inventory*, expect a reduction in inventory as the sharing of information in an information core should better support the timing of purchasing decisions.

3.1.3 Technology

A solid technological infrastructure must be in place to support the demands of a meta-database that can provide real time access to information by all members of a project team. With the emergence of information technology, such as the Internet and high-speed fiber-optic data transfer, organizations have been able to share ideas, transfer designs, and stimulate collaboration among departments with increasing ease. Limitations such as geographic proximity to other team members have become much smaller barriers now that data can be shared in virtual space (Friedman 2006). By substituting data bits for physical objects, huge reductions in time and resources can be realized.

A lifelike rendering of the product must be presented to members of various departments if they wish to virtually manipulate product capabilities. To do this, programs such as CAD/CAM have been created. CAD/CAM and similar programs greatly enhance the effectiveness of engineers and allow organizations to inexpensively move their planning and design functions to geographical regions that offer comparatively inexpensive technical designers and data analysts (CIMdata 2003a, b; Engardio 2007).

One of the areas most able to benefit from this new technology is destructive product testing (Grieves 2006). If a product must be destroyed to test its static or dynamic load limits, significant costs will be incurred during the design and testing phase. Destructive testing costs limit the amount of testing that can be conducted. If a digital model can be tested, prior to physical testing, then many of the incompatibilities of early designs can be resolved. Furthermore, if a digital model can be housed in virtual space, where members of each product lifecycle phase have access to it, an additional savings in time can be achieved as the team members are able to work concurrently, instead of consecutively (Gould 2003).

In the last two decades, better information systems have allowed the automotive business to grow in the billions of dollars (IBM 2004). More efficient information systems have resulted in a reduction of wasted time, energy, and material and allows for the sharing of increased product-based information. According to one study, engineers and designers find information about ninety percent faster in digital environments than in non-digital environments (IBM 2004).

Ways in which to think about the potential impact of PLM on waste reduction with regard to time, energy, and materials across technology might include: time – *time to locate information,* expect a reduction in time to locate information as it would take less time to access data in an information core than in potentially multiple personal hard copy or electronic files; energy – *amount of energy spent in distribution of parts to subassemblies*, expect a reduction in energy due to better factory layout designs than by physical trial and error; and materials– *amount of scrap used in testing*, expect a reduction in scrap due to increased use of virtual testing versus physical testing.

3.2 PLM Innovations Conceptual Framework

Assuming wasted resources (time, energy, and materials) are captured; the opportunity to reallocate these resources to innovation is available. In essence, resources can be reallocated in support of product quality improvement and/or

Innovation Components	PLM Elements	
	Product	Process
Functionality		
Quality		

Fig. 3 PLM Innovations conceptual framework

increases in product functionality, and/or improvements in processes. Thus, the benefits of PLM are not only in waste reduction, but opportunities to potentially generate new revenue streams present themselves as a function of product and process improvements (Fig. 3).

3.3 PLM Data – Characteristics

The current body of scholarly literature focuses on PLM as an approach to control information flow and access to this information in support of the product lifecycle, e.g., plan/design, build, support, and dispose (Fig. 4).

Before operationalizing the proposed conceptual frameworks above, it is important to review the underlying characteristics that are an integral part of PLM, namely, the singularity, correspondence, cohesion, traceability, reflectivity, and cued availability of the data in each phase (Grieves 2006). If these characteristics are not intact, data in the information core will be compromised, and the PLM initiative will likely fail. PLM can only work effectively if the data in the information core reflects reality, and that that reality, at all times, is recorded or reflected in the data of the information core. In this

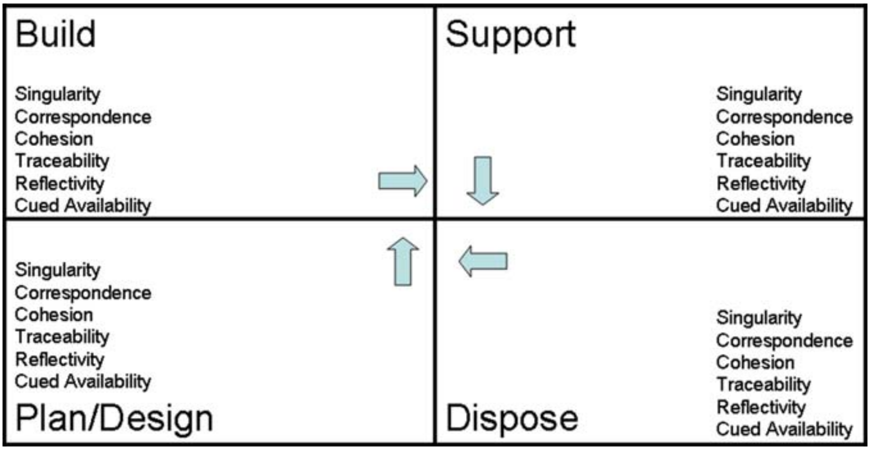

Fig. 4 Product lifecycle

manner, there should be a one to one correspondence between the data that describes and is stored about a particular product and the physical reality of that product.

- **Singularity** – Much like in version or document control, singularity refers to the identification and agreement on which version of the product information everyone is working. The issue of controlled versions is critical. In the case when a product is tangible, data about that product can be readily assessed, verified, and documented. However, in the case of a virtual product, there has to be system by which changes from one version of a product file to the next version can be tracked and catalogued. In this manner, the cataloguing feature of an information core helps to prevent the potential for wasted time, e.g., the time individuals erroneously spend on working off an older version of a product data file.
- **Correspondence** – Refers to the linkage between a physical object and the data that describes that object. If one begins with a tangible product, correspondence is largely an exercise in data extraction, e.g., developing the methodology and technology that allows the physical features of a product to be coded, catalogued, and digitally shared. Even in the case of a virtual product, the data that is extracted about the virtual product should permit the complete physical build-out of that virtual product. The concept of start or smart parts is dependent upon a one to one correspondence between the virtual product and its component parts in the physical world. Because engineers can fully understand the constitution of a product and its parts, be it virtual or physical, they can choose to start with a pre-existing part that will serve their purposes, versus wasting the time and energy required to design and create a redundant new part.
- **Cohesion** – Refers to the ability to reconcile different representations of a product and its parts, depending on the perspective, e.g., mechanical, electrical, three-dimensional, etc. The concern here is not with just the representation of the product and its parts, but the potential impact a change in one perspective may have on another, e.g., the impact of a change in the electrical perspective on the mechanical perspective. Given the new generation of software development, changes in one perspective may automatically create changes in the remaining perspectives, thereby potentially reducing time and energy wasted. Time required to reconcile multiple versions of a bill of materials (BOM) may soon be a thing of the past.
- **Traceability** – Refers to the ability to follow the developmental path of a product over time due to it having been documented. Digitized data over time allows one to run and re-run tests over multiple virtual products, from which multiple analyses can be conducted. Start and smart parts, for example, would have already been tested and the results of their tests would be traceable. In this manner, time, energy and materials can be saved. Additionally, given the increases in lawsuits, product liability cases, and claims of violations of governmental regulations, traceability is important in a company's defense.

- **Reflectivity** – Is the ideal that changes in physical products or parts are captured, without any or with little lag, in virtual counter-part products. Because of reflectivity, information can be substituted for what would have been otherwise wasted time, energy, and material. Capturing "as-built" information and updating this information through out the life of a product is one of the benefits of PLM.
- **Cued Availability** – Is simply being able to have the right information at the right time. An added benefit of this feature is that usable information may be made available as a function of the search engine. This feature is expected to improve in the future as relational search technologies mature.

4 PLM Logic Model

A clear understanding of a project's conceptual framework can contribute to the successful performance of many important developmental and evaluative tasks along its life span (Savaya and Waysman 2005). A structured approach that analyzes a product at all stages of the lifecycle for maximum effectiveness and efficiency is therefore essential. The project logic model assists in describing and articulating the project theory by guiding and structuring the process (Savaya and Waysman 2005). A logic model is a diagrammatic representation of the logical or causal relationships among project elements and the problem to be solved, thus defining measurements of success (W.K. Kellogg Foundation 1998). A logic model illustrates the logic or theory of the program or project while focusing attention on the most important connections between actions and results. Furthermore, the project logic model helps to build a common understanding among staff and with stakeholders which is essential for the successful implementation of PLM. Another important characteristic of logic models is that it helps project personnel "manage for results" and informs project managers of "gaps" in the logic of a program and focuses attention on the need to resolve them (Nakabayashi 2000, Bell 1998).

4.1 Developing PLM Metrics Based on a Logic Model

The model (Fig. 5) combines two views on innovation. It provides the perspective for a suite of potential metrics that help assess and develop a company's capacity for PLM (Muller et al. 2005).

The various components of the model include:

- **Inputs/resources** – addresses the allocation of resources to effect the balance optimization (tactical investment in the existing business) and innovation (strategic investment in new businesses) (Simmons 2000). The resource inputs include capital, labor, and time.

How of PLM Program				*Results from Program*			
Resources/ Inputs *(What we invest)*	**Activities /Processes** (*What we do*)	**Outputs**	**Customers** *(Who we reach)*	**Short-term outcome/ Objectives** *(Change in: knowledge, skills, attitudes, motivation, awareness)*	**Medium-term outcomes/ Objectives** *(Change in: behaviors, practices, policies, procedures)*	**Long-term outcomes** *(Change in situation: environment, social, economic, political conditions)*	**Impact**
Time	Initial ideation	Ideas & Concepts	Design Collaboration Team	Design reuse	Generation of new business	Waste reduction Innovation/ New Products Continuous Improvement Sustainable Green manufacturing	RETURN ON INVESTMENT
	Concept design	Design Capture & Accessibility	Engineers/ Designers	Virtualization	Improved corporate communication		
	Product design	Change Control & Change Capacity Configuration Management Metrics Commercial Cost of Risk	Engineers/ Designers	Faster time to production	Software integration		
Energy	Manufacturing design	Product Development & prototype	Suppliers/ vendors	Cost reduction	Globalization		
	Production	Resource Optimization Product Quality	Engineers, Manufacturers	Cost performance Larger market share	Product quality		
	Delivery to the customer	Completion Performance	Wholesalers/ merchants/ vendors/ retailers	Premium pricing Increased profitability	Improved business cycle time Customer satisfaction Error reduction		
	In-service support	Portfolio Management	Customers	More efficient service to customers	Service quality Knowledge/ document management		
Materials	Retirement from use.	Portfolio Management	Government Agencies: EPA	Environmentally friendly product disposal mechanisms	Sustainability		
EXTERNAL FACTORS INFLUENCING PERFOMCENCE (+/-)							

Fig. 5 PLM logic model for developing metrics (examples provided)

- **Process** – assesses the extent to which a company's competencies, culture, and conditions support the conversion of innovation resources into opportunities for business renewal (Harbour 1997).
- **Outputs** – are the product or service delivery/implementation targets for PLM. These include:
  - *Completion Performance*–visibility of how well teams are doing in terms of conformance to stage gates and specific milestones and delivery points
  - *Resource Optimization* – reporting team efficiency and productivity, capturing and reporting resource usage around key processes, productivity indicators, resource planning and profiling for "follow the sun" global operations
  - *Change Control and Change Capacity* – visibility of the impact of changes in terms of direct and indirect costs, reporting on frequency and scope of change transactions, volumes of changes, speed to completion, e.g., of the Engineering Change Order (ECO) cycle
  - *Configuration Management Metrics* – the "single record" capability of the PLM system to report changes to the various baselines
  - *Project or Product Quality* – capture and reporting of re-work and scrapping levels, identification of compliance levels and "right first time" outcomes.
  - *Product Development and Portfolio Management* – Linking in sales yield and estimates of re-use value to determine which products bring the best returns

  - *Commercial Cost of Risk* – Project slippage, additional resourcing, and commercial penalties, among others (PTC 2004)

- **Customers** – refer to the users of the products/services (Harbour 1997). The target audience the PLM project is designed to reach.
- **Outcomes** – are the changes and/or benefits resulting from PLM activities and outputs (Simmons 2000). The short-term outcomes refer to the changes in learning in terms of knowledge, skills, and attitudes that have come about as a result of the implementation of the PLM project. Intermediate outcomes refer to the changes in behavior, practices, or decisions, which are a result of PLM. Long-term outcomes are the changes in conditions which include such results as waste reduction, innovation and new products, continuous improvement and sustainable green manufacturing.
- **Impact** – is the return on investment in strategic innovation of the PLM project.

Every project has factors that are outside of the control (positive or negative) of the company that may influence the outcome and impact of its program/project and these factors are referred to as the External Influences. External influences include the economic climate, the global market, and government regulations among others (McLaughlin and Jordan 1999).

The difference between accurately measuring whether or not success has been achieved is crucial in the decision making process. Metrics for the input assess whether or not adequate and appropriate resources have been allocated to the PLM project. Process metrics on the other hand, focus on whether the PLM activities are being conducted appropriately. These metrics focus on quality issues (Harbour 1997). The efficiency and effectiveness, which are the most critical measures, apply to the outputs and outcomes. Output measures determine the extent to which the manufactured products and services are meeting customer requirements and needs. Outcome metrics measure the effectiveness and impact of the PLM project on meeting organizational goals. These metrics focus on the extent to which the PLM project has met its originally stated objectives waste reduction, innovation, and sustainable manufacturing.

5 Summary

The goal of this chapter is to provide a PLM Process Plan, PLM Waste Reduction and Innovations Conceptual Frameworks, and a PLM Logic Model for Developing Metrics for organizations interested in assessing how well they are “PLMing”. As previously discussed, many organizations have yet to implement PLM fully as the question of return on investments remains elusive. As a normal course of business, executives must justify their current and future PLM investments as a function of organizational performance. Since 2001, a number of businesses have launched a PLM initiative based on the understanding that if successfully implemented, PLM leads to enterprise efficiencies and opportunities. However, industry reports that benefits of PLM are difficult to assess as the same benefit can be expressed as a function of time, cost, or quality; and often times, the benefits overlap (Stark 2004). While important, defining metrics that accurately measure the impact of PLM is no easy task.

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Reliability-Based Collaborative Design Platform for Hydraulic Actuation System

Shaoping Wang, Hao Wang, Fang Wang, and Jian Shi

Abstract This paper presents a reliability-based collaborative design platform (RCDP) for hydraulic actuation system wherein the reliability design and reliability analysis are implemented in whole design process. The central idea of RCDP is to decentralize the complex system into several subsystems, in which the propagation of designed parameters as well as shared parameters are considered throughout the multilevel hierarchy and the integrated optimization can be achieved with distributed optimization. Since system parameters are not necessarily deterministic, the probabilistic design is exploited to guarantee the system performance both in structural strength and reliability in lower level of product design. Upload the local designed parameters that are related to upper level, we can solve the bi-level optimal design problem through establishing the appropriate objective function and constraint. Taking full advantage of inherent interface of commercial design software or developed medial file, RCDP can exchange information, access public data and verify the design variables dynamically within different disciplines so as to achieve the performance-based optimization with reliability constraint. RCDP has clear advantages compared with other single discipline design method, i.e. high interoperability, rapid developing process, well performance verification and enough product uncertainty design. On the basis of several common commercial software, e.g. material, mechanical, dynamics, control, hydraulic and reliability, RCDP provides suitable design flow that can join the multidisciplinary design method and reliability analysis synthetically to satisfy the interdisciplinary requirement. Application of hydraulic actuation system design indicates that the reliability-based collaborative design can give suitable room to accommodate the conflict and coupling among different individual discipline design in time that can save the design time, decrease the loss due to improper design and achieve the design optimization.

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1 Introduction

With the increasing of the demand for the high reliability and safety, more and more engineering designers think much of reliability-based design and multidisciplinary design optimization (MDO) when they develop a complex system. However, direct integration of reliability-based design and MDO may present tremendous implementation and numerical difficulties (Agarwal et al. 2003). How to design a complex product with integrated optimization in design process considering the reliability is an important problem demanding urgent solution. Especially to the complex control system, its performance is related to the structure, dynamics, frequency width, power matching and reliability whose integrated performance depends on several disciplines such as mechanics, kinematics, dynamics, cybernetics and reliability, so reliability-based MDO facilitates considering the multidisciplinary design to achieve the integrated performance optimization. Whereas the traditional design of control system always concerns some disciplines while ignores others, it may lead to design conflict among different disciplines. For example, traditional engineering design of aircraft actuation system is carried out on static parameters (cylinder geometric size, servo valve and hydraulic power selection) and dynamic performance (frequency width, amplifier coefficient and control parameters), but it seldom considers its weight, cost and reliability. If the initial designed parameters can not meet the requirement of other disciplines, the compensating redesign process likely results in waste of resources and extension of the design cycle, and frequently pushes to the limits of design constraint boundaries, leaving little or no room to accommodate uncertainties in system design. So the field of MDO has seen rapid advancement from uni-discipline design (Xiaoping et al. 2008) in mission definition stage, conceptual design phase and preliminary design phase that can aid system engineers to identify interactions among different disciplines and improve integrated performance of comprehensive product. MDO allows designers to incorporate all relevant disciplines simultaneously since it can exploit the interactions between the disciplines (Michael et al. 2004). Practically, it is really difficult to realize multidisciplinary optimization for comprehensive product design because participating disciplines are intrinsically linked to one another. Furthermore, such an integrated implementation is also subjected to complexities introduced as a result of a large number of design variables and constraints.

Several approaches for MDO have been developed during the 1990's, all of which had as an objective the coordination of the interacting disciplines during the design optimization process (Bennet et al. 1997). At the same time, the increasing concentration on economic factors and the attributes known as the "ilities" make it possible to achieve optimization in performance, manufacturability, reliability and maintainability. So the innovative MDO framework and software are mushrooming. In 1990 s, Dr.Mark B. Tischler developed a MDO software-CONDUIT (Control Designers United Interface) in NASA, and applied it into UH-60 helicopter and X-29 aircraft (Andersson et al. 1998). Dr. Eric Hallberg, affiliated with American navy graduate school, developed RFTPS (Rapid Flight Test Prototyping System) to realize the multidisciplinary simulation (Hallberg et al. 1999). The latest MDO framework emphasizes on automation, optimization and integration of design process, which is widely used in engineering application such as aircraft, launch vehicle and generator (Takahashi et al. 2005). In 2002, Jean Yues Trepanier and Abdulsalam Alzubbi developed a MDO framework VADOR that compose of graphic interface, data server, implementation server and data management system to realize the interdisciplinary design (Abdulsalam et al. 2000). Subsequently, Weiming Shen presented MDO environment-WebBlow, which adopted Web interface, agent computational resources and data management based on HML (Shen et al. 2002). It is reported that MDO can improve product quality, decrease cost and shorten the design period to 1/5 the original.

Since system parameters are not necessarily deterministic, the system parameters (e.g. material properties, boundary conditions, loads etc.) should be stated probabilistically (Robert and Mark 2000), this class of problems is called reliability-based multidisciplinary optimization. Reliability design method used to calculate the failure probability or reliability of current point (only a design point), and reliability-based optimized design method is not only to identify the nature of the design results largest, smallest or more goals, but also to meet the constraint conditions when it comes to the minimum reliability (or maximum failure rate).Therefore, in order to create a problem of the reliability-based optimization design, the general characterization of optimal design will require some changes, such as adding some random variables, and change the qualitative constraint to be random reliability constraint. R. Sues's reliability-based multidisciplinary design optimization randomizes the system parameters, such as material performance, boundary condition and load, and optimize them with integrate MDO method under uncertain factors (Sues and Cesare 2000). Xiaoping Du presents concurrent sub-space uncertain analysis method to design a system with Monte Carlo method (Du and Chen 2005). Dr. Harish Agarwal utilized response surface to realize the multidisciplinary design optimization (Harish and John 2004). D. Padmanabhan did some research work on reliability-based optimization with approximate technique (Padmanabhan 2003). Although the existing reliability-based MDO methods aforementioned are effective in system multidisciplinary design, they pay more attention to the component designed parameters whereas the system performance is seldom taken into account.

Hydraulic actuation system is an important element of aircraft whose performance and reliability influence its flight character and track capability directly. How to design an optimal hydraulic actuation system becomes bottleneck of flight control system when redundancy and fault-tolerance are adopted in system design. This paper presents a reliability-based collaborative design platform (RCDP) based on product database for hydraulic actuation system whose trait is to carry out reliability design, allocation and analysis traversing all the design process. In addition, the hierarchical decomposed multilevel optimization strategies are utilized to achieve the more robust design including multiple disciplines simultaneously and decrease the large computational effort. An effective component database, engineering knowledge library and product data management (PDM) are provided for designers to be interactive and access them conveniently.

Based on actual commercial uni-discipline software, such as mechanical design software Pro/E, reliability analysis software Relex, dynamic simulation software ADAMS, hydraulic system analysis software AMESim, finite element analysis software ANSYS and control software Matlab, RCDP makes full use of various disciplines design and analysis tools to get more reliable design results under graphical user interface, independent drive engine, methods of rapidly integrated legacy and suitable computing environment. Herein, the knowledge and information of various disciplines should be managed properly so as to achieve the entire optimization in product life cycle design.

The outline of the paper is as follows. Section 2 introduces the idea and design flow of RCDP, in which the probabilistic design, interactive interface, multilevel optimization, data management and realization of RCDP are discussed. Section 3 provides the application of hydraulic actuation system that indicates the effectiveness of RCDP. We present discussions and conclusions in Section 4.

2 Reliability-based Collaborative Design Platform

An overview of the reliability-based collaborative design platform is shown in Fig. 1 wherein reliability oriented and performance-based are considered synchronously based on related commercial software–called RCDP. RCDP was designed to facilitate rapid development of complex hydraulic servo system considering reliability and achieve integrated performance optimization.

Generally, users should be up on the design specification and requirement when they start to design a product that depends on several condition and constraint. RCDP provides some standard scheme in engineering knowledge library; designers can select them to obtain their preliminary design. If the preliminary design parameters pass the back-check in other disciplines including reliability, we can get the final system design and generate prototype to verify its performance. Once the all performance meet the design specification,

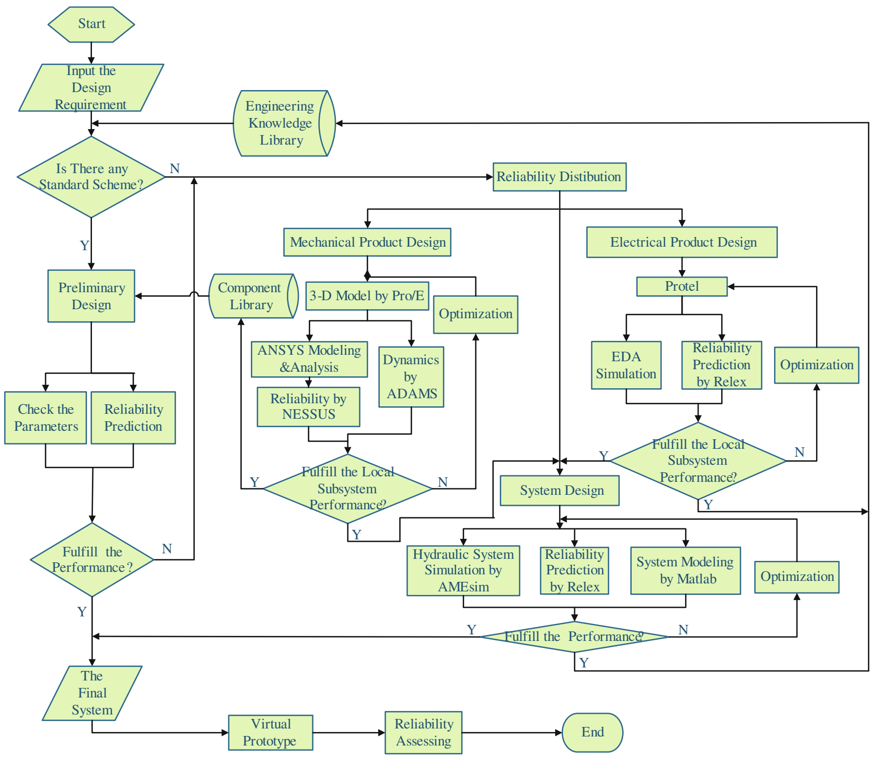

Fig. 1 Overall description of RCDP

RCDP provides the reliability assessment report to accomplish the complex product design. On the other hand, users can design the product independently with abundant component library, convenient design platform and necessary tools if RCDP can not provide the suitable design scheme. Because the reliability-based design method is quite different in component design and system design, RCDP decomposes the design process of complex hydraulic products into two levels, viz. component level and system level, in which the probabilistic design is adopted by treating stochastic quantities as random variables in component level and the performance-based analysis is exploited to realize the design optimization considering reliability constraint in system level. With the appropriate interface, it becomes possible to verify the design variables in two different disciplines through exchanging information dynamically, and model the propagation of uncertainty throughout the hierarchy of elements that utilize the simulation-based technique to joint the relationship between two levels. In the event of product design, multidisciplinary reliability oriented is provided that consists of the following disciplines:

mechanics (ProE), electronics (Protel), hydraulics (AMESim), cybernetics (Matlab), dynamics (ADAMS), finite element analysis (ANSYS) and reliability (NESSUS and Relex).

2.1 Collaborate Design Based on Probabilistic Distribution

Since the performance of complex hydraulic servo system depends upon several disciplines which interact and conflict each other sometimes, the collaborative design platform should support the multi-discipline design software, assemble the subsystem with appropriate interface and manage the different kind of data effectively. In hydraulic control system, servo valve and cylinder is typical mechanical product whose performance depends on mechanics, dynamics and reliability. A solution of integrated design is put forward based on Pro/E, ANSYS, ADAMS and NESSUS, in which the 3D model is firstly designed with CAD software package Pro/E according to static performance of hydraulic servo system. Then transfer the designed geometrical parameters in *.igs document to ANSYS to carry out the structural finite element analysis that provides the automatic command flow recording function with generating *.lgw document. Meanwhile, ADAMS can load the 3D model through the *.igs file to analyze its dynamics. Considering the product parameters are not necessarily deterministic, the reliability design software, named NESSUS, is adopted to perform probabilistic analysis for designed structure. As a result of command flow from ANSYS, we can get the determinate design parameters, then select the random variable and probability density from list and establish response function of individual parameters. Then select the random variables and their probability density from built-in list and define the failure probability expression with stress-intensity interference model. Herein, the response functions are utilized to build the bridge of individual parameters and adaptive importance sampling (AIS) is exploited to calculate the failure probability of product whose sampling space is defined using a limit-state boundary. For instance, the tensile load acting on an uniform bar (L) and the cross sectional area of the bar (A) are assumed to be independent random variables wherein the corresponding probability distribution function submits normal distribution as follows:

$$
\begin{aligned}
f(L) &= \frac{1}{\sqrt{2\pi}\sigma_L}\exp\left[-\frac{1}{2}\left(\frac{L-\mu_L}{\sigma_L}\right)\right] \\
f(A) &= \frac{1}{\sqrt{2\pi}\sigma_A}\exp\left[-\frac{1}{2}\left(\frac{L-\mu_A}{\sigma_A}\right)\right]
\end{aligned}
\tag{1}
$$

where μ_L, σ_L denote mean value and standard deviation of the variable L respectively; μ_L, σ_L are mean value and standard deviation of the variable A respectively.

The force in bar is:

$$P = f(L, A) = L / A, f(P) = \frac{1}{\sqrt{2\pi}\sigma_P} \exp\left[-\frac{1}{2}\left(\frac{P - \mu_P}{\sigma_P}\right)\right]$$
$$\mu_P = \mu_L / \mu_A, \sigma_P = \sqrt{\sigma_L^2 \left[\frac{\partial f(L, A)}{\partial L}\right]^2 + \sigma_A^2 \left[\frac{\partial f(L, A)}{\partial A}\right]^2} \tag{2}$$

If material strength of the bar is s and its probability density function is$g(s)$, the failure probability of the bar can be described as:

$$F = P(s - P < 0) = 1 - \int_{-\infty}^{\infty} f(P) \left[\int_{s_0}^{\infty} g(s)\, ds\right] dL \tag{3}$$

Select response model with user-defined as

$$P = f(L, A) \tag{4}$$

Let the coupling function as

$$z = -\frac{\mu_s - \mu_P}{\sqrt{\sigma_s^2 + \sigma_P^2}} \tag{5}$$

Then the failure probability of product is:

$$P_f = 1 - \phi(z) \tag{6}$$

It is easy to obtain $\phi(z)$ through referring Normal distribution table. With NESSUS and ANSYS, we solve the problem as follows.

Firstly, build the bar finite element model in ANSYS, and edit the command flow *.lgw file.

Secondly, describe the problem statement in NESSUS as:

$$P_f = P\{s - L < 0\}$$
$$P = f(L, A) \tag{7}$$

Select the $P = f(L, A)$ expression's response model as *.inp file editing from the ANSYS fore-defined *.lgw file, then mapping the variable parameters to the *.inp. NESSUS controls ANSYS to calculate failure probability under updating the input parameters (viz. L and A) with the sampled values by AIS and extracting relevant results (viz. stress) from ANSYS output *.rst file.

Finally, NESSUS can provide the statistic report. Figure 2 shows the operational principle and data flow of NESSUS.

In NESSUS, the start point of reliability design is the product failure mode that is subjected to design parameters and failure criteria. User can select the

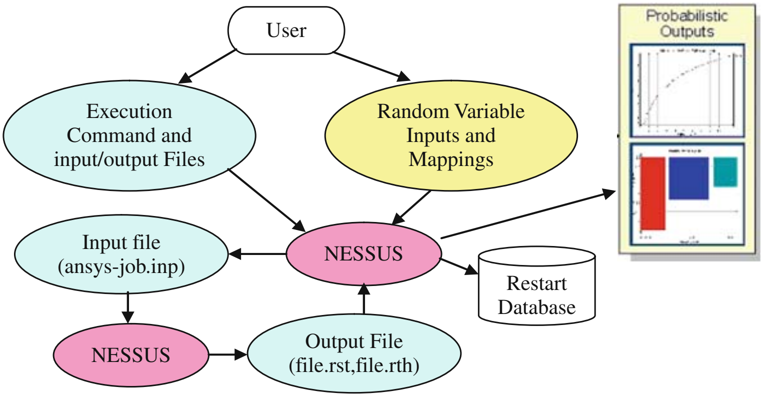

Fig. 2 NESSUS operational principle

probabilistic distribution from provided list for design parameters, and establish the status equation or response function to calculate the failure probability of product. The executive process of collaborative design based on probabilistic distribution for mechanical product with Pro/E, ANSYS and NESSUS is shown in Fig. 3.

Figure 4 shows the main interface of RCDP, in which the design methods are listed on the left such as component design, system design, reliability analysis and system optimization. Users are convenient to select or design the hydraulic product with 3D modeling based on component database and engineering library in the middle field and add the designed component in defined format to the database when the designed product meets all the design requirements. Once the product design is accomplished with mechanical package or electronic package, users can design the hydraulic system with collaborative design method considering electronics, dynamics, cybernetics and reliability synchronously. In system design, we focus on the performance-based design under multiple disciplines, so system optimization strategy is adopted to balance the design requirements in different fields, in which the reliability analysis is executed in whole design process.

Since much attention has been paid to the development of procedures to couple powerful multidisciplinary optimization techniques with probabilistic design method, it is easy to achieve the integrated optimization solution based on different disciplines after collaborative design. For the system design, we adopt current state-of-art optimization that emphasizes the performance by cooperating control performance software-Matlab with reliability analysis software-Relex. The Relex Reliability Studio integrates a suite of reliability analysis modules encompassing reliability prediction, Reliability Block Diagram (RBD), Failure Mode Effect Analysis (FMEA), Fault Tree Analysis (FTA), maintainability prediction, Markov Modeling and LCC. It can calculate reliable

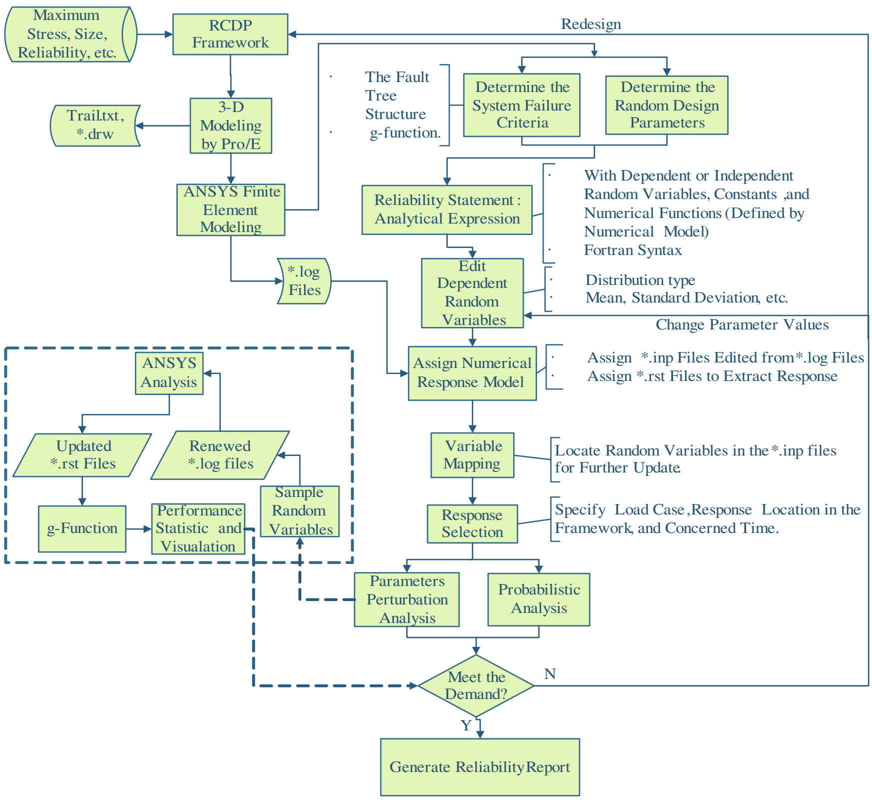

Fig. 3 The collaborative design process of mechanical product

probability or failure probability and obtain the weak item of the analyzed system with appropriate algorithm. In addition, Relex can describe the system performance degradation and repairable process dynamically, so the reliability-based collaborative design platform can realize the reliability identification in whole design process.

2.2 *Interface Between Multidisciplinary Software*

In the process of collaborative design of complex product, we obtain the design parameters that are rooted from specific discipline, and then we may ask the question: "Will this design perform well under other discipline?" To answer this question, the convenient way is to transfer the design parameters to other discipline software to verify its performance, which can guarantee well performance in different discipline for designed product. Fortunately, most of the

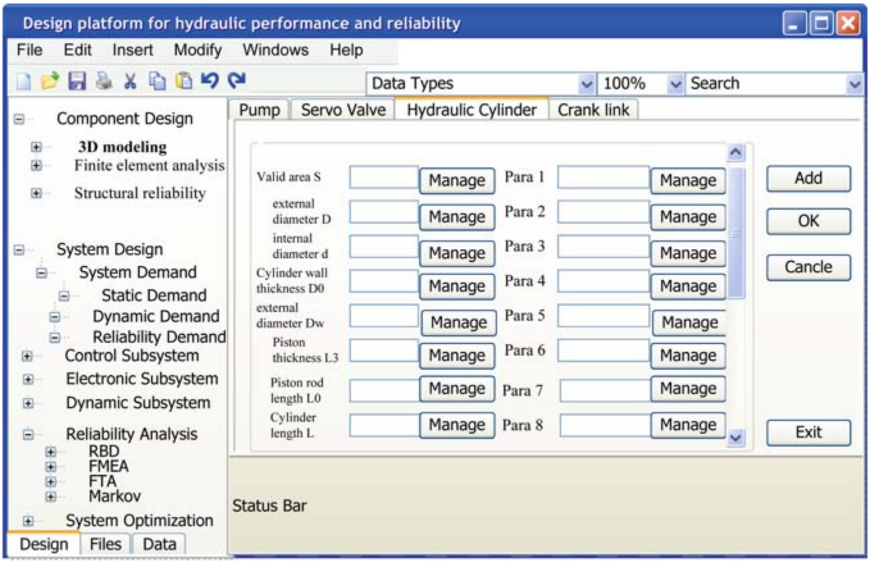

Fig. 4 Main interface of RCDP

commercial design and analysis software have interface with other software package so as to improve their collaboration capability. The interface makes it possible to exchange information, access public data and realize the integrated optimization among different disciplines. Even if there is no interface between two packages, it is also easy to develop executable code based on input and output application file mode. Users can export files designed by one discipline and import it into another discipline environment to check if the designed parameters satisfy the performance or not. Developers can create their own "relationship" on the basis of their design demand that makes the change of the model easier. So it is important to obtain the well designed interaction interface between two disciplines that can exchange data dynamically and save the developing time effectively in complex product design. Table 1 lists the standard interface and self-developed interface between current commercial software packages.

Taking the Relex and Protel as an example, although both packages don't provide mutual programmable interface, we establish the medial files via Excel as their bridge. User can design the electronic or electrical circuit with Protel, and export the components list in Excel format. Then the *.xls file is standardized by the MDO platform and guided to Relex to predict its reliability (shown in Fig. 5). It is obvious that the MDO platform is employed to reduce the computational expenses significantly with the appropriate interface that makes information exchanging easier.

Table 1 The interface of commercial software

No.	Software1	Software2	Interface Implementation
1	AMESim	Matlab	There are the AMERun-MATLAB interface, AMESim to Simulink Interface, Simulink to AMESim Interface in the AMESim suite.
2	AMESim	iSIGHT	AMESim can create files directly readable by iSIGHT using the MDOL format.
3	VC	Matlab	Visual C++ employs Matlab as a computation engine by Component Object Model (COM) on Windows
4	ANSYS	NESSUS	NESSUS employs *.log files and variable mapping to control ANSYS to operate.
5	ANSYS	iSIGHT	iSIGHT imports ANSYS code as simcode.
6	VC	iSIGHT	iSIGHT imports *.exe as the simcode.
7	VC	SQL Server	Visual C++ accesses SQL server by Open Database Connectivity driver (ODBC)
8	Excel	Relex	Relex outputs and inputs part list in *.xls file.
9	Excel	Protel	ProtelDXP outputs part list in the .xls file.
10	Pro/E	ADAMS	ADAMS can load *.igs files generated by Pro/E.
11	Pro/E	ANSYS	ANSYS can load *.igs files generated by Pro/E.
12	ADAMS	Matlab	Output * .mdl files to Matlab/Simulink
13	ADAMS	iSIGHT	iSIGHT imports Adams analysis code as simcode.
14	Matlab	iSIGHT	iSIGHT embeds Matlab into the “Insert” toolbar.

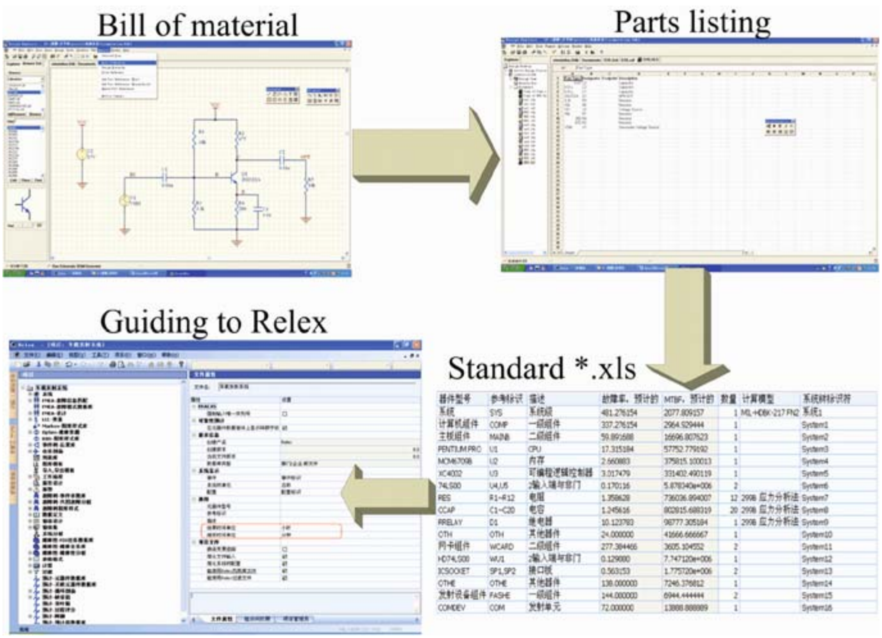

Fig. 5 Medial interface between Protel and Relex

2.3 Optimization Based on Hierarchical Decomposition

If hydraulic servo system is complex enough, design optimization can be accomplished by decomposition. The system is divided into several subsystems, and the subsystems can be divided into components and so on. Hierarchical decomposition facilitates employing decentralized optimization approaches that aid systems engineers to identify interactions among elements at lower levels and to transfer this information to higher levels, and has in fact become standard design practice, as evidenced by the organizational structure of engineering companies. In RCDP, the PDM is exploited to provide user necessary information about component and engineering experiences.

Multidisciplinary design optimization is an effective method and tool for comprehensive engineering system design whose objective is to find the overall optimal solution by means of the collaborative effect caused by multidiscipline interaction and shorten the design period concurrent computation. While multidisciplinary design optimization is also faced with much challenges such as computation complexity and difficulty of information exchange, and some method and technology such as system decomposition, approximate analysis and totally sensitive analysis. Recently, collaborative optimization is considered as a promising MDO method, which aims at complex system design, distributed, multi-level optimization. Its motivation is dividing multidisciplinary complex system design problem into subjects (or subsystems) design optimization problems, and reducing the size of optimization problem, through system-level constraints to coordinate sharing design variables and coupling design variable between disciplines shown in Fig. 6.

In Fig. 6, the system consists of 3 levels, viz. level 0 (system), level 1 (subsystem) and level 2 (component). Suppose the local design parameters of component $i$are $r_{ij}(i = 1, 2, \cdots n, j = 1, 2, \cdots n_i)$ in level 2, in which $j$means the number of component. Herein the parameters $\tilde{r}_1, \tilde{r}_2, \cdots \tilde{r}_q$ come from level 2 are exported to level 1 to affect the subsystem design that is named shared parameters. If $x_{ij}(i = 1, 2, \cdots m, j = 1, 2, \cdots n'_m)$ denote the local design parameters

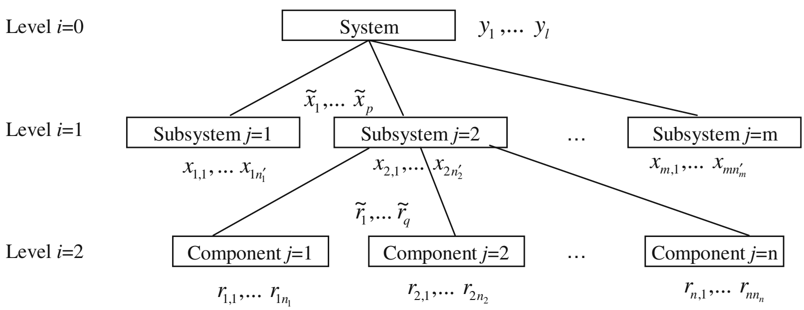

Fig. 6 Hierarchical decomposition of complex system

of subsystem$i$, the design procedure must balance both local variables and shared variables to achieve well performance. Similarly, the system design should consider the influence of the shared parameters of $\tilde{x}_1, \tilde{x}_2, \cdots \tilde{x}_P$ come from level 1 and local design parameters $y_1, y_2, \cdots y_l$ of system. Hence, both local design and interaction between lower level and higher level should be integrated in product design to obtain the optimization design results under multilevel hierarchy.

Directing to the complex product in real application, this paper presents an optimization method in the multilevel hierarchy. The original optimization is carried out from component viz. the lowest level to get the designed variables, in which some of the variable values pass up to higher level as shared design variables. In the higher level, both local design variables and shared variables coming from lower level are considered to achieve the optimization wherein minimize the gap between what higher-level elements "want" and what lower-level elements "can". Through numbers of iterative optimization between the higher-level and lower-level, we will eventually find an optimal design of the consistency based on the state variables coupling and design variables sharing.

Suppose that i and $j$denote the level and element respectively, the optimal objective function of system can be described as:

$$\min f(\tilde{x}_1, \cdots \tilde{x}_P, y_1, \cdots y_l) \tag{8}$$

Subject to

$$\begin{cases} g_{ij}(\tilde{x}_1, \cdots, \tilde{x}_P, y_1, \cdots, y_l) \leq 0 \\ h_{ij}(\tilde{x}_1, \cdots, \tilde{x}_P, y_1, \cdots, y_l) = 0 \end{cases} \tag{9}$$

with

$$\begin{cases} x_{ij} = f_{ij}(x_{i,1}, \cdots, x_{in'_j}, \tilde{r}_1, \cdots \tilde{r}_q) \\ y_k = f(y_1, \cdots, y_l, \tilde{x}_1, \cdots, \tilde{x}_P) \end{cases} \tag{10}$$

where the vectors $r_{ij}, x_{ij}$and $y_k$denote the local design variables in each level; $\tilde{r}_1, \cdots \tilde{r}_q$ and $\tilde{x}_1, \cdots \tilde{x}_P$ indicate the bi-level shared variables; g_{ij} and h_{ij} denote the design inequality and equality constraints respectively.

In RCDP, iSIGHT is adopted to realize the multidisciplinary design optimization that can deal with the interaction among disparate disciplines and balance the target difference to achieve the integrated optimization results. Figure 7 shows how to balance the interaction between cybernetics (Matlab) and hydraulics (AMESim) with iSIGHT.

Once we accomplish the design of hydraulic servo system with AMESim according to the static and dynamic requirement, we can get the parameters of servo valve, cylinder and displacement sensor such as flow coefficient K_Q, flow-pressure coefficient K_c and area of cylinder A. Introduce them to Matlab to get

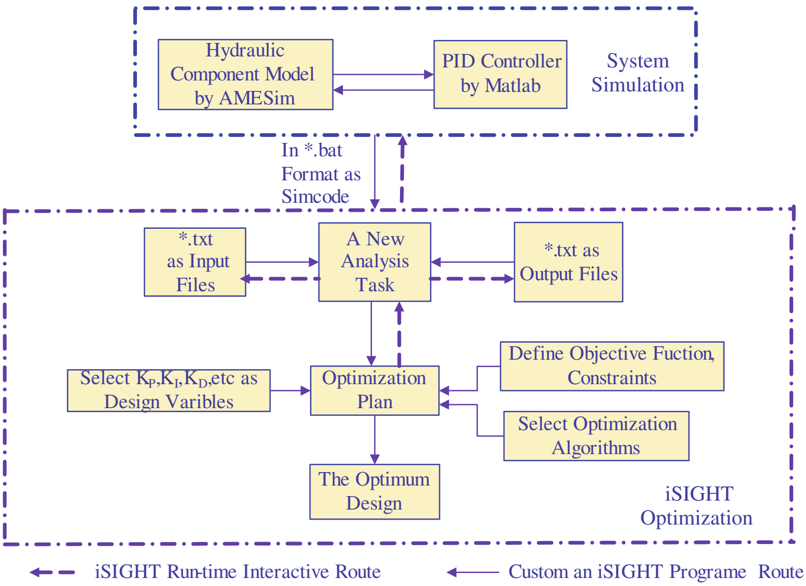

Fig. 7 Optimization between cybernetics and hydraulics with iSIGHT

the system transfer function. In order to satisfy system control performance, appropriate PID controller should be designed, in which the proportional coefficient K_P, integral coefficient K_I and the differential coefficient K_D can be adjusted dynamically. If it is impossible to achieve the system performance requirement under current hydraulic components no matter how to adjust the PID variables, we should redesign the hydraulic component's dynamic parameters with AMESim. On this condition, it is necessary to balance the design variables in two disciplines. Herein, we select the optimization software—iSIGHT to realize the design optimization. We select K_P, K_I, K_D as design variables and set the optimization of hydraulic actuator as a new analysis task. Defining the response time as objective function and reliability as constraint, iSIGHT can recommend suitable algorithm to obtain the optimal K_P, K_I, K_D based on cybernetics. If the response time of system or reliability can not satisfy the requirement, redesign in hydraulic discipline and cybernetics discipline will be implemented until the integrated performance is fulfilled.

Especially, iSIGHT can run other software and launch the iteration process automatically by assigning input parameter file, output file, simulation code and control flow. Users are convenient to choose the CAD/CAE tools, mathematical and programming tools, internal developed codes and the "intelligent design engine", make these tools assembly and establish the integrate analysis process through a simple graphical interface. iSIGHT enables the data to transfer from one tool to another in a seamless manner operation. For instance, iSIGHT can run Pro/E with the notepad type file and run ANSYS with the *.igs type file. During Pro/E running, it will automatically record every operation step and save the command flow to a trail.txt file. iSIGHT automatically passes on the Pro/E geometrical model to ANSYS, and reads the performance parameters such as the greatest stress, the maximum deformation from ANSYS output *.rst document. The "intelligent design engine" has four modules: experimental design, optimization algorithms, quality engineering methods and approximation method that can be used individually or synthetically. For optimization, users can adopt the optimizing plan recommended by iSIGHT which is the most suitable for the design problem, or combine the iSIGHT optimizing algorithm or develop internal programs to get the most reliable and robust strategy according to the nature of the problems and professional experience.

2.4 Data Management

Database is the center of the platform, and it is the foundation of other function modules. According to the operational process shown in Fig. 1, RCDP is supported by two databases, viz. the engineering knowledge database and system component database. These two databases play very important role in the entire design process. They not only provide useful design information to designers but also attribute and control method of components, and new items can be added into the database on finished design. So the databases can be continually expanded to facilitate future design. Data can be uploaded or downloaded between local resource library and center database by the transfer function module of database.

Figure 8 shows the database and PDM of RCDP, in which the knowledge database can be divided into three categories:

1. **Model knowledge database** – Toward some subsystems of special application, it is easy to establish its design template whose design parameters construct its model knowledge database.
2. **Engineering design knowledge database** – It is obtained based on engineering experience of research object such as typical displacement servo system, force servo system and velocity servo system. Such databases mainly include knowledge of design characteristic, design sequence, design experience during engineering design that can provide recommended primary scheme for designer at the beginning of design process.
3. **Parameters design knowledge database** – This database includes knowledge of interactive parameters and scopes of design parameters. Such database will provide basis to multidisciplinary design parameters optimization.

In the beginning of new product design, the designers are accustomed to consult the similar product design. If there is ready-made design in RCDP, users may generally select a specific scheme by the aid of engineering database

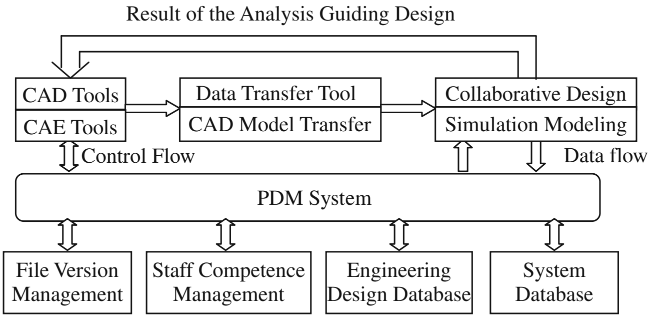

Fig. 8 Database and PDM

according to the design requirement. Otherwise, the designers have to follow the reliability-based design process to realize the multidisciplinary design optimization. In this case, the system will be divided into subsystems by the appropriate reliability allocation, and then the collaborative design based on component database is carried out. After verifying the performance and reliability, the new successful design application can be accessed into database with standard data format.

The function of PDM is to manage the product database and product R&D. Collaborative design platform can take advantage of powerful data integration and management capabilities to achieve effective management to design activities which including workflow simulation, simulation dedicated database and model libraries, design files. PDM system is the best CAD/CAPP/CAM integration platform, which helps a team or an enterprise to achieve information integration, process integration and functional integration in heterogeneous and distributed computing environment. In RCDP, SQL Server 2000 is adopted to integrate and manage the different defined data that can interactive transfer with data accessing technology. Table 2 shows the function parameters description in RCDP.

Table 2 The function parameters description

No.	Character name	Data type	Description
1	ParaId	int	Parameter number, PK
2	EngId	int	Engineering number, FK
3	ParaName	Varchar 20	Parameter/component/scheme name
4	ParaValue	decimal	Parameter value
5	PartNo	int	Component number (FK)
6	ParaImage	image	Graphical value
7	ParaType	Varchar 20	Parameter type: system, structure and reliability
8	ParaDescribe	Varchar 20	Parameter/component/scheme name

2.5 Realization of RCDP

Aimed at the characteristics of hydraulic servo system, a solution of integrated design architecture is put forward aforementioned, which is multidiscipline oriented and hierarchy. The collaborative design and simulation of all disciplines is performed concurrently whose results are transferred into the unified PDM database for future applying. While some tools provide the interfaces for collaborative simulation listed in Table 1, it is convenient to check whether the shared variables which are determined by the uni-discipline satisfy with the requirement in the other disciplines or not. So the integrated optimization should be executed to guarantee the optimal performance and reliability.

RCDP is designed based on VC++ 6.0 and SQL Server 2000, which can carry out distributed collaborative design including mechanical design, electronic design, reliability design, hydraulic design, control design and unified data management. Herein, iSIGHT plays an important role in collaborative integrated design with graphical interface and convenient assembly. Figure 9 shows the integrated software, data standard and operation principle wherein STEP standard is adopted in collaborative design platform.

Fig. 9 The data standard of RCDP

3 Application of Hydraulic Actuation System

Hydraulic actuation system (HAS) is a hydraulic displacement control system that can manipulate the rudder according to the flight profile. To design this kind of system, the designers will use many disciplines knowledge such as mechanistic, kinematics, dynamics, cybernetics, hydraulics and reliability. Figure 10 shows the structure of hydraulic actuator whose design requirement is listed in Table 3.

With RCDP, the designer can design HAS according to the Pro/E->ANSYS->NESSUS sequence by aid of the component database and engineering database as shown in Table 4. The dimension model of actuation is shown in Fig. 11.

After finishing the components design we will enter the stage of system design. After deduction we can get the transfer function of HAS:

$$G(s) = \frac{K_V}{s\left(\frac{s^2}{\omega_h^2} + \frac{2\zeta_h}{\omega_h}s + 1\right)} \tag{11}$$

where $K_V = K_A K_s K_q K_f / A$ is the gain coefficient; K_a means amplifiers coefficient; K_f denotes feedback coefficient; K_s expresses coefficient of servo valve; K_q shows the flow coefficient of servo valve; ω_h and ζ_h are inherent frequency and damping of dynamical structure respectively.

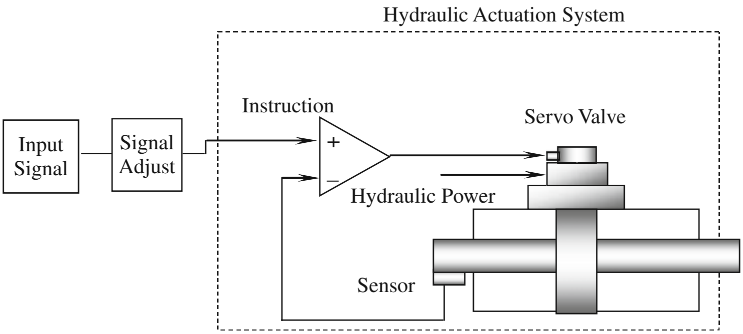

Fig. 10 Structure diagram of hydraulic actuation system

Table 3 Design requirement of hydraulic actuation

Number	Meanings	Symbol	Design requirement
1	load	F	294000 N
2	pressure	P	7 MPa
3	distance	S	0.1m
4	velocity	V	0.12m/s
5	reliability	R(t)	0.999

Table 4 List of components

Code No.	Name	View	Reliability
ZDQ0603001	piston		0.99987
ZDQ0603002	earring		0.99988
ZDQ0603003	sleeve		0.99991
ZDQ0603004	seal		0.99999
ZDQ0603005	seal		0.99999
ZDQ0603006	bearing		0.99999
ZDQ0603007	bearing		0.99999

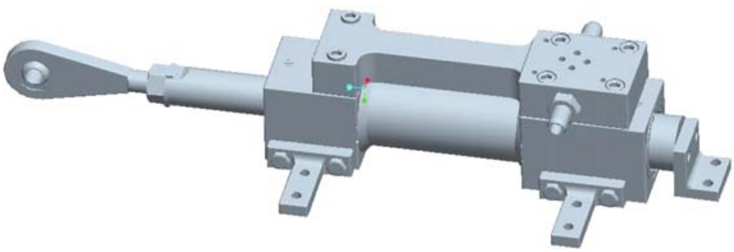

Fig. 11 Dimension model of actuator

Firstly, we will define the variables to be design and optimize. Let X_1 is K_a, X_2 is K_f, X_3, X_4, X_5 are PID controller coefficient K_p, K_i, K_d respectively, X_6 expresses piston external diameter, X_7 is piston internal diameter, X_8 indicates load force and X_9denotes hydraulic cylinder material strength δ. Herein, X_6, X_7, X_8 are sharing design parameters which participate in the two-subsystem design optimization process.

Secondly define the objective function of HAS as:

$$\begin{cases} Rise\ time\ T_r < 0.05s \\ Amplitude\ Margin > 6dB \end{cases} \tag{12}$$

Constraint:

$$\begin{cases} reliability > 0.9999 \\ 130 \leq X_1 \leq 150 \\ 1 \leq X_2 \leq 1.2 \\ 6.5 \leq X_3 \leq 7 \\ 8 \leq X_4 \leq 12 \\ 2 \leq X_5 \leq 2.5 \\ 0.1 \leq X_6 \leq 0.3 \\ 0.01 \leq X_7 \leq 0.15 \end{cases} \tag{13}$$

With reliability-based collaborative design and hierarchy optimization, we can get the optimal values listed in Table 5.

Table 5 Optimizaition results of HAS

Parameter	Min value	Max value	Step	Result of optimization	Unit
X_1	130	150	0.5	149.5	
X_2	1.00	1.20	0.01	1.12	
X_3	6.5000	7.0000	0.0005	6.8555	
X_4	8.0000	12.0000	0.0005	10.0000	
X_5	2.0000	2.5000	0.0005	2.4065	
X_6	0.10	0.30	0.01	0.16	m
X_7	0.01	0.15	0.01	0.08	m
X_8				294000	N
X_9				280	MPa

After optimization, we can obtain the system step response and bode chart of open-loop curves as shown in Fig. 12.

At the same time, we can obtain the fault tree of HAS and provide the reliability prediction shown in Fig. 13.

With the computation algorithm, we can get the reliability of HAS is 0.999999933 in 10 hour that not only satisfies the design requirement but also approaches the real condition.

4 Summary and Conclusion

This paper presents a reliability-based collaborative design platform based on corresponding commercial software and appropriate interface, in which the design optimization of hierarchically decomposed multilevel systems is carried out under uncertainty. We extended the deterministic formulation of product design to account for uncertainties with structural reliability design software—

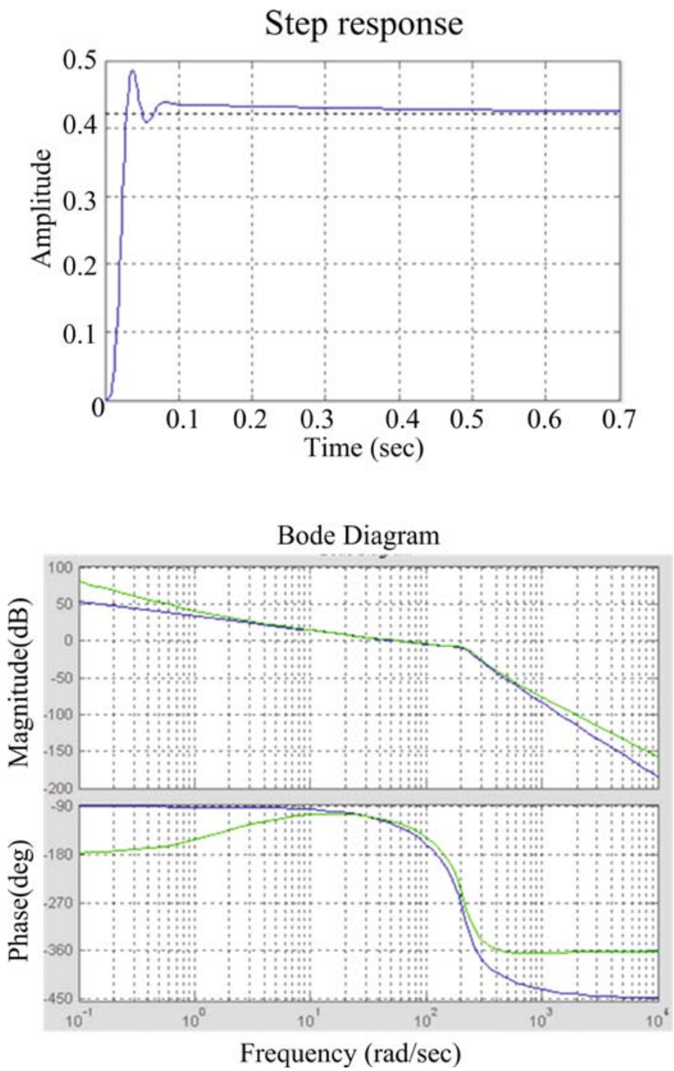

Fig. 12 Step response of system

NESSUS, in which designer can select the probabilistic distribution according to the product characteristics. We adopt inherent interface or develop the medial file as interface between two packages that builds the bridge connecting the interdisciplinary interaction and makes it easy to achieve integrated optimization among multiple disciplines. In addition, we modeled the propagation of uncertainty with shared parameters and run the software in given variable domain iteratively with intelligent design engine of iSIGHT. With local

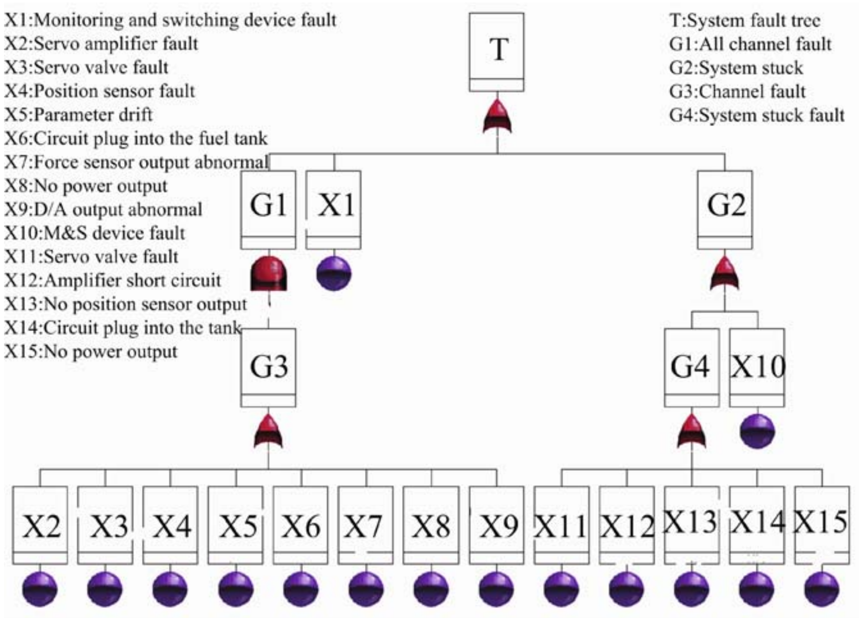

Fig. 13 Fault tree of HAS

variables and bi-level shared variables, the performance-based design optimization can realize. Finally, the reliability analysis with Relex is carried out to assess the system reliability, maintainability and availability to guarantee the integrated performance optimization.

The following issues deserve special attention:

1. Exploiting the reliability-based collaborative design method to design a complex product can fully consider the interaction among different disciplines and achieve performance-based integrated optimization.
2. Making the most of the inherent interface or provided medial files in RCDP can facilitate designer to obtain the performance verification of other discipline and achieve the interdisciplinary design optimization.
3. Effective database and PDM can reduce the developing period and make the designer easy to obtain the reliable, robust and best design scheme.

Application of HAS indicates that RCDP can improve the design effectiveness, shorten the development period, economize designing resource and achieve the reliability evaluation.

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The 4 + 1 Dynamic Management System of Lifecycle

Junichi Yagi and Eiji Arai

Abstract The life cycle management of a complex product like a constructed product needs to reconsider its engineering framework. The recent development of science, specifically physical and brain research provides us with an ingenious clue. The virtual control of time is now within our scope. This manuscript suggests its possible engineering implementation.

Keywords Lifecycle management · Virtual time machine · Sensor network · Unification of parts and packets · Complexity of system

1 Introduction

Control of construction process must deal with a bulk of scheduling elements that are produced by multiple heterogeneous players, contractors, sub-contractors, and parts makers. Their scheduling elements are necessarily intermingled and linked with each other. The whole schedule is managed and adjusted as one giant flow of processes. One small change in a tiny part of the whole schedule may possibly propagate its influence into the whole. Every such complex system which is non-linearly linked often shows some chaotic behavior, and at worst leads to a catastrophe. Upon this peculiar condition, construction process management is conducted on site holistically at every moment from the commencement and completion of a construction project. There are varieties of causes that force scheduling change. It is of critical issue when a signal of change is dispatched within a complex system. If timing gets lost, disastrous consequence may result with severe cost loss. It is also critical where a change occurs among multiple players, as well as what happens.

Two to three million parts needed for a building, depending on how to count, and yet the vast bulk of construction parts should be registered somehow in a database, if the entire lifecycle management of a constructed product should

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ever be achieved. Parts comparability with this parts-level information retrieval will make possible replacement of parts in a building to its full extent, even perhaps structural modules, not to mention replace of the infill. It will eventually erase the current dichotomy between renovation and newly-build in its entirety.

The lifecycle of constructed products is quite lengthy, thirty years or longer. The construction parts have various lengths of life-span, or different clocks, days to years or to decades. So, the constructed products have temporal hierarchies in addition to structural hierarchies. However, compared to construction stage where the construction environment is dynamically changing within a rather compact period, the time flows much slower at the operational stage, gradually decaying and reaching to the point of threshold.

A proper engineering decision making is expected to be quite hard for the lifecycle management of any constructed product of high complexity with quite distinct characteristics over stages. This manuscript tries to suggest how to attack this non-trivial issue.

2 Physical Background

The lifecycle of housing begins with construction by assembly of a bulk of building components from bolts and nuts to a large span of columns and beams. The resulted product is a complex physical hierarchy of hierarchies of components, exerting directly or indirectly characteristic influences upon other components both within and across the hierarchies, some stronger and some weaker. Truly, it is tried in design to minimize couplings among the hierarchies and between components within a hierarchy. Such architectural effort is typically exemplified by modular construction, which joins structurally and functionally modules with modules but not with the constituent components within a module. The modules are encapsulated and *relatively* independent so that they interact through a rather small "window" of interaction at their surface envelope. Much effort is extended along the same line to decomposing of skeleton and infill, where structural skeleton like beams and columns detach functionally from interior settings like equipments and fixtures so much as it becomes possible to replace the interior modules, while keeping the structural skeleton intact. It seems very reasonable to keep the skeleton in use longer, for the skeletons have longer clock for their lifecycle compared to the infill. Keeping the skeleton longer fits the purpose of saving energy and resources.

However, it is hardly believed that the modular independence remains intact at the second stage of inhabitation or living stage, much longer period for lifecycle, where the decaying process proceeds with full of interactions by operations, human or otherwise. Such complex system often renders progressive deterioration in dissipation so that the modular independence will be eroded away, and the essential interdependence among hierarchies and components becomes dominant to determine the fate of the system for the rest of the lifecycle. It may be said the second stage of living or operation is a phase of "melting pot" of interactions. The flow overshadows the rigidity of structures.

It is therefore not so appropriate to hold a presupposition of classical mechanics of rigid body for consideration of dynamic transformation of the complex system throughout lifecycle. It is true at construction stage most of design follows the classical mechanics of rigid body. Some of structural analyses already goes beyond it and employs nonlinear model for fracture analysis of concrete, the coupling between the upper structure of building and earth soil, not to mention the analysis of seismic or wind effects upon building. It must go beyond further for modeling the dynamic flow of the system transformations. Eddington's argument (1958) [1] is quite suggestive in that regard. Eddington, who argued that, in a purely algebraic approach to physical phenomena, there are elements of existence defined not in terms of some hazy metaphysical concept of existence, but rather that existence is represented by an idempotent in the underlying algebra of transformations. He suggested the physical phenomena are not so much as they exist but that they *persist*. They persist not in the sense that they are static, but rather that they continually transform into themselves (idempotent $p^*p = p$, when it acts on itself, it remains itself or it persists) [2]. Physical phenomena should be viewed as relatively persistent phenomena under the underlying algebra of ceaseless transformations. This view gives us much better representation of the reality that nothing constructed is immune from transforming into other states or decaying. Changing is more basic than existing (or persisting, saying properly).

The temporal order of movement is thus the primary concern as long as the management of lifecycle is at issue. However, a real management project of lifecycle cannot be represented solely by the parametric time, for it consists of series of engineering decisions for all sorts of "this or that"; this event or that event, this sequence or that sequence. At every moment of decision, all the engineering potentials or possibilities must be activated as alternative choices and references [3], [4]. Two streams of activities in the form of potentials then flow into the current activity at present, one from the past and the other from the future. Two streams get convoluted and interacted at present, bounce around their possible ways of engineering settlement, and then come to a final settlement for their optimal or better mixture in the end. Thus the whole of engineering potentials is transformed into a unique event at present or decision now. Hiley (2000) [5], who provided an algebraic interpretation for Bohm's implicate order, gave a very suggestive and vivid metaphor for this account;

> The movement of a symphony involves a total ordering which involves the whole movement, past and anticipated, at any movement. We hear new notes reverberating

> within the memory of the previous notes. This together with the anticipation of future notes constitutes an unbroken movement. We comprehend movement in terms of *a series of inter-penetrating, intermingling elements of different degrees of enfoldment all present together*.

The last line in italic is particularly important to make proper engineering decision, that is, to regress freely back to any point of time in the past, anticipate the world paths to future, and return back to the current engineering work at present. It is the issue dealt in this manuscript how to implement this mechanism in engineering decision making throughout the lifecycle of engineered products.

3 4 + 1 Dynamic Mangement of Lifecycle

3.1 Introduction

An engineering decision making faces a series of opposite alternatives for choice, seemingly equally valid, from which it is forced to choose one, oftentimes under severe contention which way to go may lead to possibly far different consequences or distinct patterns of consequences. It is the norm for decision making for lifecycle management, rather than otherwise, to make a choice out of multiple alternatives. We confront with burning potential of opposites almost at every critical decision point– to the left or to the right, up or down metaphorically, A or $\sim A$, speaking most generically, where both opposites *coexist* in the acting potential (Whitehead, 1978 [6]), and both are rushing toward realization but neither yet are chosen.

The primary requirement for lifecycle management is therefore to engineer an adequate mechanism to make a proper choice among ordered information represented by the spontaneous symmetry breaks of potentials in result of interaction with the engineering environment or boundary conditions. It is no less than to *engineer* the convolution of two streams of information flow, one from the past and the other from the future, interpenetrating two temporal phases, freely coming-and-going between them, and eventual settlement at present with a focused image mirroring the past and future.

The etymology of the word, *ubiquitous* goes back to Latin, *ubiqu*- everywhere + *itas*– ity, meaning “Being or seeming to be everywhere at the same time; omnipresent”. The stem of the word, *ubiqu* refers to everywhere in space at present or omni*present* in that regard. It is not “omnitempo”, lacking of the meaning, “every time, anytime”. The National Institute of Advanced Industrial Science and Technology (AIST), Japan’s largest public research organization began a project, called “Virtual Time Machine” [7] project, which tries to extend the ubiquitous technology to the “omnitempo” technology that covers real-time sensing, pattern recognition, data mining, behavior mining, active tag, active database, the world simulation for possible scenarios, world

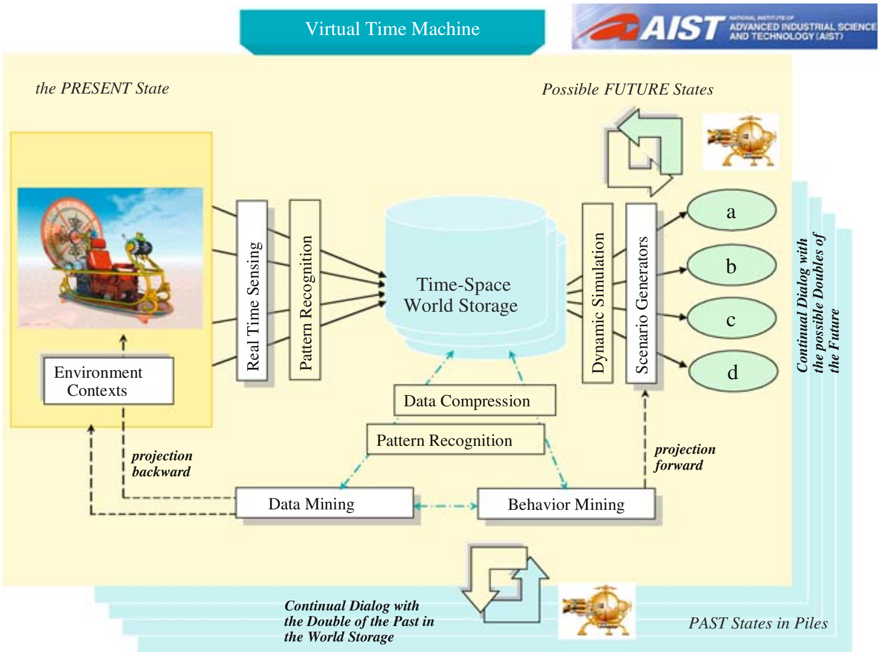


Fig. 1 Virtual time machine (Report on Virtual Time Machine by National Institute of Advanced Industrial Science and Technology, 2004)

storage, and virtual temporal transportation (Fig. 1). It is an ambitious engineering project indeed, but not so much ambitious as Hawiking's *real* time machine, whose probability of realization he figures 10 to the minus power of 10 to the power of 60 [8].

The world storage may have a storage capacity as large as petabytes (10 to the power of 15 bytes), which stores multimedia information captured from active sensor networks (Google uses two to three petabytes for indexed information worldwide in total). The network nodes are constituted of various sensor devices and tags. The key technologies (Fig. 2) are (1) data and behavior mining; monitoring and analysis of large amount data through sensing devices and extraction of hidden behavioral intents or meaning from a bulk of data, (2) temporal human interface; to contract or stretch time, realizing free walk-through in time, moving forward and moving backward, (3) possible worlds simulation; to simulate various world paths, future consequences or scenarios enacted by current choices to be made with enabling technologies; genetic algorithm, vision technology for flow line, sound spectrograph, robust sound recognition, information storing in 4D virtual space, volume graphic cluster, ultra-sonic sensing for human movement, Bayesian network, grid technology, multi-agent simulation, ubiquitous agents, automatic generation of tags, magneto resistive random access memory.

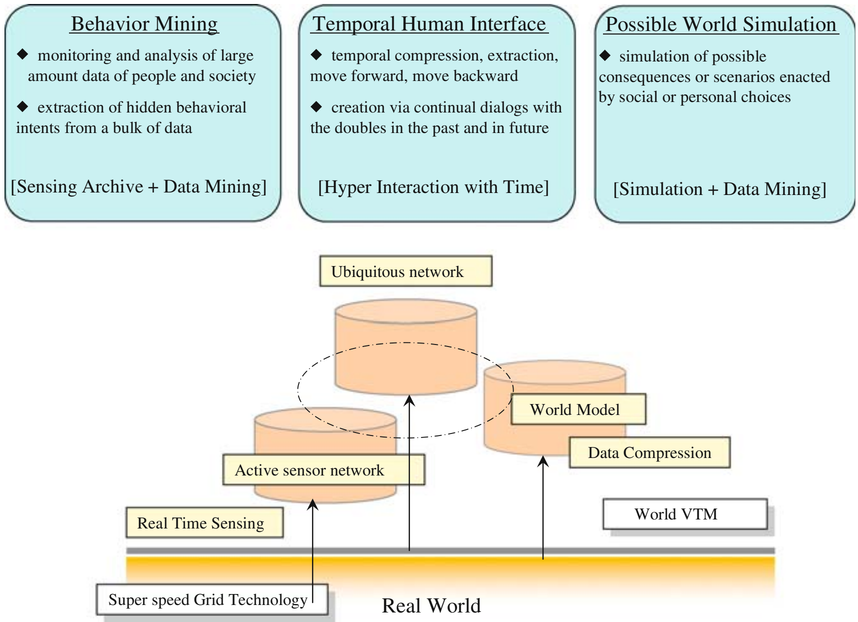


Fig. 2 Virtual time machine structure (Report on Virtual Time Machine by National Institute of Advanced Industrial Science and Technology, 2004)

3.2 Requirements

One of the basic requirements for management technology for "living" stage of inhabitation is to retrieve freely the needed information of architectural components from the past archive which contains history of change in attributes of the components and structures. Then automatically or semi-automatically reconstituted is the whole 3D design, which faithfully represents the current architecture of complex structures.

The causal chain among the functional requirements, physical system behaviors, and human behaviors is shown at Fig. 3. The horizontal box represents the living stage, where the physical system environment interacts with inhabitants continually throughout lifecycle. The vertical box represents the construction stage, where the inhabitants' requirements determine the housing functionality. It must be noted that the construction stage includes continual retrofit, re-make, and repairing long after newly built. Maintenance and upgrading of the physical system must be considered as critical activities for the lifecycle management. The horizontal and vertical boxes are the view of the same lifecycle process from different perspectives; the former represents the challenges imposed by change in the relation between human and physical

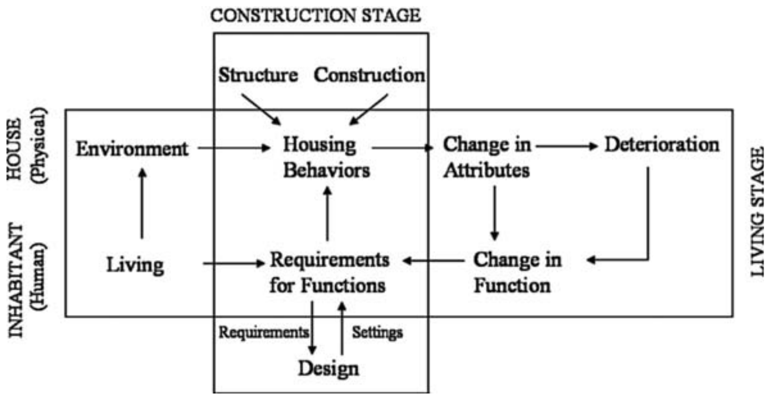


Fig. 3 The causal chain among the functional requirements, physical system behaviors and human behaviors

environment, and the latter represents the counter-acts against the engineering challenges encountered during the lifecycle.

3.3 4 + 1 Adaptable System of Lifecycle Management

The 4 + 1 adaptable system of lifecycle management is a housing version of AIST's virtual time machine or "omnitempo" engineering. It is an engineering response to science, Eddinton's algebraic interpretation of physics, and Hiley's ingenious view of physical orders, and temporal order in particular, mentioned at Section 2. In order to complete our response, our list of research tasks is presented below;

1. Parts oriented construction with hierarchical system of components covered by distributed network of multi sensors, radio frequency identification tags, RT middleware and super micro central processing unit, micro-actuators, and long-lasting battery in addition.
2. Updated reformulation of architectural design via data acquainted by sensors.
3. Design technology for easy-to-recyclable parts and structure.
4. Open supply chain of replacing parts.
5. Behavior mining, data mining, potential simulation, temporal human interface of transportation.
6. Evaluation of maintenance and upgrading.

The 4 + 1 adaptable system is structured by four functional spaces and the axis of temporal sequences as depicted at Fig. 4. The former constitutes four functional spaces categorized by their characteristic functions: (1) self-descriptive functional space, (2) self-sensing functional space, (3) self-searching

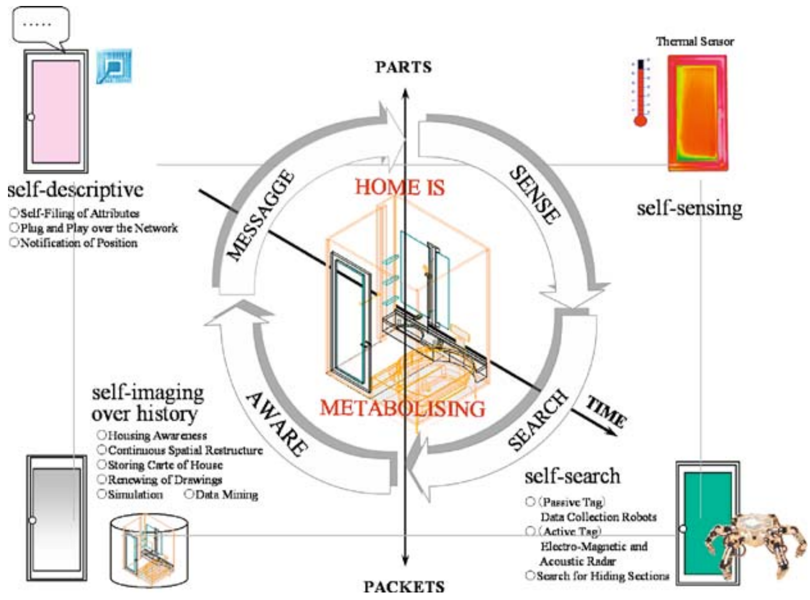


Fig. 4 The 4 + 1 adaptable system of lifecycle management

functional space, and (4) self-imaging over history functional space. The latter of " + 1" part is temporal integration of four functional spaces by circulating four functional spaces in order of self-descriptive, self-sensing, self-searching, and self-imaging over history.

Each categorical component of the 4 + 1 system will be described below in order.

1. Self-descriptive

   When a new component is introduced into the existing complex hierarchical structure, the newly built-in component describes its own spatial and temporal position within the hierarchy on its own, such as its subservient spatial order for assembly and temporal order of durable period. The self-filing mechanism can be realized by plug and play mechanism of radio frequency identification tags attached to components over the tag network which covers everywhere in the architectural system. Tags may contain physical properties such as material property, stress characteristics and distribution, archival manufacturing record, quality information, product specification in addition to spatial and temporal characteristics.

2. Self-sensing

   The tag network is superposed by the sensor network, most of whose nodes are embedded on tags with various sensing devices for temperature, moisture, ultra red, acceleration, wind loading, strain measuring, sound loading, light intensity, smoke, olfactronics, electro-magnetic and other sensors currently available or available in the future. Their position is either static or movable within the network distributed over the whole hierarchies. The sensor nodes function in either static or reactive mode. They function either in individual mode or in collective mode, where the latter may make a target object having hybrid sensing characteristics detectable with better precision. A house thus becomes a sensing house device with sensory nerves. It is not just sensing, but activating a series of proper events in reactive mode. For an example the skeleton is exposed by various loadings such as seismic, moisture, wind, light and other relevant loads constantly over lifecycle, whose unavoidable consequence is its aged deterioration. When the sensor network detects the accumulated loads beyond its threshold, extracting needed information from the central database, it activates an event of warning locally. Some of sensor nodes may not be activated always, they may be in sleeping mode and activated only when some events detected by other nodes. Or some sub-network of sensor nodes may even be detached from the whole network temporally, and works locally as an independent network.

3. Self-searching

   The tag nodes are either passive or active tags. When a relevant tag is positioned deep in the hierarchies, it becomes difficult to retrieve necessary information from the tag. The electro-magnetic wave detection device on tags is installed and then the hiding tags can be accessed as star dusts in the sky can be detected in the same manner. Micro-robots play a role of supplemental detection for the shielded tags, which loiter around the network now and then. Or let hiding tags establish peer to peer communication with neighboring tags, and relay the contained information.

4. Self-imaging over history (memory)

   Terabytes hard disks are already commercially available, and petabyte (10 to the power of 15), exabyte (10 to 18) will soon be available. AIST's conception of "world storage" is no longer imaginary. Sensed data via the sensor network will be stored piles by piles over time in even a single hard disk. Scenario-based potential simulation, temporal transportation from the past to future, and the other way around, behavior mining, data mining, and pattern recognition are all made possible by the world storage. Memories are prerequisite and basis for consciousness, which is produced by pattern matching current sensory input with memories as in our brain [9, 10]. The world storage is not just reservoir for electric contents like texts, images, sounds, movies, patterns, but also computation mechanism is attached to each data point whose value change activates events over some thresholds and propagates signals through the whole network.

5. Self-awareness (+ 1: self-dialog over time)

   A proper engineering decision can be made when one can freely access to the entire history, basing on which one can simulate the future consequences. The pattern matching to the past data produces engineering awareness. It is not once for all activity, but recursive dialog with the story of the past and future [11]. It is something like continual communication with its own double in the past and future, which immediately recalls Bohm's self-recursive mirroring loops of the spontaneous and unrestricted act of "lifting into attention" [12]. The technology needed to realize the free self-dialog over time is a control mechanism of compression, expansion, backward-flow, forward-flow of time, and creation and sharing of time axis at will in a virtual world of space-time.

4 Experiments

4.1 Introduction

The lifecycle of a construction project consists of three phases, design phase, construction phase, and maintenance phase as depicted at Fig. 5. The stakeholders change their roles as the phase proceeds; the main players at design stage are owners and designers, at construction stage, they are general contractors and traders, and at maintenance phase they are users and facility managers. The holders of architectural documentations also change, as the stakeholders change. The architectural models also change as they do. It is imperative to develop an engineering mechanism to share the disintegrated information for the lifecycle management.

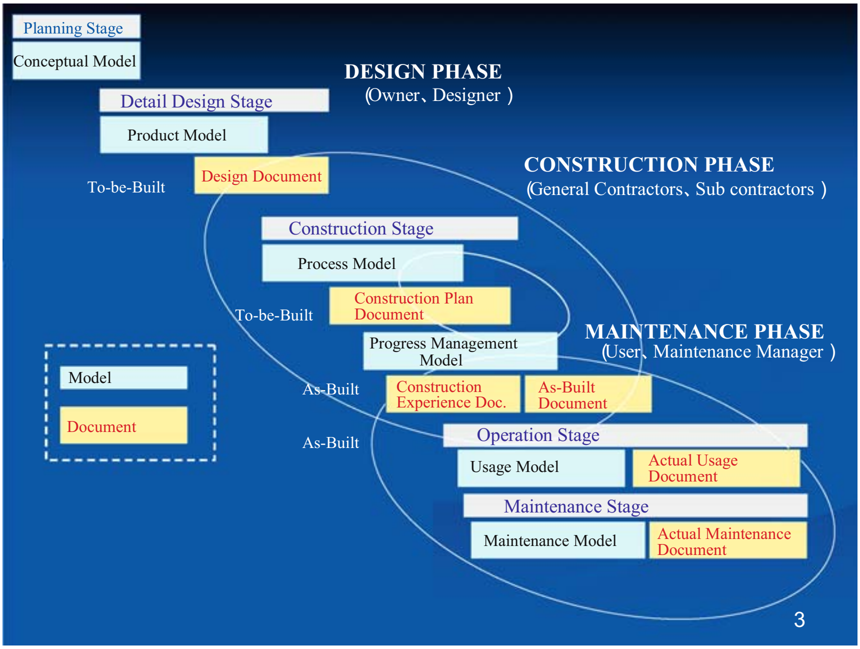


Fig. 5 The lifecycle of an architectural product

Some in-situ experiments are conducted, one at construction phase (Section 4.2), and another at maintenance or operation stage (Section 4.3) along the line of the afore-mentioned views developed at the previous sections. Various types of disturbance factor exist for the architectural lifecycle management. It is difficult to manage related information by using conventional model. A new concept of "Parts and Packets unified architecture" [13] is proposed. Data as information packets related to parts are carried by parts themselves and can be handled to manage whole system of the hierarchies of parts. It is integration of "parts and packets" with a control mechanism of their dynamic flow throughout a perplexedly complex network of product lifecycle in construction. It is a unified controller system which operates parts and packets together.

Both experiments focus on the issue how to obtain the necessary information from the architectural components and parts, and how to use this information for construction and maintenance respectively. The same mechanism is employed for both cases, using IC tags, sensor network, active database, 3D CAD representation and work-through, RT middleware for the network operation.

4.2 Construction Phase

Construction is surely production activity, but is better characterized as project-type production, defined as "a course of *concerted actions* intended to achieve some chosen purpose for production, within a given period of time, under some given constraints on available resource (man-power, material, and money), and with responsibility for sustainment of environment". It is therefore of critical importance to allocate production activities properly according to the well-planned process model and scheduling. It is, however, more indispensable to adjust the pre-assigned model and scheduling dynamically to the continually changing production conditions and environment to concert the needed actions. It is of primary concern for a project type production how to achieve the dynamic equilibrium at every stage from the commencement of the project to its completion which makes possible concerting the needed actions. The combination of radio frequency identification and active database (or glue logic) may open up promising that they might provide the mechanism which achieves the required dynamic equilibrium for construction activity without hindrance or halt of production at worst.

The dynamic nature of construction activities is exemplified at Fig. 6.

The in-situ experiment of construction control is conducted at some construction site of a residential building of nine floors located in Tokyo. For the construction site is located in a dense area of a town, the control room is located at a room in a nearby hotel, 75 m away from the construction site. The construction process is thus remotely monitored and controlled. The oriented antennas set at both site and control room establish wireless connection between them. The experimental settings are depicted at Fig. 7. Two types of

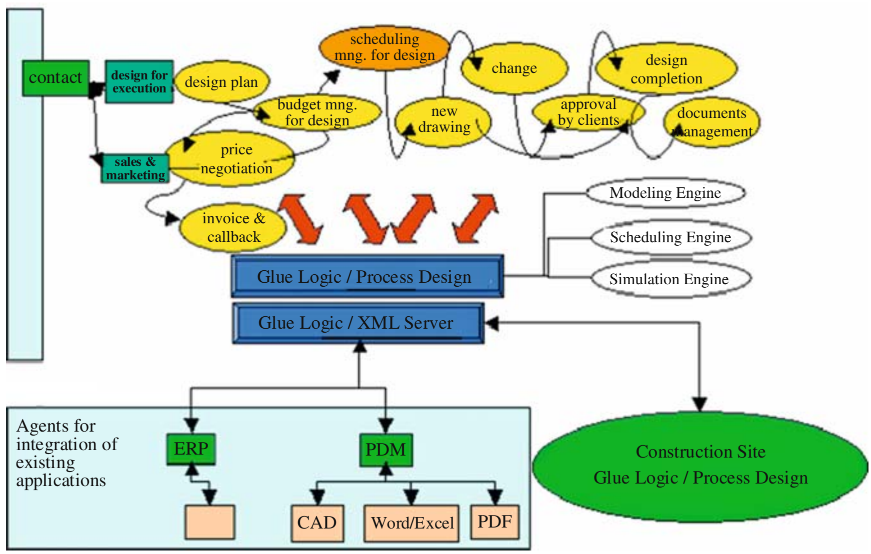


Fig. 6 Dynamic process of construction

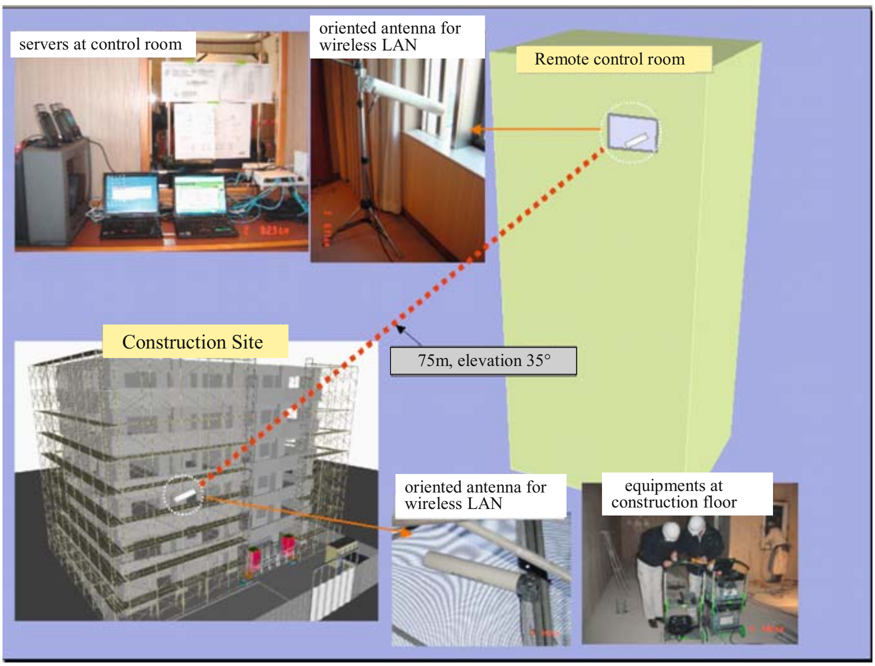


Fig. 7 On-site experiment setting

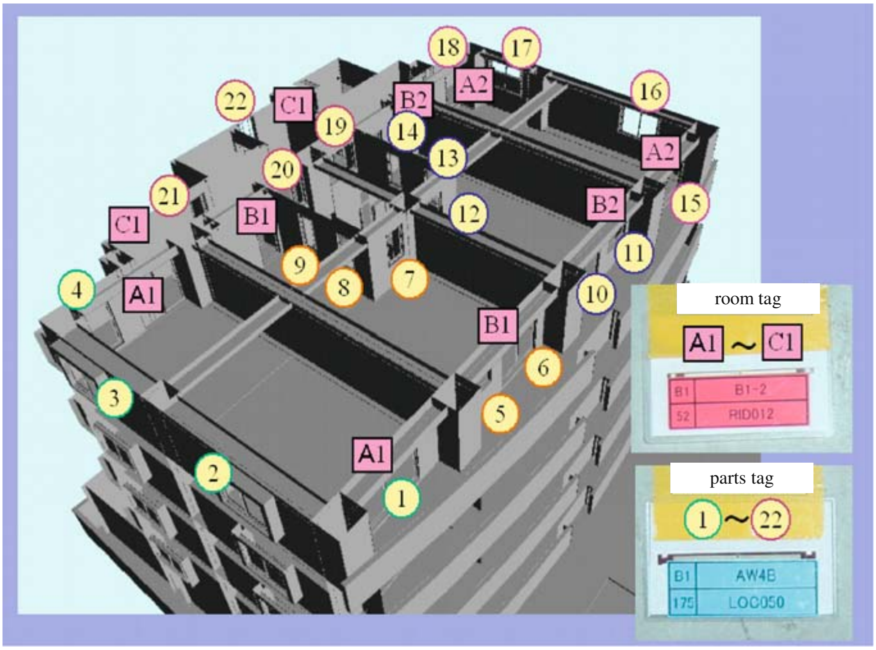


Fig. 8 Distribution of tags on construction floor

IC tags are distributed on each construction floor as depicted at Fig. 8; one type is fixed at each room for identification of location, and the other is tag attached to each component (window sash) as control target.

Once parts are manufactured, chip-implanted parts are shipped to a construction site, assembled, and installed on site. Despite that the parts are dislocated spatially as well as temporally, or are reconfigured in succession as they become more integral part of a building under construction, simple act of reading the product URL on tag triggers to change the attributes of these parts in the data management system of active database. As the parts' attributes are changed, they autonomously trigger to send messages to the pre-assigned addresses with a simple logic attached to each data point. Every data point therefore contains attribute, simple logic, and address. Millions of data points are passing information each other. This very bulk of acts of passing and receiving change the state of the whole data base, dynamically. Hence the data base collectively behaves like an autonomous giant controller as well as self-renewing data repository. Figure 9 shows the real time control for progress of construction by this mechanism from manufacturing thru shipping to installation on site.

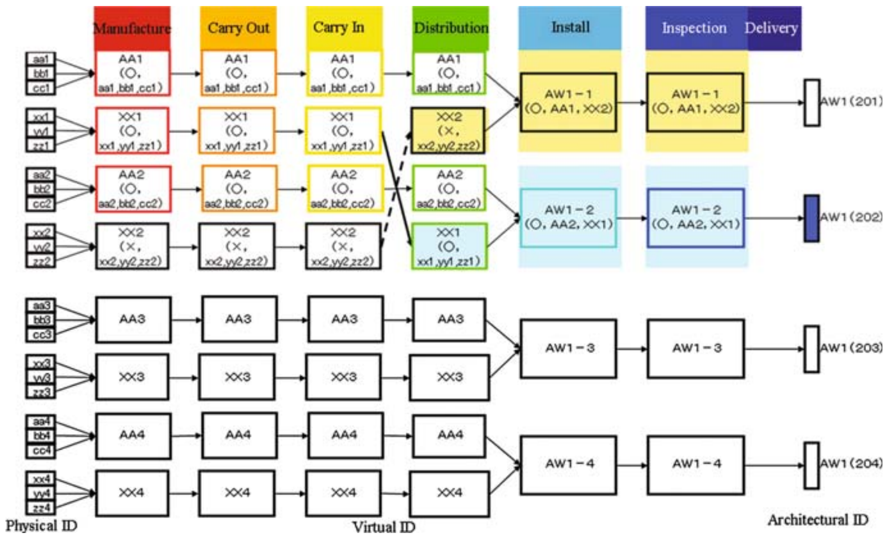
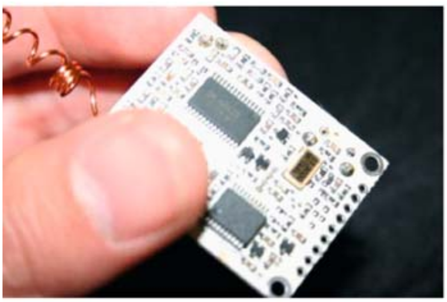


Fig. 9 Progress control of components installation

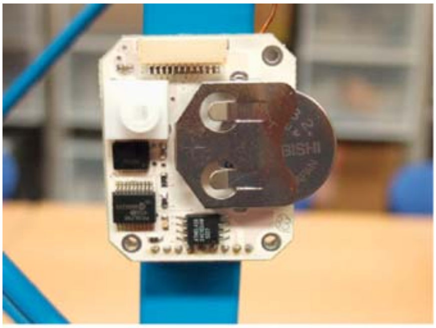
4.3 Maintenance Phase

The experiment for the operation stage is conducted at a warehouse of wines of repute, located at Tokyo bay water-front. The temperature and moisture control is critical for the warehouse to keep the quality of wine intact. A sensor for temperature and moisture is installed on IC tags of active type (Fig. 10) developed by AIST [14]. Some special IC tag is developed, which uses very weak radio wave for communication to save battery. The I/O port is secured by 4 bit on the tag, to which a sensor module is connected. The used sensor is shown at Fig. 11 with specification.



CPU	PIC16F88
CPU Clock	4MHz
Program memory	4Kbyte
Frequency Band	303.2MHz
Distance	About 10m
Baud rate	4800bps
I/O Device	LED
Free I/O port	I/O(4bit)
Function	RSSI Measurement
Battery	3V(Button Type)

Fig. 10 Active IC tag module



CPU	PIC16F88
CPU CLOCK	4MHz
Program Memory	4Kbyte
Extended EEPROM	128kbyte
Option Module	RTC
Sensor Unit	Sensirion SHT11
Sensor Specification	
Temperature	
Measurement Range	-40 to 123.8℃
Resolution	0.04 ℃(12bit mode)
	0.01 ℃(14bit mode)
Humidity	
Measurement Range	0 to 100 %
Resolution	0.5% (8bit mode)
	0.03 % (12bit mode)

Fig. 11 Sensor module for temperature and moisture

The configuration of the installed network is shown at Fig. 12. Several wireless access points are set up, one wireless LAN server station with three wireless relay stations. The sensor installed tags distributed in a part of the warehouse communicate with the relay stations via faint radio wave.

The monitoring of temperature and moisture is conducted for two weeks at the warehouse, whose typical results are shown at Fig.13.

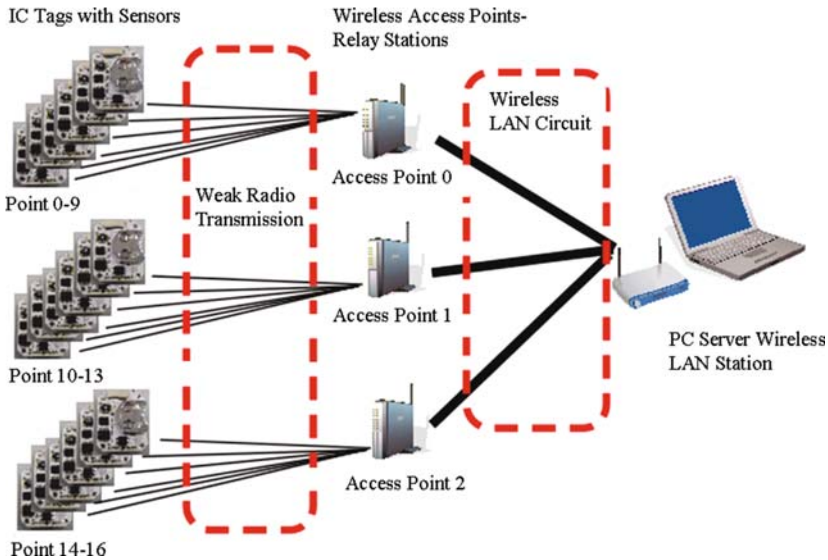
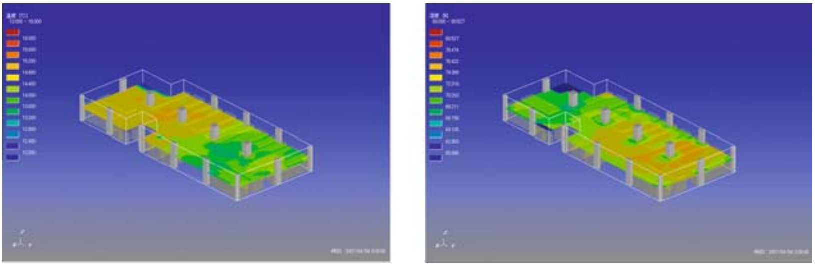


Fig. 12 Network configuration



(a) Temperature distribution (b) Moisture distribution

Fig. 13 Network configuration

5 Conclusion

The 4 + 1 adaptable system of lifecycle management is an engineering response to scientific knowledge obtained by the recent development of physics and brain research which suggest that a proper engineering decision can be made by recursive dialog with the story of the past, something like continual communication with its own double in the past, or like Bohm's *self-recursive mirroring loops* of the spontaneous and unrestricted act of "lifting into attention". The free self-dialog mechanism over time must be engineered. A control mechanism of compression, expansion, backward-flow, and forward-flow of time, and creation and sharing of time axis at will in a virtual world is the basis for the necessary engineering dialog with the past experience as well as its mirroring image in the future, potential world simulation.

Some in-situ experiments are conducted from the views above mentioned. Various types of disturbance factors and difficulty of decision makings exist for the lifecycle management. "Parts and Packets unified architecture" is proposed to open a way toward the solution. Data as information packets related to parts are carried by parts themselves and can be handled to manage whole system of the hierarchies of parts. It is integration of "parts and packets" with a control mechanism of their dynamic flow throughout a perplexedly complex network of product lifecycle. It is a unified controller system which operates parts and packets together.

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A PLM Tools Taxonomy to Support Product Realization Process: A Solar Racing Car Case Study

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Abstract Product Life-cycle Management (PLM) is a wide research issue exploring the information and knowledge in the entire product lifecycle to improve and increase innovation for a given product. The management of the information and knowledge related to the whole life cycle is supported by different Knowledge Management tools such as Product Data Management (PDM) and Expert Systems. PLM receives support from PDM systems in the many activities of the lifecycle from product design and creation, through dissemination and after sales services, up to product dismissal and recycling. Besides PDM systems, there are other knowledge management tools which haven't been integrated into the PLM. A particular shortcoming to integrate tools and techniques for the design process within a PLM environment is the lack of a PLM tools taxonomy. This paper presents a new PLM tools taxonomy to support product realisation process

Keywords PLM tools · PLM taxonomy · PDM systems integration · Engineering Design · Expert systems

1 Introduction

Product Life-cycle Management (PLM) is a research area adopted by companies, which can drive the life of a product by integrating their information, knowledge, individuals, activities and software. The stages that a product undergoes through its life are basically development, production, market activities, use, maintenance and disuse. Many authors and companies have defined their own phases, but there is a general agreement that products are designed, manufactured, distributed, sold and used; most of them are maintained, and they are disposed or recycled when they need to be retired.

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The whole life cycle of a product is usually very long. This causes a disagreement regarding the PLM definition, its stages and the tools it comprises [1]. It also makes it too broad for a single tool to include all the capabilities it requires which in turn causes a lack of integration among several tools used throughout the PLM stages. Therefore, the product's knowledge, which most of the time comes in disparate formats, is not always shared among its life-cycle [2]. For instance, there is no standard regarding Computer Aided Design (CAD) formats, and the technology to migrate from one format to another only handles geometry representations of the product (Bill Of Materials are being included already but there is no standard either).

The aim of this paper is to present some types of PLM tools that support the engineering design stage in a PLM environment using a PLM tool taxonomy.

2 PLM Definition, and Its Stages

2.1 Literature Survey of the PLM Concept

The concept of Product Life Cycle (PLC) has been addressed since the 1950s [3] or 1960s [4]. However, it must be stated that there is a difference between PLC and PLM, and that there are two points of view for the stages comprised in the life cycle of a product. Some authors consider it as the different profit and sale levels that a product has through its life. In this case, a product's time in the market is divided into introduction, growth, maturity and decline [5], [6]. This concept is much older than the actual PLM, but is still used in the production, sales and marketing niches. Researchers in this area use it to increase the revenues by predicting the market behaviour, and taking actions towards these predictions.

On the other hand, PLM intends to increase innovation [1], reduce errors [7] and be more competitive [8]. One of the first public attempts to define PLM was in the late 80s by Konstantinov [9]. His work was situated in the design management area, and as it would be expected, the conception of PLM has changed since then.

There are many researchers working in the PLM area. This situation has lead to the proliferation of many representations and definitions of PLM stages. Besides, they increase due to the fact that each "company will have to develop a life-cycle concept for its products"[10]. However, an agreement can be found about the underlying concepts in most cases.

Table 1 presents a summary of the different stages conceptualized by several representative authors. Alting's work [11] was selected for being a seminal source. The definitions provided by Aca [12] and Guerra et al. [13] are an

Table 1 Representative PLC representations (Adapted from [8], [11], [12], [13], [14] and [15])

[11]	Need recognition Design development				Production	Distribution	Usage	Disposal	
[12]	Product development	Process development	Facility development		Production Sales	Usage and maintenance	Disposal		
[13]	Ideation	Product development	Process development	Facility development	Production Sales	Usage and maintenance	Disposal		
[8]	Product design	Process planning	Factory planning	-Marketing -Procurement	-Sales -Distribution	After sales Quality Maintenance	Production planning	Production scheduling & control	
[14]	Requirement analysis and planning	Concept engineering & prototyping	Product engineering	Manufacturing engineering	Manufacturing and production	Sales & Distribution	Disposal Recycle		
[15]	Imagine	Define		Realize	Use/support/ service	End of life			

example of the evolution of the PLM concepts. Kovács et al. [8] dissect their representation to facilitate the identification of most subprocesses included in the life cycle. Grieves [14] is a representative author in the industrial sector for the PLM area. Stark [15] provides a condensed representation, comprehensive definitions and several points of view of the PLC concept. A list of PLM definitions is provided in the appendix.

Table 1 presents the PLC definitions by many authors. Aca's work [12] is partly based in Alting's [11], and provides another cycle which is divided into two major classifications: engineering and supply. These have three stages respectively. Based on his work, Guerra et al. [13] add an ideation stage at the beginning of the cycle. Similarly, Kovács et al. [8] propose an engineering stage subclassified into product design, process planning and factory planning. They also present two other stages with subclassifications: support activities chain and operations chain. These three stages are parallel. Grieves [14] proposes seven stages which are shown. In turn, Stark presents different points of view about the life cycle, including the user and manufacturer perspectives. The table shows a condensed version of these two.

In the following sections, these concepts will be used in an attempt to provide an integrative and more general definition of the PLC, which is depicted in Fig. 1

Fig. 1 Stages of PLM

2.2 Relationship Between Concurrent Engineering and PLM: The Development Stage

A look into the early stages of the PLC shows that product design and product development are interpreted differently by many authors. According to Suh [16] , design is “an interplay between what we want to achieve and how we want to achieve it”. He states that every designer follows these tasks: (1) know or understand their customer’s 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, and (5) check the resulting design solution to see if it meets the original customer needs. Likewise, Aspelund [17] says that “design is a plan of action, created in response to a situation or problem that needs solving.” In his opinion, there are seven stages in the design process: conceptualization, exploration/refinement, definition/modeling, communication and production. In this case, production is referred not as mass-production, but to prototypes or single pieces. Conversely, development, as it is defined by Otto and Wood [18] and Aca [12], include both design and manufacturing plans.

As it is depicted in Table 1, Alting [11] specifies that the development work normally begins based on an assessment of a need recognized in the market [10]. In his definition of Product Development, Aca describes four subactivities called Conceptualization, Basic Development, Advanced Development and Launching, where Basic Development includes the gathering of customer requirements information [12]. Guerra et al. [13] mention the ideation stage and keep the market requirements given by Aca within Product Development [19]. Grieves also takes into consideration that there is a need prior to the formal definition of the product [14]. Finally, Stark mentions the previous existence of a “dream in someone’s head” [15] which is later concretized.

In a PLM environment, the development stage should comprise a holistic view of the whole PLC [1]. Concurrent Engineering (CE) fits and is used in this phase, because its focus is on the integrated design of products, and its goal is that outset developers consider all elements of the product life-cycle [20]. CE intends to prevent adverse choices regarding a product by bringing together different disciplines such as product design, manufacturing, procurement, maintenance and marketing [21, 22]. The collaborative design of a product and its manufacturing processes needs information on product features, manufacture, services and costumer requirements while the design is simultaneously going on [23]. This information includes part and plant layouts, designs and manufacturing rules, as well as any other useful information for the product life-cycle [23].

Note, however, that CE only happens at the development stage of the PLC. For example, it doesn't comprise the actual production, but its planning and design. In other words, the only physical results from CE could be partial or complete prototypes.

2.3 Production and Market Activities

Production and **market activities** are related. For example, it is difficult to distinguish the boundaries between materials requirements and procurement. On the one hand, a brief examination of Table 1 shows that every author coincides in the existence of a production or realization stage. It should be noted that Stark refers to "realize" as the production phase [15]. *Production* basically refers to the manufacturing and quality assurance tasks, i.e. everything that happens in the shop floor. Materials acquisition is also considered as part of this stage. The squared boxes of Table 1 are included in this phase

On the other hand, it can be seen by the arrow boxes in Table 1 that there is an overlapping between **production** and what will be referred as *market activities*. According to Jüttner et al. [24], the product life-cycle management needs to "balance fast response to changing consumer demands with competitive pressure to seek cost reductions in sourcing, manufacturing and distribution". In Aca's work [12], production and sales are mixed into a single phase. This representation is followed by Guerra et al. [13]. However, it can be seen that the rest of the authors keep market, sales, or distribution separate from the manufacturing or production stage.

Market activities include marketing and trade of goods. Therefore, supply (or distribution), sourcing (or procurement) and sales are also part of this stage. The market requirements are communicated to developers to include clients' needs into product specifications. Note that these are restricted by production capabilities. The market behaviour also determines the strategy of the company towards New Product Development (NPD) and investments. The supply chain management requires both the business administration and engineering planning, and is determined by both the production volume and distribution channels

2.4 Use and Maintenance

As it happens with production and market activities, *use* and *maintenance* have a direct relationship. The use stage is customarily related to the customer or operator [15]. As the product is used, it will eventually need support, repair, service or upgrade to keep it in good conditions, change its application or improve the way it works. From a life-cycle perspective, the manufacturer plans this in advance. Furthermore, product-service supply is increasingly becoming more relevant to the point that companies could solely provide accompanying services for products manufactured by themselves or another company [8].

Even when it is not shown in table 1, Alting specifies that there are companies and user costs due to warranty service and maintenance during what he calls the usage stage [10, 11]. In his graphic representation of PLM Grieves does not include **use** or **maintenance**. However, in his definition of PLM, he states that the product life goes "from its design through manufacture, deployment and maintenance-culminating in the product's removal from service and final disposal" [14]. This clearly reflects that the product is obviously used at some point of its life, and that it is prone to maintenance. In the case of Stark, he differentiates **use** from support and service as it is perceived by the client and manufacturer. In his words, "when the user is using the product, the manufacturer will probably need to provide some kind of support" [15]. All of the above denotes that there is a concern about **maintenance**, and reinforces the argument that it is strongly related to the **use** phase.

From a corporative perspective, there are basically two options for maintenance: outsourcing and in sourcing. In the first case, the buyer may come to an agreement with the manufacturer as to receive maintenance from them, or may sublease another company which is specialized on that service. In the in sourcing case, the company can direct its own resources to give support to the product. The advantage of outsourcing is that it enables companies to concentrate on their core competences. Therefore, they don't have the need to train and maintain a department or specialist for this task. Most of the time, this requires that external entities involve in the daily activities of the assisted company, which is not always beneficial. This is rather true for high-tech enterprises that need to keep a low profile about their processes.

In Fig. 1, the use and maintenance stages are separated due to the fact that the user and service provider most often deal with the product at different times and locations, and they have different goals towards the product.

2.5 Disuse

The ***disuse*** of the product comes when it doesn't provide enough benefit to the company or user, and needs to be recycled, refurbished for sale or disposed.

Stark [15] calls it end of life, Grieves [14] addresses it as disposal and recycling, both Alting [11] and Aca [12] call it disposal, so do Guerra et al. [13]. Kovács et al. [8] include recycling as part of their PLM definition as well. The intention behind the term **disuse** is to state that the product may or may not continue existing after it is not used anymore, that there are many possibilities for what happens afterwards, and that it is no longer used for the purpose for which it was designed. It also reflects that its owner may change, but its lack of usefulness determines its retirement.

3 PLM tools taxonomy and techniques

Figure 2 presents a taxonomy of digital tools and techniques used in PLM. The proposed classification takes into account that people within a company have different profiles regarding their activities and the tools they use. The PLM tools are divided into three major categories: tools for engineering, for knowledge management and for business activities. Except for ambient intelligence (see Fig. 2), the engineering digital tools are implemented for concurrent engineering within the development stage (see Fig. 1) presented in Section 2.2. Business tools refer to the software used in the market activities (see Fig. 1). In a simplified way, Knowledge Management (KM) tools are used to transfer and manage data throughout the stages of PLM (see Fig. 1) and their respective tools (see Fig. 2), so they are used by both business and engineering tools.

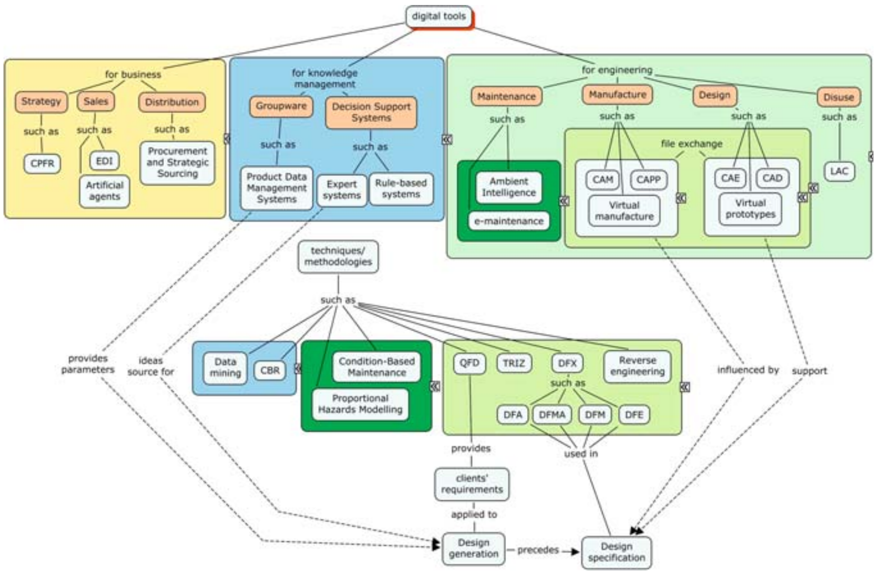

Fig. 2 Taxonomy of the digital PLM tools and techniques

Representative examples are presented for most of those subclasses. Going from specific to general, these tools are implemented in their respective stage and are linked to the rest of the tools (view Fig. 1). For example, CAD software is used for engineering design in the development phase.

3.1 PLM–KM Digital Tools

Knowledge Management Systems (KMS) are represented in the middle of Fig. 2. These are information systems which make knowledge available to people as required [14]. They are a mean to create, share and use knowledge [15]. These tools are divided into Groupware and Decision Support Systems (DSS). Gallupe defines Groupware as "Software and hardware that enables workgroups to communicate and collaborate" [25]. It is a new type of computer software and work processes to collect, document, classify and organize knowledge [26]. The definition provided by Gunnlaugsdottir is "collaborative technology which allows people to communicate with each other, co-operate on projects and share information and knowledge" [26]. Beyond this definition, she states that:

> The groupware links employees together and connects them with the information and knowledge base of the organisation, offering them the opportunity to use it and expand it. Records are safely stored in an organised, central database where all authorised employees have access to the latest versions of manuals and other documents and records. The system offers also version control, that is how many versions were made and who wrote each version. [26]

The most common Groupware used for PLM is the Product Data Management (PDM) system which aids companies in managing all product-related data throughout the product life cycle (view Figs. 2 and 3). 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 systems keep data shareable, transportable, secure, accurate, timely and relevant [15], The fist term, shareable, refers to data that can be easily 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. It can also be said that timely data is current and up-to-date. Finally, it can be called relevant if it is really useful for the decision in turn. Likewise, PDM systems provide the platform in which every kind of user can access the information to share or modify it. However, software such as CAE or CAM tools (see Fig. 3) should be used to modify the integrity of the given data. In Fig. 3, the data is represented by NC codes, marketing statistics, user manuals, repair reports, profit of recycling and CFD data. This resembles the idea that PDM systems connect data throughout many other applications, but doesn't modify it.

Fig. 3 PDM as the data bus (left) and elements of a PDM system (right)

An expert system is a Knowledge Based System (KBS) that emulates the decision-making ability of a human expert. Remark that an expert can solve problems that most people cannot or can solve them much more efficiently [27]. "In the commercial world, however, there are systems that can effectively and efficiently perform tasks that do not need an expert" [7], for instance, Rule-based systems [28].

Note that an expert system is limited to a determined activity. For instance, an expert system for maintenance cannot be used for engineering analysis.

Some of the expert systems developed for product design are: ProPlanner® and Expert system for product manufacturability and cost evaluation. Some Rule-based systems are: Product audit tool®, and Boothroyd & Dewhurst's DFA and DFM Concurrent Costing®.

It is important to mention that the digital tools for business and the digital tools for engineering are integrated by the knowledge management tools. Furthermore, some of the business or engineering tools already have knowledge management tools embedded. For instance, there is software for design and manufacture that shares files indistinctly (e.g. CATIA® and DELMIA® from Dassault Systèmes®) and can create design rules for product families (e.g. the Knowledgeware module from CATIA®).

3.2 PLM Business Digital Tools

The business administration, sales and marketing department are essential for an extended enterprise. The market activities have not been fully integrated to the PLM maybe because the PLM concept was coined within the engineering niche. However, the people involved to what has been referred here as market activities also deal with valuable information regarding the product life-cycle. Therefore, the information they provide also drives the life of the product.

Some companies use different strategies to be more competitive. One of the most comprehensive and detailed **strategy** tools is the Collaborative Planning, Forecasting and Replenishment (**CPFR**) [29] (view Fig. 3). The Voluntary Interindustry Commerce Standards (VCIS), which is responsible for the adoption of the bar-coding, and the Efficient Consumer Response (ECR) Europe claim that it helps retailers and manufacturers to get more accurate forecasts, reduce stock-outs, increase sales, reduce inventories [29], higher order fill rates, and faster cycle time [30]. The CPFR is Web-based, and its goal is to coordinate trading partners on various activities such as production and purchase planning, demand forecasting, and inventory replenishment [31].

Figure 2 shows **artificial agents** as part of the sales tools. Firstly, it must be understood that the "Agency Theory studies the contractual relationship between two parties" [32]. An **artificial agent** is a Knowledge Based System able to communicate, interact and negotiate with other agents, which can be intelligent, human or artificial [33, 34].

Electronic Data Interchange (EDI) (see Fig. 2) allows a computer-to-computer exchange of business data for a transaction without human intervention [30]. EDI is used to reduce cycle time, improve inventory management, increase productivity, reduce costs, improve accuracy, improve business relationships, enhance customer service, increase sales, minimize paper use, and increase cash flow [30].

Procurement and Strategic Sourcing tools are very common for business practices such as Customer Relationship Management (CRM) or chain supply design tools. This type of tools is used for the **distribution** management of the product (view Fig. 2). "An e-procurement B2B system is an open system that enables the organisation to reach and transact with suppliers and customers in virtual markets" [35].

3.3 PLM Engineering Digital Tools

Four basic categories are presented for the engineering classification of the PLM digital tools taxonomy. It can be seen from Figs. 1 and 2 that these correspond to the development, production, maintenance and disuse stages presented in Section 2.

From left to right, the first engineering tools classification is **maintenance**. In most cases, the digital tools used for this activity are limited to the development stage, where the disassembly process is modelled, for example. Even when this approach is useful for servicing products, there is much more information about what is actually done in the repair shop during the maintenance stage which needs to be integrated into the PLM.

The term **ambient intelligence** was coined by Emile Aarts of Philips [36]. It is defined as "the convergence of ubiquitous computing, ubiquitous communication, and interfaces adapting to the user" [8]. It is a field of information systems that is rapidly increasing, and could be used to provide valuable information about the current status of the product [8]. This information could be sent and received from the shop floor to the KMS of the company to integrate the support department with the other departments of the company such as procurement (to get spare parts) or development (to improve designs through Design for Maintenance). Emilini points out that the "Maintenance of ambient intelligence environments and of their components is also expected to play a significant role with respect to health and security issues" [37].

One of the most promising tools to incorporate the **disuse** (see Fig. 1 and to the right of Fig. 2) stage within the PLM is the Life-Cycle Assessment (LCA) [38]. This kind of software can evaluate the environmental impact of a product (as well as processes or activities) throughout its life [39] by compiling an inventory of relevant inputs and outputs [40]. Some of the most popular tools for this assessment are GaBi4 and SimaPro 6 [39].

The most thoroughly digital tools that are used within PLM are the Virtual Concept tools. These include the **manufacturing** and **design** software for the development stage (see Section 2.2). The design tools are able to produce virtual prototypes of products, reducing scrap and improving quality of products [41]. These virtual prototypes are digitized versions of the real products that can be tested and simulated in near-to-in-situ operation. The Virtual Manufacturing tools support the design and simulation of process by means of layout planning, factory flow simulation, ergonomics and DMU kinematics [42].

3.4 Techniques and Methodologies Used for PLM Tools

The digital tools use several embedded methodologies or techniques to accomplish their goals. In the case of KM tools, two very common techniques are Data Mining (DM) and Case Based Reasoning (CBR). DM is an advanced technology that can process large amounts of information, discovering useful information and knowledge to support decisions [43]. CBR is a technology that provides KMS with some degree of intelligence by comparing the situation in hand to past captured experiences to solve the present case [43].

Maintenance is a fertile area to develop for PLM. Reliability prediction is one of the most difficult issues to address in this regard, because there are many variables involved. However, failure can be prevented by techniques such as Condition Based Maintenance (CBM; see the center of Fig. 2) which is used to determine when preventive maintenance should be performed [44]. CBM means maintenance tasks based on the current status obtained from in-situ, non-invasive tests [45]. It requires data from products to determine when service is to be done. Therefore, this technique is used by ambient intelligence tools to infer whether maintenance is needed or not [8].

Another technique used for the maintenance of products is the Proportional Hazards Modelling. It is a technique that can make use of oil analysis results collectively to perform statistical control thresholds to asses the risk of failures [44]. But again, it requires a knowledge source which could be populated by the ambient intelligence tools. This data would relate to (1) failure/replacement data; (2) inspection data; (3) maintenance action data; and (4) installation data [44].

There is a wide variety of techniques for design. Figure 2 presents four of these. First, Quality Function Deployment (QFD) is a way to identify customer's requirements [1] to generate clear engineering specs thus, minimizing the waste and changes in products [46]. TRIZ is a Russian methodology that is primarily useful in identifying physical working principles to solve technical problems by finding implicit contradictions in a problem. 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[1], DFM[2], DFMA, DFE and DFR are just some of the most common types of methodologies [47]. Every special case of DFX follows a set of rules, guidelines or procedures to accomplish its ends All of the above (QFD, TRIZ and DFX) can be integrated into the development tools to generate and specify designs in some way (view dotted arrows in Fig. 2), for instance, by the integration of expert systems and CAD software [48].

4 Case Study

The case study in this section shows how the tools presented in the PLM taxonomy are applied on a redesign project. The case study was taken from the PURDUE solar racing project. This project involves the construction of the 7th generation of a solar racing car, or in other words, it consists of improving the current solar racing car. This project started on September 2006 and will finish during spring 2009.

The scope of this experiment is the hub system redesign. DFX process framework will be followed in order to achieve that, and will be supported by the "Methodology to support DFX process using a PLM framework" [48], which includes the next stages: (1) Defining product requirements, (2) Design for Assembly application and (3) Creating new knowledge and expertise. Each of those stages are matched with the property step from the Methodology to support DFX process using a PLM framework.

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

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

4.1 Defining Product Requirements

This is the first stage to be achieved in this case study. The product requirements are provided mainly by the product customers. The costumer requirements are then translated from common language into technical parameters to modify using a QFD methodology. In this case study, the last solar racing car team was considered as customers due that they have the use and building experience of the last version.

After an interview with the "customers" they provide the next requirements for the product:

- Mechanical systems must be improved. Those systems include chassis & Roll Cage, Uprings, Axles, Hubs, Brakes, Training Arm and Steering.

4.2 Design for Assembly Application

The main issue in this stage is the application of DFA tool designed by Boothroyd in order to perform the DFA task. However, before that, is necessary to collect the useful product information available. In addition, the PDM application will be executed in order to support this stage. The methodology steps developed in order to support the mentioned issues are the second and the third ones, which are: Getting Design for Assembly (DFA) information and Product data-information management through a PDM system.

4.2.1 Getting Product Information

The product information collected corresponds to the hub system only, due that it was the section assigned to this case of the study (Fig. 4). The product information collected consisted in CAD files, Drawing files, CAM application files, report documents and pictures files. CAD files and drawings format was pro-e; CAM application files include mainly finite element analysis. Report documents include Vehicle impact analysis and mechanical systems analysis.

4.2.2 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 provide it at the designers in the best way. However, according with the methodology proposed, previously to PDM application 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.

Solar racing car has six stages into its lifecycle (view Fig. 5). 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,

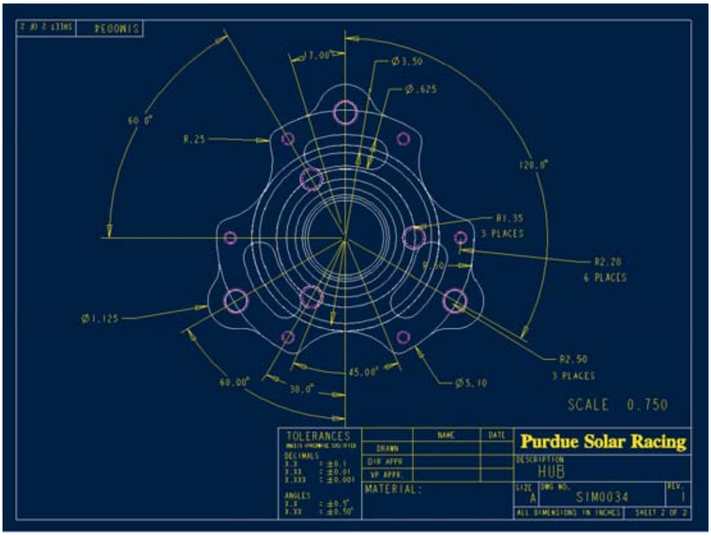

Fig. 4 Hub Drawing (*Top View*)

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.

4.2.3 Defining PLM Actors

Once solar racing car lifecycle has been defined, it is necessary to define who the actors are at each stage in order to analyze what kind of information is generates by each one as well as to decide which information must be shared them (Table 2). For instance, product designers could need some material properties information, while marketing is just interested in which will be the final solar racing car shape in order to create some publicity about it.

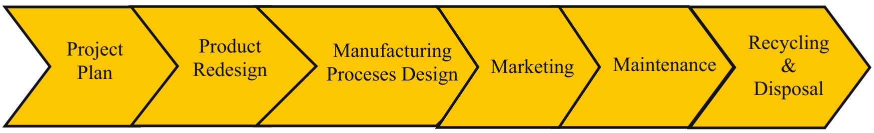

Fig. 5 Solar racing car lifecycle

Table 2 Actors into solar racing car lifecycle

	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

4.2.4 Organizing Information

The information collected was organized following the organizing product information class diagram proposed in the methodology (Fig. 6).

4.2.5 PDM System Application

In this case study, Teamcenter® Community is the commercial software holding the PDM system. The Teamcenter community is used for managing the product information through the entire solar racing car lifecycle. Then, in order to star using Teamcenter community, is necessary to create the Teamcenter Community site for the user̀s access. 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.

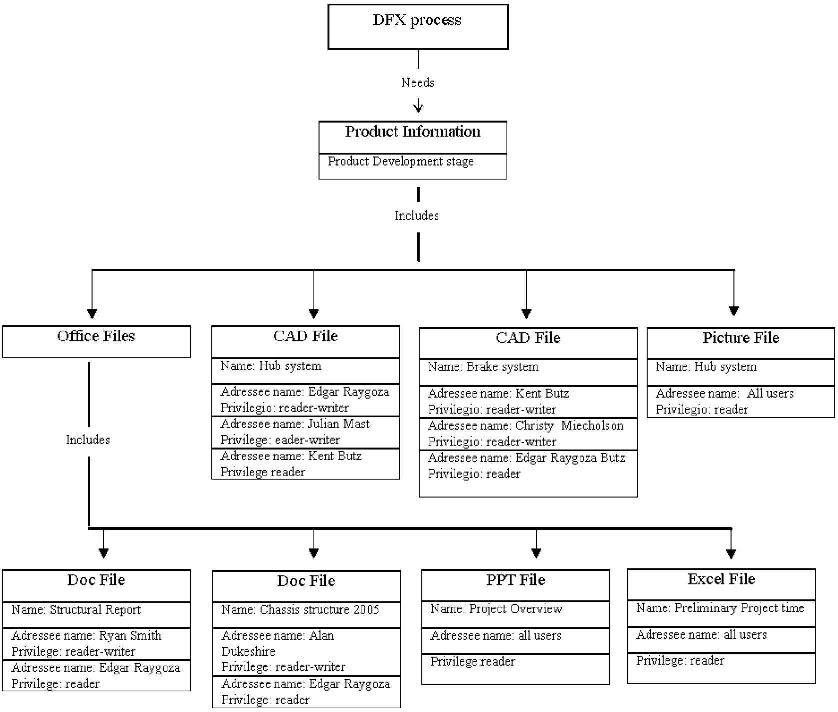

Fig. 6 Organizing information through UML

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 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.

4.2.6 Boothroyd DFA Tool Application into PDM Environment

After applying Boothroyd's methodology it is necessary to define the most economic assembly method for the particular project. Boothroyd proposes three categories of assembly: manual assembly, special purpose transfer machine assembly and robot assembly.

The most economic assembly method can be determinated 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 in Fig. 7.

The worksheet filled with the information of the assembly is shown below as Fig. 8.

After analyzing the assembly with the support of the worksheet above, it 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 Fig. 9.

4.3 Creating New Knowledge and Expertise

The final stage is the creation of new knowledge and expertise, and the third step of the methodology supports this stage in order to capture those knowledge and

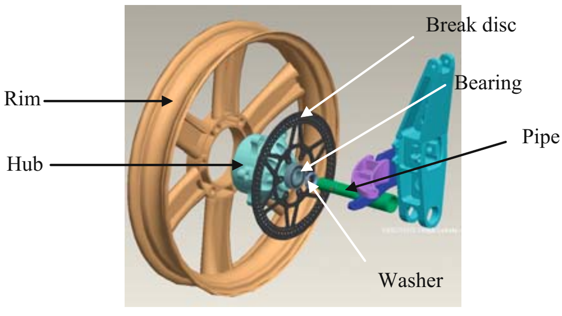

Fig. 7 Hub system assembly exploded

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. 8 Worksheet for Hub system sub-assembly

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 CLIPS.

4.3.1 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.

4.3.2 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

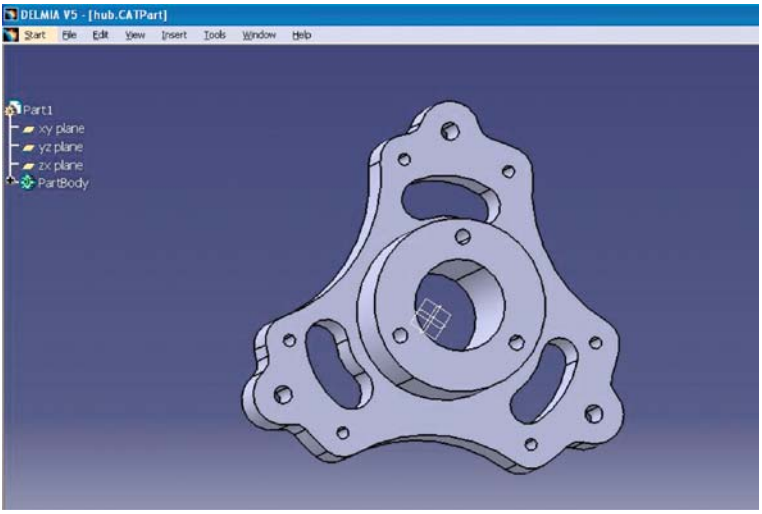

Fig. 9 New hub design

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.

Programming 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 Fig. 10.

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.

4.3.3 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.

4.4 Results

The taxonomy presented helps to clarify PLM tools implementation. The methodology based on the PLM tools taxonomy was measured through a comparison with the last solar racing car project. The most important benefits

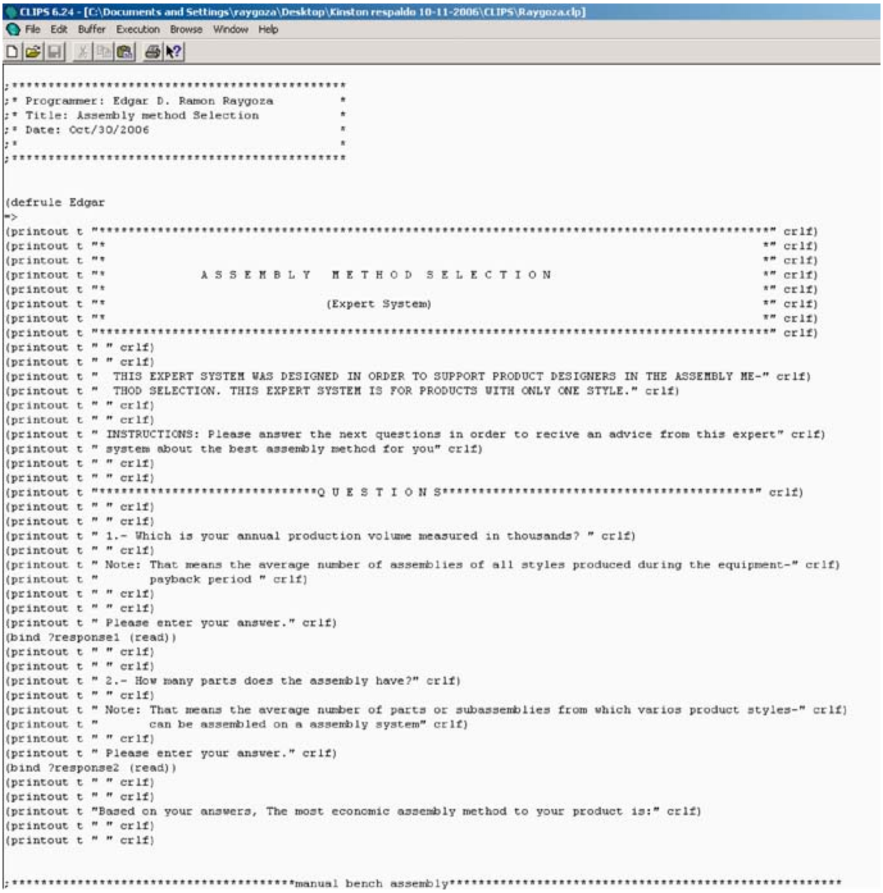

Fig. 10 Expert Systems programming

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 to organize and to share all the information related with the hub through all the designers. In addition, the **Expert System** allowed to reuse the experience of the designers. Less spent time by meetings was achieved through the use of Teamcenter community platform that established a collaborative environment between the designers. Reduction on modelling mistakes was achieved with the use of the PLM tools **(CAD)** and correct information available in the PDM and expert systems. Finally, prototypes and testing cost reduction was possible through the use of

Table 3 Summary of Results

	Last version	Current version
Spent time by searching information and knowledge	96 hours/ 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 & Testing	USD$780.00	0

the **CAM-CAE** technologies available into the PLM tools. All the depicted points are summarized in Table 3.

5 Conclusion

It can be concluded that the PLM tools classification into business, engineering and knowledge management is a good first approach to identify gaps in the integration of the software used for the different stages of the product life-cycle.

This article shows that it is important to improve the understanding between the development stages of a product and the ways in which the information and knowledge can be administrated within and among such stages. Therefore, it is extremely important to define new frameworks and their respective taxonomies to improve the implementation of new PLM tools and concepts. In this sense, the present work has defined a taxonomy to clarify the use of those tools, and broadens the vision to incorporate new concepts.

In this way, the definition of new taxonomies allows to reach a better understanding and integration of the different stages that comprise the integral product development, and the different tools they use. The integration is not only benefited in the product realization phases, but also in the globalized collaboration of different organizations that could interact for such realization.

The conception of the framework was leveraged by the PLM tools taxonomy. It is a novel way to bring together Expert Systems, DFX and PDM systems. These are PLM tools which had not been fully integrated previously.

The value added up to now in this research is that even though a PLM taxonomy has been defined to support the implementation of PLM concept, additional research is needed to explore new scenarios of the interconnection between the applications used within each product life-cycle stage. New PLM taxonomies are required to develop collaborative environments to foster the coordination and cooperation among global groups, supported by tools and methodologies that enable intellectual capital sharing in real time.

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Appendix: Several PLM Definitions

Thimm et al. [49]

Product Life-Cycle Management (PLM) is a strategic business approach that consistently manages all life-cycle stages of a product, commencing with market requirements through to disposal and recycling (see Fig. 1). PLM involves a multitude of stake holders (e.g., customers, suppliers, and regulators), who require various levels of detail and representations of information.

CIMData [50]

"PLM is not just a set of technologies, but 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. PLM forms the product information backbone for a company and its extended enterprise."

Kovács et al. [8]

"The PLM concept appeared in the second part of the 1990s. This concept provides a platform to share product-related knowledge across an extended enterprise, from product design and creation, through dissemination and after sales services, up to product dismissal and recycling . . . PLM is defined as 'a new integrated business model that, using ICT technologies, implements an integrated cooperative and collaborative management of product related data, along the entire product lifecycle, dismissal included'."

Chiang et al. [51]

"Amann et al. (2002) defined PLM as 'a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination and use of product information across the extended enterprise from the concept to the end of product life – integrating people, processes, business systems and information.' Extending from product data management (PDM) scope, CIMdata (2003) defined PLM in 11 key functions. They include (1) document and content management, (2) engineering change process management, (3) collaborative product design, (4) bill of materials management, (5) supply chain integration, (6) part classification management, (7) product service management, (8) program and project management (PM), (9) product portfolio management (PPM) and analysis, (10) data authoring and analysis, and (11) digital manufacturing."

Jüttner et al. [24]

"Product life cycle (PLC) management as the integrated, information-driven approach to all aspects of a product's life, from concept to design, manufacturing, maintenance and removal from the market, has become a strategic priority in many company's boardrooms."

Turban [7]

"(PLM) is an integrated, information-driven approach 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."

"PLM's goal is to streamline product development and boost innovation in manufacturing. PLM has the potential to vastly improve a company's ability to innovate, get products to market, and reduce errors."

Stark [15]

"(PLM) is a new activity for manufacturing companies that opens up new business opportunities..."

"PLM manages each individual product across its lifecycle – from 'cradle to grave'; from the very first idea for the product all the way through until it is retired and disposed of."

"(PLM) enables the company's complete portfolio of product to be managed in an integrated way..."

"PLM is a holistic business activity addressing many components such as products, organisational structure, working methods, processes, people, information structures and information systems."

Grieves [14].

"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".

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Social Issues of Product Lifecycle Management: Developing Cross Cultural Virtual Teams; Supporting Today's Green Manufacturing Imperative; Educating and Preparing Tomorrow's Workforce; and Impacting Inter-Organizational Relationships in Supply Chain Management

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Abstract Product Lifecycle Management, as an enterprise-wide, information-driven business approach to reducing wastes and reallocating captured resources in support of product and process innovation, is not without its challenges. Major social issues are considered in this chapter, concluding with an example of a PLM-like application. The first topic for consideration addresses the context in which PLM is practiced, namely, the virtual environment. In particular, the challenge of working in a cross-cultural virtual team environment is presented and a theoretical model in support of creating a successful and productive team is suggested. The second topic addressed in this chapter proves to be timely given the current debate on how best to mitigate and adapt to the effects of global climate change. In this section, PLM is presented as a strategic business initiative that simultaneously drives green manufacturing while supporting organizational sustainability. The third topic addresses how best to prepare tomorrow's workforce for a PLM environment. The issue of education is discussed in terms of a practitioner-based, competency model. Finally, an example of a PLM-like application in support of the development of inter-organizational relationships in supply chain management in higher education is presented.

This chapter represents the collective work of Dr. Cynthia Tomovic and named students. Each section of this chapter was pressented previously as separate papers by students at the International Conference on Comprehensive Product Realization, 2007 in Beijing, China.

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1 Introduction

Globalization of business is forcing managers to grapple with complex issues as they seek to gain or sustain a competitive advantage. With expanding world markets and increased international business competition, comes a corresponding demand for organizations and individuals to be knowledgeable about and prepared to operate in the global environment. Innovation, adaptation, and adoption have determined, to a large degree, the economic fate of nations, business, and industry working in a global economy. The key to survival for many organizations is the ability to capitalize on the potential of advancing new knowledge/technology. In spite of its promise, however, technology transfer and assimilation demands substantial changes in the way in which organizations operate. While technology helps to eliminate a number of barriers to globalization, many significant barriers remain, notably those involving people and the organizations we build around them.

The benefits of adopting a new knowledge/technology are undeniable, however, human factors and organizational relationships either enhance or constrain potential quality, productivity, and financial gains. Successful organizations know that they cannot put their faith in new knowledge/technology alone, as human issues are equally important and often demand even greater attention than technology.

Product Lifecycle Management (PLM) is an integrated, digital formation-driven approach to conducting business – comprised of people, processes/practices, and technology affecting all aspects of a product's lifecycle, from its design through manufacturing, deployment and maintenance, culminating in the product's removal from service and final disposal. Be definition, given that PLM is driven by digital information, users must become somewhat electronic savvy. However, just as it is important for people to be knowledge about the technical side of PLM, it is equally important that they be knowledgeable of its human side. The aim of this chapter is to explore social issues associated with PLM, namely, the virtual environment as the context in which PLM is conducted; the practice of PLM as a strategy in support of green manufacturing in the fight against global warming; the education preparation of tomorrow's workforce for a PLM environment; and to illustrate the impact of information sharing on the development of inter-organizational relationships in supply chain management. In essence, this chapter suggests that the success of today's "high-tech" initiatives, like PLM, are dependent on "high-touch" people-driven considerations.

2 Virtual Environment – Context of PLM: A Model in Support of Cross-Cultural Team Development

The importance of a well functioning cross-cultural virtual team (CCVT) is imminently important in today's global environment. Having a successful CCVT can be the difference between being the market leader or struggling to survive in today's global business arena. The diversity and flexibility of virtual cross-cultural teams, however, can be difficult to achieve. The introduction of collaborative PLM tools may prove to be critical to organizational success. From the components of virtual teams to the cultural elements needed to create a CCVT, this section of the chapter covers many aspects of CCVT. The Cross-Cultural Virtual Team Model (CCVTM) presented can be used to create a virtual team in a multinational corporation and may be tied back to the integration of a PLM system. A successful PLM system is the key element within the CCVTM. Conversely, the CCVTM supports and strengthens the PLM system.

2.1 Cross-cultural Virtual Teams

In today's business world, leaders must pay greater attention to communications and the social system among their employees. It is critical that organizations control how employees collaborate and coach them in how to interact with one another. It is challenging to establish Virtual Team Management since technology is a substitute for human face-to-face interaction. While time and space constraints are concerns of virtual team environments, companies launching a global virtual team with PLM support must address issues of cultural differences among the team members. PLM enables easy access to information, knowledge, and data sharing; yet some of its users fail to maintain well organized teams because they have not considered cultural distinctions of its members. This section provides suggestions for creating cross-cultural virtual teams, as well as, provides examples of difficulties concerning the implementation of cross-cultural teams.

2.1.1 Components of Virtual Teams

Individuals tend not to consider cultural differences and think that people are the same across cultures. However, culture has a major impact on the effectiveness of teams. According to Gannon, team members from the same cultural background are said to be of average effectiveness; while multicultural teams

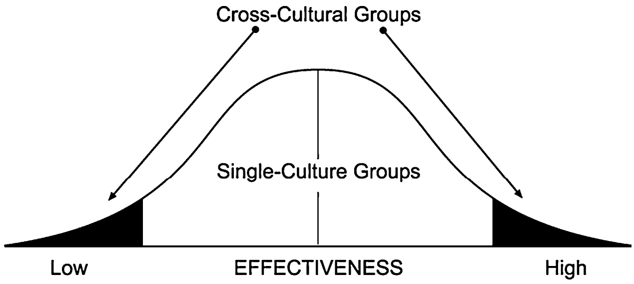

Fig. 1 Model of cultural impact on team effectiveness (Adapted from Adler (1983))

tend to be either highly effective or ineffective (Gannon 2001). Citing Kovach, Gannon suggests that the level of effectiveness is directly related to the leader's role in choosing team members so as to avoid the risk of low effectiveness. This paradox is displayed on Fig. 1 that shows the relative productivity of 800 teams consisting of 4 to 6 members (Gannon 2001). This figure illustrates that certain cultural factors may aid or present team effectiveness. While single-culture groups are limited in their effectiveness level, multi-cultural teams have the potential to increase productivity.

This model suggests that multi-national teams are an asset in today's global environment as they provide high productivity and different approaches to tasks. However, individuals from different cultures vary in terms of their communication and group behaviors, including the motivation to seek and disclose individuating information and the need to engage in self-categorization, identify with a particular group (Gudykunst 1997). According to Hofstede, one of the dimensions of cultural variability is individualism-collectivism. Individualistic culture members tend to value the needs, values, and goals of the individual over the needs, values, and goals of the group. In collectivist cultures there is an opposite tendency (Hofstede 1980). Hofstede suggests that members of individualistic cultures are likely to be less concerned with self-categorizing, are less influenced by group membership, can easily adjust to changing groups, and can involve themselves in more open and confident communication than their counterparts from collectivist cultures (Hofstede 1980). Members from both types of cultures represent a vast array of experience and training which, if managed appropriately, could collectively lead to greater team performance due to the richer synergy created based on a broader spectrum of viewpoints. When having such diverse cultural backgrounds in one team, there are essential factors that link all members together and enable effective management of the team. These important factors, presented by Hastings (Hastings et al. 1994) include:

- **Trust** – team members expect their partners to deliver to agreed times and specifications. Creating trust among team members that represent different attitudes may not be easy, knowledge and a willingness to work together to overcome cultural differences for mutual benefit is required (Cartwright 2003). Members' reaction to particular stimuli in the first communication events often produces patterns that may prove to be long-lasting in a team. Thus, it is important to encourage team members to be tolerant, to learn about and from one another, and to be willing to adapt and change communication behavior accordingly. Regarding the electronic environment, it has been suggested that electronic communication, without the ability to send non-verbal cues, e.g., gestures, accents, dress codes, etc., may actually enhance team member trust and hence impact productivity (Jarvenpaa and Leidner 1999).

- **Control** – choosing the priorities for control by a team and leaving out some elements for an individual to decide on priority. A team's responsibility lies mostly in meeting objectives and remaining within budget. Teams need to be focused, especially in a virtual environment. The tactic of filling in the subject line on everyday messaging helps to maintain focus on the task (Lipnack and Stamps 2000).
- **Motivation** – motivation is a critical element for a high performing project team, especially in a virtual environment. Virtual team members need to overcome the sense of isolation (Nauman and Iqbal 2005). There is no presence of physical contact and so the team needs to look for substitutes. Chat rooms and video communications helps to support team bonding (Hastings et al. 1994).
- **Communication** – differences in culture and language hinders communication. When co-workers are dispersed, socializing is significantly reduced. They rely heavily on information technology to communicate (Nauman and Iqbal 2005). Cartwright describes one virtual team he worked with in which members prepared cue cards that were held up during the videoconference. They read: "LAUGH", "RUBBISH", "WHAT?", and other replies and were found very effective (Cartwright 2003).

Nauman and Iqbal (Nauman and Iqbal 2005), in their article on challenges of virtual project management, present some recommendations for improving the virtual processes:

- Members in virtual team environments often have expertise in a specific area, so there is great need for knowledge sharing via effective communication and knowledge management techniques.
- Face-to-face communication in the beginning of forming a team is an essential condition in establishing higher levels of trust and motivation among specialists working from geographically dispersed locations.
- Managers or team leaders must be communication mediators between the members of virtual teams in order to reduce conflict.
- A single communication point is a must to avoid idleness and conflict.
- The suitable use of telephones, video-conferencing, and face-to-face meetings should be considered vital for effective communication.
- Leaders should effectively implement roles and responsibilities which are essential.

2.1.2 Creating Virtual Teams

In order for a well performing group to be formed it needs to go through several stages. There are five steps: forming, storming, norming, performing, and adjourning. Some groups go through the stages in a different order or omit some of them, but this model is good at describing a group's development (Tuckman, 1965). The forming stage is best accomplished if the team members meet physically if possible. This effort is said to be expensive yet it pays off when the team starts working on the project. In this stage, trust is already present owing to the fact that the members have already been acquainted with one another. Many companies initiate the project by bringing people together and allowing them to interact socially. In the case of conflict where it is hard to define an attitude of an individual on the other side of instant messenger, teams need to rely on the individual making their feelings known to the group (Cartwright 2003).

According to Duarte and Snyder (Duarte and Tennant-Snyder 2001) there are six essential competencies in creating virtual teams:

1. Performance Management and Coaching (team, individual performance, compensation)
2. Appropriate use of Information Technology
3. Managing Across Cultures
4. Aiding in Team Members' Career Development and Transition.
5. Building and Maintaining Trust and Networking
6. Developing and Adapting Standard Team Processes.

2.2 *Introduction to Cross-cultural Studies*

Since virtual teams are such an integral part of the PLM process, it is important to create them in such a way as to achieve a high level of communication, trust, and coordination. When forming virtual teams across cultures, rather than groups that are formed within the same culture and/or country, some variables come into account that can dramatically affect group performance. In order to understand these variables, two different cultural studies are considered; Geert Hofstede's study of Cultural Variables and the Project GLOBE study. After a thorough review, the most important lessons will be selected and compared with what was learned about effective virtual team construction. The overlaps between these studies form the basis upon which the present cross-culture virtual team model was constructed. A discussion of the two studies and their relevance to the development of the model follows.

2.2.1 Hofstede's Value Dimensions

Geert Hofstede is a Dutch expert on the interactions between cultures, be it national cultures or organizational cultures. He developed his system over the course of several years from 1966. In his book, Culture's Consequences he posits that his research is critical to understanding not only organizational continuance, but to understanding mankind itself.

Hofstede believes that the "survival of mankind" will revolve around people learning to work together and accept others' cultural differences. He goes on to state that within the confines of human nature, understanding the thinking of a foreign culture is "not an intellectual luxury." Instead, he believes that gaining a heightened understanding of vague cultural differences is one of "the main contributions the social sciences can make to practical policy makers in governments, organizations, and institutions—and to ordinary citizens" (Hofstede 1980).

It is important to note that Hofstede's book was written in 1980, over 27 years ago before the rise of globalization as it exists today. Awareness and interest in global business has flourished since Hofstede's writings. His extensive work with IBM and later, the work of other researchers, led to the construction of a four dimensional framework (with a later fifth added) for assessing cultural differences. Hofstede's five dimensions are:

- **Power Distance** – This dimension addresses how less powerful organizational members both accept and/or expect the distribution of power to not be equal. It is defined from the perspective of the subordinate and not the superior of that subordinate. What this represents is whether or not a society endorses and accepts a disproportion of power by subordinates as well as superiors. While most societies differ in this dimension, sometimes the difference is extreme (i.e. some cultures Power Distance is so great that questioning authority in any way can lead to major consequences, whereas in others it is so small that the concept of superior and subordinate are vague or non-existent).
- **Individualism** – The individualism dimension shows the level of group integration within an organization. Highly individualistic cultures value personal responsibility, e.g., work by one's self, emphasis on and the taking care of one's own needs without extensively relying on other people. On the other hand, cultures ranking low in individualism are more prone to be bonded through group activity (collectivism). Collective cultures support the development of a collectivist attitude from birth and it continually reinforced in the society. Collective cultures often base much of their society on rewarding the actions of the group, where as individualistic cultures reward individual effort.
- **Masculinity** – Masculinity is a gender-based dimension in which behavior is described as being more male or female-like in expression. Hofstede's study revealed that there is a difference across cultures in the degree to which expectations of males and females are differentiated. In less differentiated cultures, males and females tend to act similarly, and both tend to express values and behaviors that western cultures associate with females, e.g., modesty, caring. In highly differentiated cultures, there is a greater degree of differentiation in male and female behavior. Both males and females tend to express values and behaviors that western cultures associate with male

behaviors, e.g., assertiveness, competitive, though females in these cultures tend to express these tendencies less than their male counter parts.
- **Uncertainty Avoidance** – Some cultures are based on highly structured ways of doing things and are intolerant of change while others are more open to accepting change and the inherent risk of the unknown. This dimension can also describe a society's aversion to accepting values that differ from their own (e.g. religion). Cultures that rank high in uncertainty avoidance tend to develop highly structure rule-bound societies. People within these cultures tend to hold a believe that there is little they can do to shape their future, they express a high locus of control. In contrast, societies ranking low in this dimension are more open to pursuits that have never been undertaken and have no specific set of rules to follow, people tend to think they create their opportunities, and as such, express a low locus of control.
- **Long-Term Orientation** (only recently applied to 23 countries) – As the name implies, long-term oriented cultures tend to base their decisions on outcomes in the future. Values such as perseverance, future ambitions, and fulfilling one's life goals are expressed in cultures with long-term orientations. Conversely, short-term oriented cultures (or ones that rank low in the long-term orientation dimension) are based more on fulfilling obligations that will have a more immediate or near term impact (Hofstede 1980).

It is fairly easy to see how Hofstede's cultural variables can assist in the development of creating cross-cultural teams. For example, should an individual from a country with high power distance be placed in a team where the group leader is from a country where power distance is low, the possibility that the leader finds the subordinate lacking in initiative is great.

2.2.2 Project GLOBE

Project GLOBE (Global Leadership and Organizational Behavior Effectiveness) is a major long-term multiphase, multi-method research project that studied cross-cultural leadership differences and similarities among countries. The study's objective was to quantify data and score it based on nine cultural attributes and six major leadership behaviors. The 62 countries involved in Project GLOBE amassed nearly 17,000 responses from managers in 951 organizations (House et al. 2004). The ongoing study of Project GLOBE has been very successful in defining human behaviors across different cultures. Questions asked include the following:

1. What qualities affect leadership?
2. What behaviors are universally accepted?

Each member in the project is referred to as a country co-investigator (CCI) and is responsible for their particular country. CCIs are responsible for studying specific cultures in which they have a certain level of expertise, meaning that they often are native to the region or have lived there long enough to understand local cultures thoroughly. CCIs collect both qualitative and quantitative data which they use to check the validity of their questionnaires, write descriptions of their specific country's culture (usually in context of the data), and give personal insights into their experiences within the culture. The CCIs are usually natives of the culture in which they collect information and most cultures contain 2 to 5 CCIs (House et al. 2007).

With the information collected by these research teams, Project GLOBE has formed nine measurable dimensions for differentiating between societal and organizational values (Javidan et al. 2006):

- **Performance Orientation** – level to which a society encourages and rewards people for performance excellence.
- **Assertiveness** – extent to which a culture endorses speaking one's mind and being confrontational versus being quiet and modest.
- **Future Orientation** – way in which a culture rewards future oriented behavior such as strategic planning and investing.
- **Humane Orientation** – extent to which a society encourages and rewards individuals for being compassionate towards others.
- **Institutional Collectivism** – level of loyalty felt towards the organization and its goals rather than one's own individual goals.
- **In-group Collectivism** – level of pride found in belonging to small groups within a society (i.e. work groups, family, religious group, etc.)
- **Gender Egalitarianism** – way a culture endorses gender role differentiation.
- **Power Distance** – level of equality distinction between superiors and their subordinates in terms of power, responsibility, and authority.
- **Uncertainty Avoidance** – society's reliance on social norms to avoid unpredictable future events.

2.3 Cross-cultural Virtual Team Success Model

The CCVTM below illustrates that the four major factors of virtual team success are clearly dependent on some type of collaborative tool, in this case, PLM and all of the technologies that accompany it. Without PLM these factors would not be achieved easily and in the same token these factors fuel PLM itself. For example, open communication between all departments – one aspect of PLM functioning – most certainly depends on trust, motivation, communication, and control.

As described in the previous sections, these factors are measured based on cultural aspects. When creating a cross-cultural virtual team these dimensions should be considered when selecting team members, or when developing cross-cultural training for potential team members. Consideration of these dimensions will likely increase the probability of team success within a cross-cultural virtual team environment.

The four major factors of virtual team are extremely dependent upon one another. For instance, if there is a lack of trust then open communication will

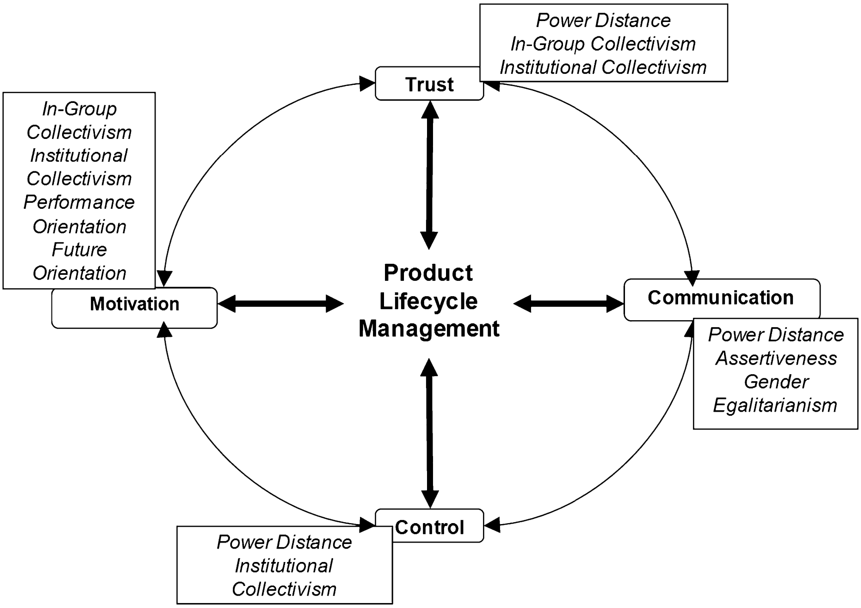

Fig. 2 Cross-cultural virtual team success model

most certainly falter. When just one of the four factors is compromised the cross-cultural virtual team will be in danger of self destruction. By addressing cultural dimensions as described, cross-cultural team productivity is likely to increase in a PLM environment (Fig. 2).

2.3.1 Trust

Creating trust among team members representing different cultural backgrounds is not easy (Catwright 2003). Building trust among team members may be facilitated by knowledge of power distance, in-group collectivism, and institutional collectivism. For example, representatives of a culture with strong in-group collectivism take pride in membership in small groups such as their family and close circle of friends, and the organizations in which they are employed. By definition, they reveal less trust to people from the outside. It may prove to be more difficult for members from a strong-in-group collective culture to embrace new assignments at first, but later they are likely to prove quite loyal. In essence, trust arises with knowledge gained about the members on the virtual team (Jarvenpaa and Leidner 1999).

2.3.2 Control

Depending on the kind of task, team members may be responsible for control over the task elements; however, objectives and meeting budgets are controlled by the team as a whole (Lipnack and Stamps 2000). Power distance and institutional collectivism are dimensions which when properly interpreted in the beginning and used accordingly, reveal prompts for team forming. Some team members may originate from high power distance and high institutional collectivism cultures, which means they may be reluctant to gain control over any aspects of team work since they prefer a leader to be in charge and set rules and regulations. Members of low power distance culture would be enthusiastic to have an opportunity to manage particular parts of a project without too much control from authorities.

2.3.3 Motivation

In a virtual environment, motivation is a significant element for a successful virtual project team. No physical contact is present in the process of cooperation and depending on the backgrounds, the virtual team members' handle this problem differently. To be more aware of these distinctions, dimensions such as in-group collectivism, institutional collectivism, performance orientation, and future orientation need to be interpreted properly. For instance, in individualistic cultures with high performance, society rewards individual members for performance excellence and encourages them to be more confident. This method would not harmonize with individuals from collective cultures that have lower performance orientations in which society rewards member and encourages them to attend to family issues over job performance.

2.3.4 Communication

In the virtual team environment with no physical contact, communication is dependent on information technology (Nauman and Iqbal 2005). The dimensions that facilitate better understanding of the communication differences include power distance, assertiveness, and gender egalitarianism. For instance, members from countries that pay more attention to gender role differences, where there are relatively few women in positions of authority, might find it hard to cooperate with women who come from an environment with a society that provides males and females equal opportunity. In order to improve communication among the team members, behavior rules and explanations may need to be introduced as a matter of protocol.

2.4 Implementation of the Cross Cultural Virtual Team Model in Fictitious Environment

The CIO of a multinational technology firm was assigned the task of creating a virtual team consisting of representatives of the company's offices in different countries. This cross-cultural virtual team's purpose was to document the IT systems of all company divisions. About a year before this team was to be created, the company had decided to introduce Product Lifecycle Management (PLM). Manager responsible for creating a cross-cultural virtual team may likely take the following actions.

First, the manager may order a demographic analysis of the employees in his/her company, with special interest in the following cultural influences:

- Power Distance
- In-group Collectivism
- Institutional Collectivism
- Performance Orientation
- Future Orientation
- Assertiveness
- Gender Egalitarianism.

Once the results of this demographic analysis were tallied the manager used them and other personal measurements and past records to best choose individuals that were likely to promote the four factors of a successful virtual team; trust, communication, control, and motivation.

Once the members of the cross-cultural virtual team were chosen, the manager started working on building the four factors into the framework of the team. The manager set up a four day conference off site. The goal of this meeting was to introduce team members face-to-face and to jump start the bonding process. Team building exercises were conducted to encourage trust, motivation, control, and communication among the team members.

After the conference the team members went back to their respective countries and divisions and began working as a virtual team. The PLM technology was in place and was available to support cross-cultural communications within the team. The communication between members was facilitated by video conferencing, e-mails, instant messaging, and phone conversations. Video conferencing helped the virtual team members feel as though they were in the same room as the other individuals.

As the team matured, benefits of PLM began to improve due to the fact that the communication, trust, control, and motivation levels were higher than when the team first formed. On the occasion when lack of communication occurred, it was repaired by the trust, motivation, and control that the cross-cultural virtual team created among its team members. The feedback loops in this model helped the company create a cross-cultural virtual team that could successfully complete the task and more; the team not only created a complete documentation system per its original assignment, but it also went on to other company wide improvement projects.

Attention to cross-cultural dimensions is important when Implementing PLM. When using both CCVTs and PLM a multinational corporation will be able to compete in all areas of their business. When implemented correctly following the CCVTM both the CCVTs and the PLM approach should grow stronger over time. An early investment in the time required to create a potentially successful CCVT will allow, later on, multinational corporation to concentrate on other business objectives.

3 Product Lifecycle Management in Support of Green Manufacturing: Addressing the Challenges of Global Climate Change

The rapid consumption of natural resources and the growing interest in global warming (Kharin et al. 2007) have motivated more and more companies to change their manufacturing strategies and processes in order to become more ecologically sound. In general, there is a desire to develop innovative manufacturing systems that align with green manufacturing goals.

Green manufacturing reduces or eliminates the use and generation of hazardous substances throughout all phases of a product's lifecycle (University of Alabama 2006). In addition to being environmentally friendly, green manufacturing has a positive effect on the bottom line; its implementation lowers costs, improves production lead time, and increases product quality (Noci 1995). Green manufacturing is seen as a competitive advantage by companies who can efficiently use financial resources, technological knowledge, and operations to implement green manufacturing practices.

In this section of the chapter, we investigate why green manufacturing processes are beneficial to companies and which green activities are currently in place. A summary of financial impacts, current sustainability practices, and regulations and policies associated with green manufacturing is presented. An argument is made that Product Lifecycle Management (PLM) can support green manufacturing strategic initiatives.

3.1 Background

A pilot study was conducted in which green manufacturing practices were investigated. Six companies were selected from the Global Round Table on Climate Change (GRTCC). According to the GRTCC website (Global Round Table on Climate Change 2006), they bring together stakeholders from all regions of the world to discuss and explore areas of potential consensus regarding core scientific, technological, and economic issues critical to shaping sound public policies on climate change. This study investigates green manufacturing, the adoption of environmentally-friendly standards, and influences to the PLM process because of green activities. As background, we provide an overview of these aspects as well as a summary of the companies used in this study.

Green manufacturing identifies methods that minimize waste and pollution during product design and production. Its main goal is "sustainability" by reducing waste on the spot and by promoting recycling such that every company does it part in conserving natural resources. Green trends have caused manufacturers' business needs to change significantly over the past and are projected to have an even greater impact given the challenges presented from global climate change. In fact, green technology has been identified recently as a key factor that will affect the overall success of a company (Cimalore 2007).

Environmental standards and regulations influence organizations to follow environmental procedures. "Organizations must comply with governmental regulations or face immediate and severe consequences" (Grieves 2006). In the past, multinational companies tended to operate with low standards (Hassan, et al. 2002). However, more recently, some companies have joined with others to self-regulate and to adopt polices that surpass US governmental regulations (Christmann 2004).

Product Lifecycle Management is an integrated, information-driven approach to improve a product's life. It achieves efficiency by using a shared information core system that helps a business to efficiently manage a product's life cycle from design to disposal (Grieves 2006). Thus, PLM support businesses as they reduce the use of wasted materials and energy.

3.1.1 Our Companies

To obtain the six companies in this study, an initial set of 10 companies was chosen at random. The companies were carefully inspected in order to secure that enough information was available to conduct an analysis of the companies' green manufacturing practices. All research is based on publicly available data e.g., (Bayer 2006), (Bayer Sustainable Development Report 2005), (DuPont 2007), (Florida Power and Light 2007), (General Electric, 2007), (The Dow Chemical Company 2006), (The Dow Chemical Company 2005), (Toyota 2007). The companies include:

- **FPL Group, Inc**. – one of the largest providers of electricity-related services. Its principal subsidiary, Florida Power & Light Company, serves more than 8 million people along the eastern seaboard and southern portion of Florida.
- **DuPont** – a company operating in more than 70 countries and offering a wide range of innovative products and services spanning many markets.
- **General Electric (GE)** – a multinational company that participates in a wide array of markets. GE is dedicated to turning imaginative ideas into products; in 2006, it recorded revenues of $163.4 billion.
- **Toyota** – a multinational corporation and the second largest automaker in the world. Toyota Corporation encompasses Toyota, Lexus, Scion, and parts of Daihatsu brands, divisions and companies.
- **The Dow Chemical Company** – incorporated in 1897 and has since expanded into over 175 countries, employs 43,000 people worldwide, and has annual sales of $49 billion.

- **Bayer** – a worldwide company that employs 106,000 employees and in 2006 had 29 million EU in net sales. Bayer's corporate mission statement includes the slogan, "Bayer: Science for a Better Life."

3.2 Financial Impacts

It is of importance to keep up with a product's functionality and cost during the life cycle of the product (Kimura and Kato 2003). Two of the biggest benefits for a company to pursue green manufacturing are additional cost saving and production increases. This is possible because a good plan enables a company to spend less money by preventing unnecessary waste rather spending additional money to dispose waste (e.g., zero-emission strategy). Alternatively, the company may reuse components or materials which represent more savings. Managers consider improvements in environmental performance one of the basic competitive priorities along with low operational costs and production lead time for higher quality (Azzone and Noci 1998). Moreover, developing efficient (and green) product and process technologies constitutes the basic cost and ecological impact parameters. The processes drive the types of raw materials used, worker's health and safety, ecological risk, materials efficiency, and waste treatment.

In order to achieve best sustainable practices, partners have to cooperate and tap into the know-how of all parties at all stages of a product. To minimize the risks and to secure the maximum result, all of them should be part of the value-adding processes (Westkamper et al. 2001).

3.3 Current Sustainable Practices

A summary of the sustainability practices is provided. Sustainability has significant potential for improving environmental friendliness while simultaneously driving improvements in productivity and costs.

3.3.1 Recycling and Disposal

A comprehensive recycling effort and disposal practice is crucial for reducing waste. The emergence of product take-back legislation in Europe and current directives in the US has forced companies to think about how to dispose their products through efficient recycling, disassembly, and reuse. There is also a focus on safe disposal of hazardous materials or substituting those materials for more environmentally friendly materials (Grieves 2006).

Our companies' recycling and disposal activities are summarized (Table 1). An entry in the table indicates a green activity is performed; when known, additional details are included in the cell. Dow Chemical's main recycled

Table 1 Recycling and Disposal. This table indicates the presence of recycling activities and active green disposal practices.

Companies	Energy			
	Wind generator	Landfill gas	Conserv.	Reduction in use
FPL	X	X	X	X
DuPont	–	–	–	–
GE	–	X	–	–
Toyota	–	–	–	–
Bayer	–	–	X	–
Dow	–	–	–	X

products are their plastics. In fact, North America, Europe, and Asia are all markets that recycle billions of pounds of plastics. Toyota uses a set of recycling guidelines, "Toyota Recycle Vision," to help minimize their negative environmental impact. Toyota adjusted product design in the 2004 Sienna minivan and the Camry Solara coupe to replace substances of concern with "greener" materials.

3.3.2 Energy Consumption

Energy consumption is clearly important in green manufacturing (Table 2). "The electricity industry is the single largest source of industrial pollution in the world, and one of the largest sources of greenhouse gas emissions. Over 80% of the world's electricity and 90% of US electricity comes from nonrenewable fossil and nuclear sources" (Starrs 2005). FLP is the US' largest developer, owner, and operator of wind powered generating plants. Half of the energy they produce comes from natural gas and only 10% comes from oil.

General Electric has pursued developing engines that use an effective and environmentally-friendly energy generation method from landfill gases. When organic substances decompose, methane, carbon dioxide and nitrogen are created. Landfill gas is a high-quality alternative for gas engines.

Bayer uses organic methods to create valuable energy. A new project launched in 2005 treats sewer sludge so that bio-gas can be extracted from the

Table 2 Energy Consumption. This table indicates energy sources used and green practices are active.

Companies	Energy			
	Wind generator	Landfill gas	Conserv.	Reduction in use
FPL	X	X	X	X
DuPont	–	–	–	–
GE	–	X	–	–
Toyota	–	–	–	–
Bayer	–	–	X	–
Dow	–	–	–	X

organic content and used for energy generation. The European Commission is supporting the development of this process as part of the "Life" environment program.

Since 1994, Dow Chemical has reduced energy consumption by approximately 900 trillion BTU's. Their current goal is a 20% reduction in the energy needed to fabricate one pound of product.

3.3.3 Water and Air Management

Water and air management has received considerable attention (Table 3). DuPont strives to reduce and conserve water at all international and domestic sites. Moreover, DuPont commits to reduce water use by at least 30% over the next ten years at global sites that are located where the renewable freshwater supply is either scarce or stressed as determined by the United Nations. For all other sites, DuPont holds water consumption flat on an absolute basis through the year 2015, offsetting any increased demand from production volume growth through conservation, reuse, and recycle.

GE's Ecomagination program, involves financial and environmental performance to drive the company's growth. It has played a key role in advancing water reuse and purification technology. GE's improved membrane materials and spiral-wound membrane element configurations has revitalized its water reuse and purification system to address fouling, temperature, pH-value, and contaminants.

Toyota's "green" complex in California conserves more than 11 million gallons water annually. The plant uses special pipelines that supply recycled water for cooling and landscaping.

Bayer reduced water usage from 2.2 million cubic meters per day (1994–2004) to 1.2 million cubic meters per day in 2005. The company's wastewater treatment plant treats contaminated water and reuses it.

Dow Chemical has made a reduction in water use by 38% since 1994. They eliminate wastewater at the source. Dow states they are "above the goal to reduce wastewater intensity by 50% and are committed to continue source reduction and recycle efforts to reduce fresh water consumption." Not only

Table 3 Water and Air Management. This table indicates green activities in water/air management.

	Water			Air
Companies	Conserv.	Reuse	Recycle/Treat	Lower emissions
FPL	–	–	–	X
DuPont	X	–	–	X
GE	–	X	–	–
Toyota	X	–	–	X
Bayer	X	–	–	lower green house gases
Dow	reduce waste water	–	X	lower green house gases

does Dow focus on eliminating water at the source, but they have developed activities to recycle wastewater wherever feasible:

- Groundwater Water – created streams from underground water via wells,
- Fresh Surface Water – water captured from canals, lakes, and rivers,
- Rainwater – captured or stored rainwater,
- Site Level Recycle – on-site water is reused, avoiding new supply,
- Seawater & Brackish – surface or groundwater is captured from brackish or seawater sources, and
- Purchased Steam and Condensate Water – use purchased water on site.

3.3.4 Products and Processes

Products and operational processes of the companies investigated have produced noteworthy environmentally friendly characteristics (Table 4). For example, FLP joined forces with the US Climate Action Partnership (USCAP) to ask the US Government to endorse mandatory policies to reduce carbon dioxide emissions. FPL endorsed the Joint Statement of the GRTCC committing itself to global action to alleviate global warming risks while meeting the need for energy, economic growth, and sustainable development worldwide. Furthermore, FLP is ambitious to become a leading green company by using natural gas as fuel to produce 50% of their electricity. Currently, nuclear sources constitute 20% and oil sources only produce 8% of total energy production. FLP has added wind sources which are soon expected to bring significant financial benefits.

Since 1994 DuPont has reduced their gas emissions measured as CO_2 equivalents by 72% and have reduced global air carcinogen emissions by 92%. By 2015, they plan to reduce their emissions at least 50% from a base year of 2004. DuPont will introduce fleet vehicles which use the leading technologies for fuel efficiency and fossil fuel alternatives. All together, this will bring DuPont's total reductions since 1990 to 96%.

Toyota leads the field in lowering emissions and improving fuel economy in gasoline-powered vehicles. Toyota not only developed and produced the

Table 4 Products and Processes. This table indicates which companies have active green products and operational processes

	Product/Processes		
Companies	Energy efficient	Fuel efficient	Operational Efficient
FPL	–	–	–
DuPont	X	X	–
GE	X	X	X
Toyota	–	X	X
Bayer	X	–	X (info availability)
Dow	X	–	–

world's first mass-produced gas/electric hybrid car, but is also pioneering fuel cell cars to further reduce air pollutants.

Bayer cut greenhouse gas emissions to 5.6 millions metric tons of CO_2 equivalents in 2004 and 3.9 million metric tons of CO_2 equivalents in 2005 as explained by Bayer's Sustainability Report for that year. In total, greenhouse gas emissions throughout the Bayer Group decreased by over 70% from 1990 to 2005.

Dow's production has increased by 32% since 1994, their total emissions of CO_2 have been successfully *reduced* by 32%. Dow has achieved this through long-term energy efficiency improvements and by converting to more climate-friendly technologies.

3.4 Regulations and Policies

Many companies are seeking to improve their environmental performance in order to join consortia, associations, and projects and to comply with environmental regulations (DuPont 2007). Satisfying the regulations and policies is not easy. For example, the End of Life Vehicle (ELV) regulation requires that by 2006 all automakers in the European Union recover 85% of a vehicle's weight and 95% by 2015. In addition, no lead, mercury, cadmium, or hexavalent chromium can be used after July 1, 2003.

Internal and external factors influence a company to follow environmentally friendly standards. External factors include customers, competitors, and regulations. This last factor induces manufacturing to rapidly implement green processes (Udomleartprasert 2004). Having environmentally friendly standards creates a positive reputation with the public, saves cost, and promotes new designs. Internal factors include ethical objectives and the desire to achieve competitive advantage.

General Electric, Bayer, and Dow follow the Waste Electrical and Electronic Equipment (WEEE) regulation when developing electronic devices. The WEEE directive requires manufacturers of electrical and electronic equipment to recycle their products at no consumer cost and prohibits the use of certain electrical materials. In addition, both Bayer and Dow abide by the RoHS Directive which prohibits the use of certain hazardous substances in electrical and electronic equipment. The directive bans from the EU market any new electrical and electronic equipment containing more than agreed levels of lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyl, and polybrominated diphenyl ether flame retardants (RoHS 2007).

DuPont follows the International Standards Organization (ISO) and agrees on specifications and criteria that they will consistently apply to all stages of a product life–in the classification of materials, in the manufacture and supply of products, in testing and analysis, and in the provision of services. To maintain effective management systems for health and safety protection, Bayer abides to the Health, Safety, Environment and Quality (HSEQ). The Sarbanes-Oxley Act of 2002 (SOX) requires all executives to certify the accuracy of their financial statements and attest to the processes, controls, and systems used in financial reports.

As the world moves to more standardized international regulations, organizations will be required to track more information. Furthermore, integrating stronger and efficient green activities complicates company planning. This brings us to the next section on PLM. PLM will be an integral part of the information systems executives will need to have in place in order to abide by the required regulations and to develop sustainable green practices.

3.5 Product Lifecycle Management

Environmental changes and the implementation of green manufacturing require a company to change its entire processes; from product planning and procurement policies to production and logistics (Azzone and Noci 1998). The PLM model, as described by (Grieves 2006) includes five major categories (plan, design, build, support and dispose) centered by an information core (Fig. 3). PLM is about product data, information and knowledge combined with people, processes, and technology. PLM can benefit a company practicing green manufacturing. For example, the information core will help a company capture and organize information, avoid the use of illegal materials, and help identify processes with negative environmental impact. As recently stated, “The Eco & PLM database manages data about all stages of the product lifecycle from procurement to disposal or recycling. This enables the evaluation of whether the product complies with the environmental laws. It also facilitates the recording of environmental data and makes quick product recall possible” (Minami et al. 2004).

Fig. 3 Relation between green initiatives/PLM. PLM model taken from Grieves (2006)

Similarities exist between environmental protection activities and the operations methods already in place throughout a product's lifecycle. Programs explaining how to keep pollution under control, reduce waste, or develop green designs may also reinforce traditional operations management such as statistical process control, total quality control and total quality management or design for manufacturability (Burgos and Cespedes 2001).

It is essential to design the product as a whole from planning, through design and manufacturing, to usage, maintenance and reuse/recycling/disposal. A sound strategy for product maintenance and improvement during usage should be established, and all the life cycle processes are to be well controlled. By such approach, reuse/recycling activities are also rationalized, made visible, and controllable. Such an approach, called Inverse Manufacturing, stresses the controllability of reuse/recycling processes, closes product life cycles, including maintenance which are also are pre-planned and controlled (Kimura and Kato 2003).

During the planning and design phases, specifications, requirements, and functionality of a product need to be determined. The PLM information core, not only would store data and design information to make it accessible, but also a library of green directives and legal issues. When building a new product, PLM can provide information on facility lay-outs and knowledge of existing equipment. This information can pre-determine which facilities are best suited to practice green manufacturing. The support of a product relies heavily on sales and distribution. PLM would provide information on warranties, product performance, hiring practices, and other product data that would make the support function more effective.

The disposal phase is the final stage of a product's life. PLM provides information on product design and material make-up which is vital for the recycle and disposal phase. Simultaneously, methods of efficient product disposal and recycling are also related to the planning and design phases of PLM. Thus, the accessibility and information sharing that PLM provides supports green manufacturing because not only does it assist companies' compliance with environmental directives and regulations, but it also greatly decreases wasted time, energy, and materials.

3.6 Observations and Conclusions

Green manufacturing changes are not easy and they may not represent an economic benefit in the beginning, however, they do represent a good long-term investment. The following observations are made about the companies in the pilot study:

- FLP, an important energy producer for the US, is engaged in substantial green energy efforts. More than half of its energy comes from natural gas and more green expansions are planned.

- DuPont has committed that by 2015 it will increase revenues from energy efficient processes and/or significantly reduce green house gas emissions.
- General Electric has become a leading company in developing green products and processes through their Ecomagination program. Furthermore, GE's belief that financial and environmental performance can work together to drive company growth will enable them to continue to undertake the world's biggest environmental challenges.
- Toyota leads green efforts in the automotive industry and is working towards a "Toyota Recycle Vision". Many of Toyota's goals have been reached due to their global earth charter that promotes environmental responsibility throughout the entire company.
- The Dow Chemical Company implementation of energy efficient processes, chemical recycling programs, waste water reduction, and lowered green house gas emissions prominently demonstrate their commitment to green manufacturing.
- Bayer is working towards sustainable development by using energy efficiently, increasing water conservation, more safely disposing hazardous wastes, and lowering green house gas emissions. Their goals are sought with efficient resource management and future-oriented climate protection activities.

PLM's objectives emphasize not to waste time, energy or materials. Green manufacturing also looks for the conservation of resources and reduction of waste. Thus, PLM can support green manufacturing procedures by tightly integrating such practices into the lifecycle of a product and yielding environmentally friendly productions.

The environmentally-friendly practices identified indicate green manufacturing is already a very actively pursued objective. However, to compete in a global world *and* to comply with the many environmental protection regulations and standards is not easy. The information core of PLM helps to lessen this burden by capturing information and storing it for use by all stages of a product's life. This simultaneously leads to competitive advantages and environmental friendliness.

4 Entry-Level Engineering Professionals and Product Lifecycle Management: A Competency Model for Education

Recent decades have witnessed the burgeoning popularity of lean thinking and its many theoretical offshoots as companies continue to look for ways to strengthen their competitive edge. One of these, Product Lifecycle Management (PLM), focuses on the goal of eliminating all forms of inefficiency from every phase of the manufacturing cycle. By coordinating information technology with organizational practices and processes, both within and across functional areas, PLM is able to substitute information for wasted time, energy, and material (Grieves 2006).

PLM has piqued the interest of corporate decision-makers across the globe. As a consequence, companies that are implementing its guidelines can be found on nearly every continent. Furthermore, as manufacturing giants increasingly turn to PLM, so too do their supply chain vendors. One of the beauties of this model is its provision for the following of manufactured goods past the point of purchase, through disposal and disassembly, to the eventual reuse and recycling of a product's component elements. Thus, although many organizations may have initially been drawn to PLM out of the desire for improved profits, others also see it as perhaps the only solution capable of helping them deal with the complexities of governmental regulatory changes.

4.1 The Competency Model Displaces the Task-Oriented Approach

Faced with the changing regulatory climate and the rapidly evolving global marketplace, organizations are also grappling with the need to bring their workforces into the future. Today's employees are finding it necessary to remain current with emerging technologies while simultaneously adapting to profound shifts in the business aspects of manufacturing. Job descriptions, once a corporate mainstay, are thus becoming outmoded as workers find themselves called upon to tackle a host of new responsibilities. For example, an editorial in the February, 2004, issue of Manufacturing Engineering notes that manufacturing engineering (ME) professionals are increasingly being asked to determine "make or buy" decisions; oversee suppliers' technologies, cost, delivery and quality; evaluate and improve their suppliers' core processes; integrate suppliers' core processes with their companies' own processes; manage and deploy supply chain management systems; and make improvements in their suppliers' designs, processes, and quality. The author therefore urges ME professionals to cultivate a wide variety of new skill sets and to embrace a lifestyle of professional resilience and personal development (Hutchins 2004).

4.2 Response from Trade-Interest Groups and Academia

Industry's call for versatile, cross-functional employees is being heard by a growing number of professional associations. One of these is the Accreditation Board for Engineering and Technology (ABET) , which responded by implementing, in 2001, a revised list of accreditation criteria for engineering programs in colleges and universities. In addition to the time-honored mandates for technical competence are new ones stating that the graduate engineer must have the "ability to engage in life-long learning," "a knowledge of contemporary issues," and "the broad education necessary to understand the impact of engineering solutions in a global and societal context"(Bell 2000).

The Society of Manufacturing Engineers (SME) is another industry trade group that likewise recognizes the need for change. Since 1997 it has been extensively researching what it refers to as "competency gaps," specific capabilities that companies insist are too often lacking among their workers. Based on its findings the SME has developed its Manufacturing Education Plan (MEP) , an aggressive endeavor aimed at addressing the competency shortfall. Central to the MEP is its list of competency gaps, which has undergone several revisions since its inception in 1997. The most recent one has designated the following fifteen items to be the most critical deficits between what education programs provide for their students and what manufacturers need in terms of their workforce:

- Business knowledge/skills
- Supply chain management
- Project management
- International perspective
- Materials
- Manufacturing process control
- Product/process design
- Quality
- Specific manufacturing processes
- Manufacturing systems
- Problem solving
- Teamwork/working effectively with others
- Personal attributes
- Written and oral communication
- Engineering fundamentals. (SME and Competency Gap Research 2004)

The apparent shifting of paradigms from task orientation to one of competencies in the workplace has not escaped the notice of academia. Faced with the revised accreditation mandates from ABET, the groundswell of importance surrounding PLM, and impressive research data from interested groups such as the SME, academe has begun test runs of innovative new curricula. One example is a cross-disciplinary manufacturing engineering course described by Chang and Miller of Purdue University (2005). The authors state that the course was redesigned to meet industry's need for a PLM-literate workforce, and that overall, it "was very successful" (p. 176). They acknowledge, however, that at the time of publication their course had only been offered once, and that further research will verify the degree of its success among future students.

4.3 The Development of a PLM Competency Model for Entry-Level Engineers

The purpose of this section of the chapter is to present a PLM competency model that contains the elements necessary for the success of entry-level engineering professionals who must function within a PLM environment. This project is being ably assisted by seven highly credentialed PLM Subject Matter Experts, all from Fortune 500 companies (i.e. Boeing, Rolls Royce, IBM, Caterpillar, EDA, and Flexware), and all of whom are members of the Advisory Board of the Product Lifecycle Management Center of Excellence at Purdue University. They will define the skill objectives that are appropriate, and from these, a minimum of 200 derivative tasks will be specified. Then, from each task, thirty to forty key skill objects will be isolated. The final list of skill objects will be used to construct a Product Lifecycle Management competency model that also conforms to standards previously designated by the Society of Manufacturing Engineers.

The tool selected for this process is a software package titled SkillsNet, developed in 1996. The program uses language descriptors that are common to the Department of Labor's Occupational Informational Network (O*Net) in order to create a valid framework with which to define task, tools, and knowledge requirements. These frameworks in turn are referred to by the software as SkillObjects. The Trainer's Guide defines SkillObject as "a re-usable detailed description of what people do in accomplishing work" (SkillsObject Trainer's Guide, 1999–2004). A SkillObject contains the following elements: a label or name, tasks, skills/abilities, tools/software/equipment/devices, unique knowledge, resources, and performance standards.

In an industrial setting, the individual chosen to generate the criteria for each SkillObject should ideally be a job incumbent who is recognized as a top-tier performer by his or her peer group. Upon receipt of a list of SkillObjects, it then becomes the task of the Work Element Editor to cull through each, and reduce, according to the following guidelines:

- Eliminate task, tool, and unique knowledge redundancies
- Clarify tasks, tools, and unique knowledge so that they are understandable to others in the occupation
- Fix spelling and grammatical errors
- Reduce the size of a task, tool, and unique knowledge list without losing important information. (SkillsObject Trainer's Guide, 1999–2004)

Following this initial editing process, each list will then undergo several more revisions before its final submission to the managers or supervisors responsible for implementation. For this study, the Subject Matter Experts will perform the function of the top-tier job incumbent described in the previous paragraph. The authors will then serve as the "Work Element Editors." This project is still very much a work in progress. At the time of this writing, surveys have been distributed and the authors await the return of data.

5 Inter-organizational Relationships in Supply Chain Management: A PLM-like Application in Higher Education Procurement

Changing business practices have altered traditional roles of purchasing professionals in many organizations. This is especially true in higher education where purchasing professionals are becoming increasingly involved in most stages of product development, in part because they can accurately predict the cost, availability and suitability of items in question. By consulting with the purchasing department in the early stages of product design, higher education organizations are able to avoid, or greatly lessen, potential problems that may arise in regards to pricing, availability, delivery, quality, and support. The need to develop and implement effective supply chain management strategies is quickly becoming a major factor in higher education resource allocation and a major focus of their purchasing departments. The application of product lifecycle management (PLM) could prove to be very beneficial in institutions of higher education.

5.1 PLM in Higher Education

New practices have pushed higher education institutions into increasingly complex, integrated supply contracts, making supplier selection critical due to the increased scope and duration of these contracts. Integrated supply chains incorporates all members of the supply chain including the supplier, transportation companies, and the university. A major responsibility of most purchasers is to resolve problems that may arise with a supplier, since the success of the relationship ultimately affects the buying firm's productivity and performance. Understanding the evolving relationship between supplier and buyer is a crucial factor to success as it affects efficiency with regard to ordering and processing orders that can be achieved in real time.

When an organization plans and executes in real time, based on a granular view of items or case locations, speed and accuracy of information exchanged is critical among the parties involved. By collaborating with key trading partners in flexible planning cycles that address consumer requirements quickly, organizations become consumer-driven. Being consumer-driven places the needs of the organization at the forefront of the supply chain with a focus on effectiveness and efficiencies.

In contrast, the traditional supply chain is slow and unresponsive. Instead of basing decisions on a finely tuned view of consumer demand, it uses data that is less consumer driven, such as warehouse withdrawals or distribution center receipts. This type of batch data provides visibility into brand or a case-level volume that describes what happened yesterday or last week – as opposed to what is happening right now. What's more, traditional supply chains operate in a series of silos with little integration, collaboration and visibility among the players, especially in institutions of higher education. The application of product lifecycle management (PLM) could positively affect the supply chain process at universities as they move toward and execute purchases based on real time, driven by the immediate needs of the customer.

According to Grieves, "systems that enable approaches such as PLM are developed and find a place in organizations for a fundamental reason: with these systems, we can substitute the use of information for the inefficient use of time, energy, and material" (Grieves 2006). The focus on increasing efficiencies and the application of technology affects the development of the supply chains at many universities.

PLM is of interest in the buyer-supplier relationship because it allows for a holistic approach to supply chain management that utilizes technology to aggregate buying. It leads to better understanding the big picture in regards to commodities. Below is a summary of Grieves' main points of PLM:

- PLM is about product data, information, and knowledge
- PLM concerns itself with the entire life of the product, from inception to end-of-life
- PLM is an approach that is more than software and approaches
- PLM crosses functional boundaries
- PLM combines the elements of people in action, processes, and technology
- PLM drives the next generation of lean thinking.

Due to the fact that PLM brings better products to the market faster, it is important to have established relationships with suppliers to capitalize on these opportunities. The fact that higher education organizations are governed by numerous state and federal statutes makes transparency in business practices essential. PLM awareness allows for the buyer/supplier relationship to develop to the point that integration of solutions, rather than products, becomes the norm. According to Stark, "many companies now offer complete solutions rather than products. This adds a new layer of challenges as solutions are more complex to develop and support than single products" (Stark 2005)

5.2 The Case for PLM Higher Education

Purchasing Departments in higher education organizations are moving away from traditional single exchange transactions toward an emphasis on creating and maintaining long-term buyer-supplier relationships. As strategic partners, these relationships generate a supply chain that must be managed. They encompass all the activities associated with the flow of goods and services, as well as the flow of information. Information throughout the entire organization must simultaneously flow both up and down the supply chain to leverage strategic positioning and to improve efficiencies. For organizations to obtain sustainability in the future they must develop a strategy for creating, maintaining, and sustaining buyer/supplier relationships based on institutional requirements. As stated by a Vice-President of the Boston Consulting Group, “As the economy changes, as competition becomes more global, it is no longer company versus company but supply chain versus supply chain” (Henkoff 1994).

Also of importance is the maintenance and development of the relationships between the purchasing organization and the supplier of the goods or services required. These relationships appear to be formulated from several different attributes of purchasing in an organization. Duffy believes that there are seven areas in which change is occurring that will affect the buyer-supplier relationships: electronic commerce, strategic cost management, strategic sourcing, supply chain partner selection, tactical purchasing, performance measurements, strategic supplier alliances, and complexity management (Duffy 2003).

At Purdue University an Enterprise Resource Planning (ERP) initiative is under way. The e-commerce mechanism installed by the software product SAP allows for aggregation of buying and management of the relationship attributes with an emphasis on partnering. This partnering effect is designed to utilize organization wide procurement quantity pricing by including all local divisions and regional campuses connected electronically for ease of tracking and ordering. This makes information sharing an integral part of the process by governing and monitoring all aspects of the procurement process including relationship management with suppliers.

5.3 Model of Strategic Relationship

While many intuit that face to face communication will become less important as technology enhances communication, one of the major finds of this study is that strategic relationships require attention. Understanding the complexities of the relationship as viewed by both the buyer and supplier is important.

In the establishment of a relationship between the buyer and supplier there emerged several attributes that make up the core of this model. These attributes are contextually different from the maintenance or future development attributes that surround the establishment core attributes. They are different in that they are specifically focused on each relationship and show little, if any variability, as the foundation from which the relationship is built. Whereas, the maintenance attributes surround the foundational core,

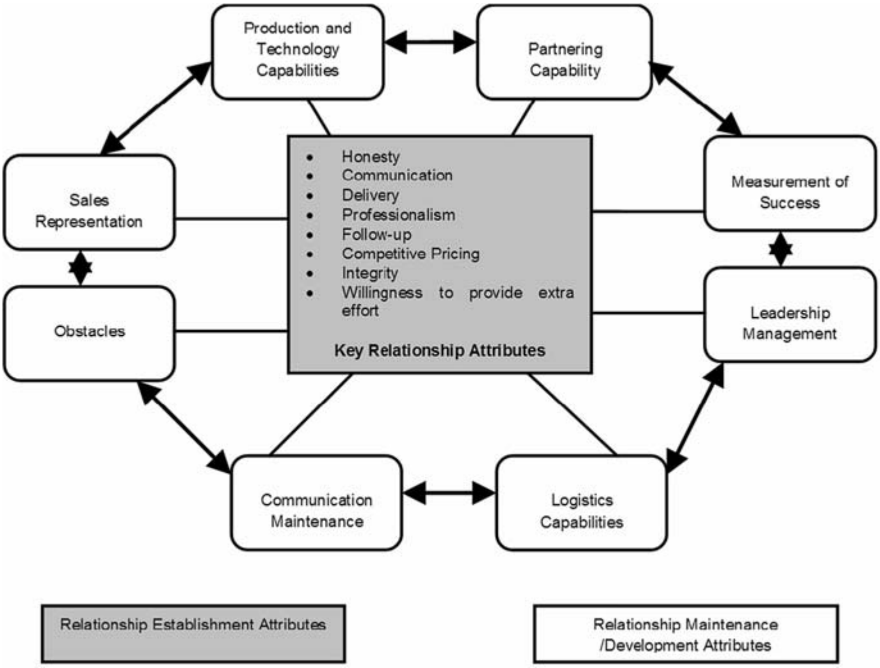

Fig. 4 Supply chain strategic relationships

establishment attributes will vary according to the industry, supplier's size, and capabilities.

The size and capabilities of a supplier are not as important when it comes to the establishment of the buyer/supplier relationship. Honesty, communication, integrity, professionalism, delivery, follow-up, competitive pricing, and willingness to go the extra effort, are regarded by the participants of this study as key attributes in the formation or establishment of a buyer/supplier relationship.

Honesty is regarded by one buyer "To be the ability for both parties to put all of their cards on the table without fear of price inflation or other unethical applications." Honesty is thus viewed as the foundation upon which communications are designed and established.

Communications rely on the honesty of both the buyer and supplier in the development of the initial relationship between the two. This communication must attend to both the buyer's and supplier's needs with particular emphasis on empathetic listening skills.

Integrity combined with honesty in communications is a fundamental element by which both the buyer and the supplier's representatives conduct themselves. The honesty at which communications are conducted is indicative of the individual's integrality. The integrity, once developed, further personifies the relations essence in regards to perception. This perception of honesty, integrity, and a degree of professionalism in the communications are regarded by participants of this research as fundamentally vital in establishing relationships between the buyer and supplier.

By having this open channel of communication between the buyer and supplier, the other core attributes of delivery, follow-up, competitive pricing, and willingness to go to the extra effort are more effectively established through mutual trust and information sharing.

Delivery in the core development stage of the model is primarily focused on time and condition of product. It is essential that the supplier understand the need of the buyer in regards to delivery.

Follow-up is the key attribute that ensures feedback is obtained and the relationship expectations are being followed-up on. If there is a delivery problem then there needs to be an open and honest dialogue to locate the problem and come up with a mutually beneficial solution.

Competitive pricing is the foundation from which the actual product builds. For institutions of higher learning it is exceptionally important to ensure that the buyers are being good stewards of the tax payers' money. One important way this is accomplished is through ensuring that the supplier with which the relationship is being developed has competitive pricing.

Professionalism is another key attribute of the inner core of the model. The sales representative and buyer both need to stay focused on the needs of the institution and the overt objective of the relationship. By presenting one's self in a professional manner, one builds the relationship on these characteristics that have a profound impact on both the buyer and supplier.

The willingness of the supplier to go to the extra effort is a summation of the key relationship attributes for developing the relationship between buyer and supplier. Without this effort, the rest of the attributes will not get the desired results for either the buyer or supplier, primarily due to a lack of effort.

5.4 Performance Metrics

In institutions of higher education, there is considerable focus on aggregating products to leverage purchases and obtain the best price. This "best price" is complex in that it must now take into consideration the quantification of a long-term relationship with a supplier. This is difficult at best, primarily due to the challenge of measuring the solution and innovative nature of the relationship. How the value of such a relationship is measured determines the strategic direction supply chain management takes in higher educational institutions. The call for developing performance metrics has been sounded.

One way of measuring effectiveness of the supply chain relationships is through standardization of processes. This, in turn, allows for the quantification of time, materials and energy levels expended in addition to the cost of a product or service. The formation and monitoring of the relationship elements provide a mechanism for working with the suppliers to achieve maximum effectiveness in aggregation of the purchasing function.

PLM supports the need for buyer/supplier relationships to meet the growing pressures and demands felt by institutions of higher learning. Brown and Duguid speak on the pressure colleges and universities feel to change to be become more effective and efficient, "the whole system of higher education is under pressure to change. Moreover, despite appearances to the contrary in some ivied exteriors, colleges and universities are changing significantly. Changing the direction of organizational vessels as large as universities, however, provides a fair amount of thrashing and churning. Consequently, it remains hard to see the ultimate directions that educational organizations might take". Since power is historically centralized in an educational institution and technology seems to dissipate distance through more effective communication, a path must be formed to provide strategic direction. This path must steer between a university's centralizing tendencies and be optimistic that technology will overcome the distance aspect and create a devolved system. This system will then rely on relationships to develop future strategic directions.

6 Summary

Product Lifecycle Management, though only in its early years, has proven to have tremendous impact. Whether trying to be first to market, improves quality, or increase customer base, PLM drives out wastes and permits the reallocation of captured resources in support of product and process innovation, resulting in potentially new revenue streams. Where once organizations considered the potential return of PLM before committing an investment, organizations increasingly consider the implementation of PLM as a matter of survival. Nonetheless, as with any change, PLM is not without its challenges, both technical and social.

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Product Design Optimization: An Interdisciplinary Approach

Sergio Romero Hernández and Omar Romero-Hernández

Abstract As new markets arise and global competition takes place, there is a need to come up with innovative-successful projects that present the best holistic alternative based on customer needs and market expectations. The present research provides a high-end technical solution to determine the best product alternative in terms of market expectations, product & process specifications, logistic and environmental performance. The integration of this framework is oriented towards rapid generation and evaluation of innovative products. The methodology is an engineering design framework based on the efficient use of design tools and computer aided design and engineering (CAD/CAE). This methodology is illustrated with 2 case studies: the design and development of a commercial fan and the envisioning of an energy efficient luminary for public lighting. The implementation of this methodology delivered a better ranked product in less time and lower cost. The correct application of these engineering concepts can be easily extended into almost any new product at its development stage.

Keywords Product design · CAD · CAE · Life Cycle Assessment

1 Introduction

Higher degrees of competitiveness demand worldwide companies to reconsider its perspective about traditional design schemes. It is necessary to come up with innovative-successful projects that present the best holistic alternative based on customer needs and expectations. Depending on the corporate strategy of the company the breach between what the company produces and what the market and customers are expecting can be overcome to result in innovative product alternatives [1]. Furthermore, cost control and product quality only sustain a level of competitive advantage, while product or service innovation is the actual source of competitive advantage in the global market [2].

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Several aspects should be analyzed to reach a successful design. First of all, the objectives of the product in development should concur with the strategical objectives of the company. Second, the time expended in the design stage should be benchmarked against the market standards, and the cost of development should be as low as possible. In this sense, it should be carefully analyzed whether the customer and market needs are fully considered in the product. The manufacturing and logistics needs of the product should also be analyzed [3]. Considerations should not be limited to the previously mentioned but can be expanded to include the marketing performance and the environmental impact along the life cycle of the product.

A hierarchy of attributes is imperative in order to consider the relative weight of each aspect during the design process. This hierarchy is typically obtained from interviews with several members of the marketing, sales, manufacturing, and research areas of the company. As such, developments in the design of a product must be defined and communicated in an explicit and hierarchical manner [4].

Nowadays, the behavior of global markets for goods demands a rapid and efficient adaptation of the products so they can meet the requirements of the supply chain, the customers and local legislation in record time. Hence, the need to apply an efficient stage of design and development of products that takes into account these aspects is emphasized. A design that does not take into account these considerations probably will present problems in further stages [5].

For any type of product, the changes required to improve its performance will have a higher cost the later in time they are implemented. This increase in cost will be exponential along the life cycle of the product; hence a modification at the production stage will be hundred times higher than one at the design stage as shown in Fig. 1. Moreover, design processes usually include several

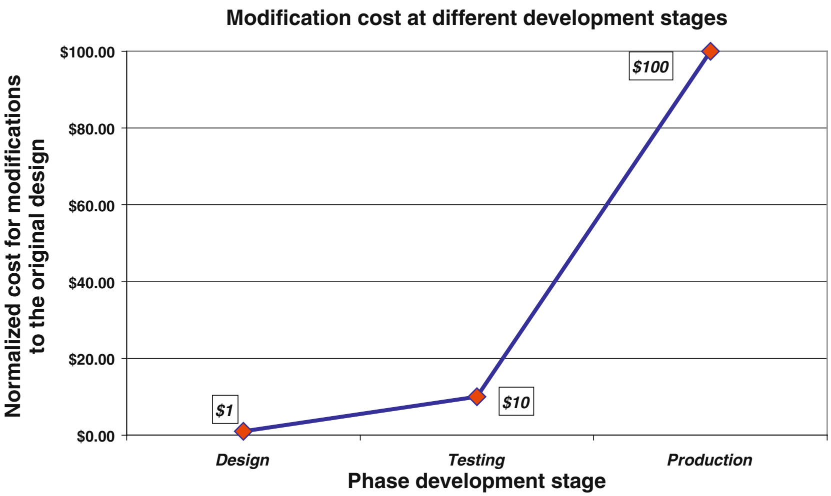


Fig. 1 Cost of modifications along a product life cycle

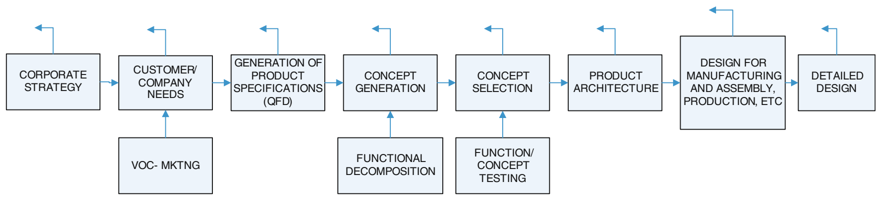


Fig. 2 Traditional PDD process

trial-and-error attempts oriented to tackle fine-tuning issues that take place during the manufacturing process design, where unforeseen dimensional errors occur. These trial-and-error attempts can be fastened with the use of simulation models and variability analysis [6].

In a traditional product design and development process (PDD), satisfaction of customer needs is achieved by the development of engineering specifications that aid the generation of several product concepts and the further selection and refinement of one of them (Fig. 2). This traditional generation and selection process is usually accelerated with the use of template-based environments were design calculations, component search, machine selection and preliminary cost are integrated into a relational database [7]. Usually the process concentrates in developing the best solution based on the operational performance of the product and its manufacture and/or assembly. Nevertheless, there are important aspects that are often overlooked, such as the environmental impact that the product will have along its life cycle or the logistic performance of the production, distribution and final disposition of the product [8].

A significant problem arises in the PDD process: market dynamics demand for fast and lean solutions. As such, the framework proposed in this work considers a series of product innovations which account for specific customer needs. The main objective of the proposed framework is to conduct rapid evaluations in order to determine those alternatives that satisfy both customer and manufacturer requirements. Moreover, this framework helps determine the most adequate environmental and logistic alternative for the design of a new product.

The interdisciplinary approach presented in this article receives inputs from various areas such as marketing, production, logistics and R&D. An efficient manner to deal with all this information lies in the utilization of efficient models that conceptualizes both holistic and component views in compact packages. At least two of these detailed models can be found in the literature [9].

2 Methodology

The Romero-Romero methodology (R-R) is based in a recursive process that on each iteration develops a new model of the product. In order to apply it, the corporate strategy has to be properly defined, as well as the mission statement for the new product. Customer needs should be properly identified, and engineering requirements of the product should be developed to satisfy them. The previous tasks can be performed by aims of marketing studies, analysis of the supply chain of the product, analysis of the processes affecting the product, and finally a legal analysis of the normativity and intellectual property regarding the new product. Once this information has been gathered, it is necessary to conduct a priorization of the product features and requirements. Most companies have used diverse methods to successfully carry out this priorization, most of them based in multiple-criteria decision tools [10]. The Quality Function Deployment methodology [8] can be used to conduct this correlation. The application of this methodology will result in a House of Quality that will work as a roadmap for the design process. Then, a first proposal of the product design can be developed by conventional means, such as the traditional PDD process presented in a previous section.

The methodology shown in this article is an engineering design framework based on design tools and computer aided design and engineering (CAD/CAE) (Fig. 3). This framework integrates not only manufacturability and cost issues but also two other fundamental aspects: environmental and logistic performance of the product along its life cycle. Based on these two performance aspects and with the use of analytical tools it is possible to envision and develop advance product designs that comply with market and usability objectives, while achieving lower environmental impacts and lower transportation costs.

For each iteration there will be a comparison between the last evolution of the design and the one before. From those comparisons trouble areas and weaknesses

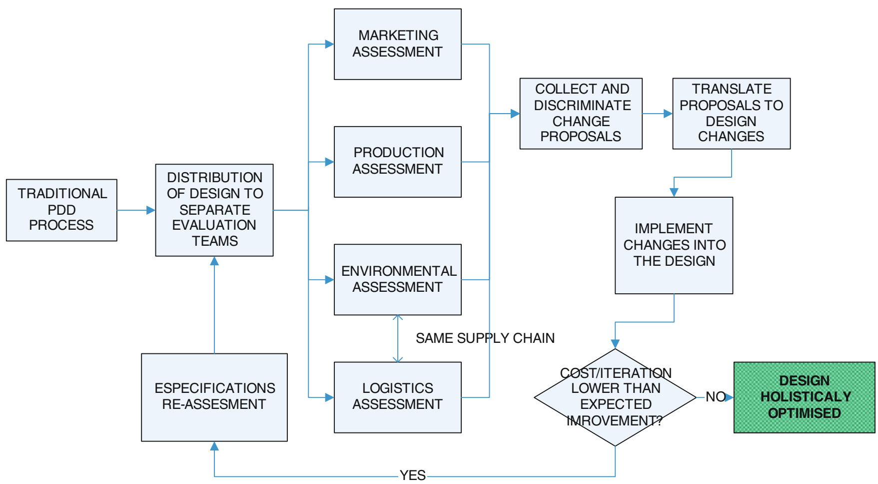


Fig. 3 Framework for product optimization

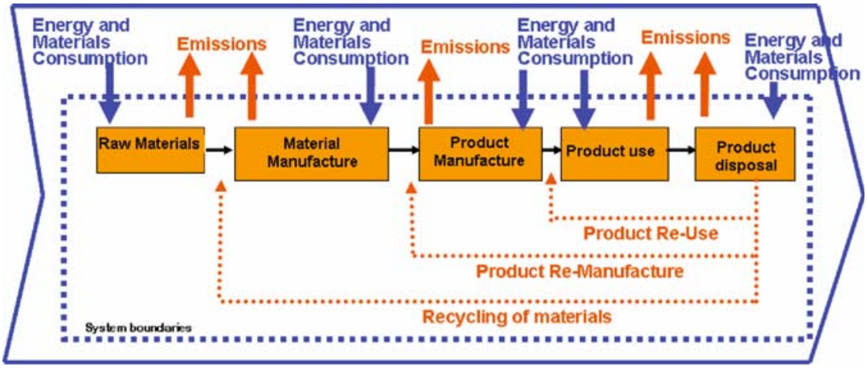


Fig. 4 Environmental assessment

in the product are identified. At the end of each iteration the environmental and logistics team propose a "wish list" of improvements, which are usually presented in a ranking of design modifications. At the end of each iteration there is a re-assessment of the design requirements.

As part of this framework, Life Cycle Assessments (LCA) have to be performed in order to identify: (i) the most adequate raw material, (ii) opportunity areas for low energy consumption and (iii) the most convenient number and shape of components in order to facilitate recyclability, remanufacturability and reusability (Fig. 4). The LCA also considered transportation and logistic issues such as (i) the effect of design size, weight and shape on storage capability or (ii) the effect of storage capability on cost and environmental impact. Furthermore, social aspects were also considered and integrated as design constraints since the conception stage. As such, designs were subject to a minimum use of hazardous materials as established in a risk assessment evaluation (also performed by the authors), based on Mackay III fugacity models and official US toxicity values. [11, 12, 13, 14]

The logistic assessment of product performance is based on an analysis of the expected supply chain of the product (Fig. 5). In a forward logistics assessment, the metrics for evaluation are the portability features of the product and its packaging (weight, volume, and stacking capability), as well as the reliability, cost and quality of the different suppliers of raw materials and parts. Moreover, environmental and logistic issues can be evaluated along the supply chain in order to identify process alternatives that lead to lower environmental impacts and consequently, to greener products [15, 16].

Suggestions from different assessment groups are collected by a multidisciplinary team that discriminates them and translates a selected few into design changes that will be passed on to the design team for implementation into the product. In order to keep control of the changes the authors recommend limiting the maximum number of changes per iteration to five.

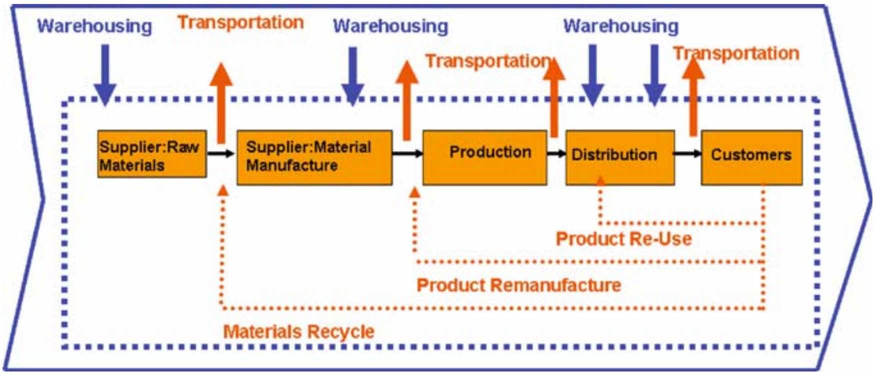


Fig. 5 Logistics assessment

3 Case Studies

3.1 Case 1: Development of a Table Fan

The following figures and tables correspond to a case study developed by the authors in order to design, develop and optimize a table fan. This product was requested in the Mexican market, so the new design took into account (i) design for manufacturability, (ii) design for the environment, (iii) design for logistics, and (iv) design for sustainability under a PLM scheme [10]. The table fan was designed from a series of inputs: market study, analysis of competitors, interviews with experts of various departments such as manufacturing, logistics, CAD and environmental engineering.

At the top of the methodology lies the corporate strategy and the product's mission. Afterwards, a detailed examination of all characteristics and constraints of the new product was carried. This examination was based on market analysis, an understanding of the supply chain and knowledge of legislation, environmental and health restrictions. All attributes are ranked in order to communicate its relative importance (Table 1).

This information is also associated to engineering requirements (performance metrics) and translated into a priority matrix – a house of quality, as illustrated in Fig. 6 [8]. The house of quality correlates customer needs with engineering requirements in a hierarchical manner. Several designs can be generated in a first stage, and then an iterative process takes place to select and develop one of them until a first generation of the product is obtained [16].

A series of technical constraints and specifications are considered mandatory for the design:

1. Blade diameters must be 40 cm
2. Electricity input must be 110 V

Table 1 Priorization of design needs for the table fan

Attribute	Percent Ranking
Low noise	11.50%
Good Packaging	8.00%
Lightweight	8.00%
Multi-speed	7.50%
Oscillation	7.50%
Assembly time	7.50%
No vibration	7.00%
Stackable	7.00%
Recyclable	7.00%
Built ‘In-house’	6.50%
Low manufacturing energy	6.50%
Tilting	6.00%
Reduced material	6.00%
Re-usable	4.00%

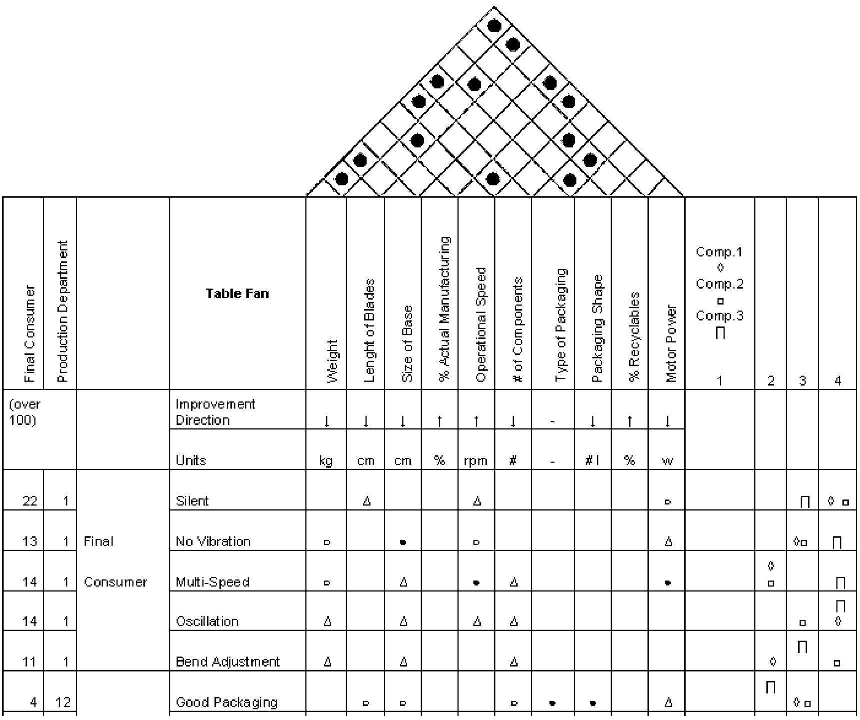


Fig. 6 House of quality for a table fan

3. Fan's size must be under 60 cm from the base to the end of the blades' house.
4. Fan's weight must be under 7.5 kg
5. Fan's base must not exceed 50 cm in diameter
6. Engine must supply at least 60 W and must be provided by a qualified supplier.

The first two constraints are based on the Mexican standard NMX-J-016, while the rest of the specifications were provided by the marketing and the design departments. It should be kept in mind that not meeting these specifications will lead to a less attractive product.

The first design was developed by aims of computer aided engineering software used in the company for the design of all its family of products: Unigraphics NX3. The first design is presented in Fig. 7.

It is important to note that the first iteration came up after undertaking a traditional methodology for product design. First of all, clients' needs were identified and expressed in terms of engineering specifications, which in turn led to concept generation. These inputs represented the base to the following activities: concept selection, product architecture and detailed design implemented in CAD [5].

The R-R methodology was then applied in order to improve the initial design. This iterative methodology compromises the new design in terms of aspects such as manufacturability, environmental performance, and logistic implications. A wish list of improvement ideas based on these three aspects was generated and used as a list for trial and evaluation attempts. Furthermore, design parameters were reviewed in order to narrow the universe of new possible changes. Conflict on the scope of improvement decisions during the iterative process were solved based on the hierarchy of product attributes presented on Table 1.

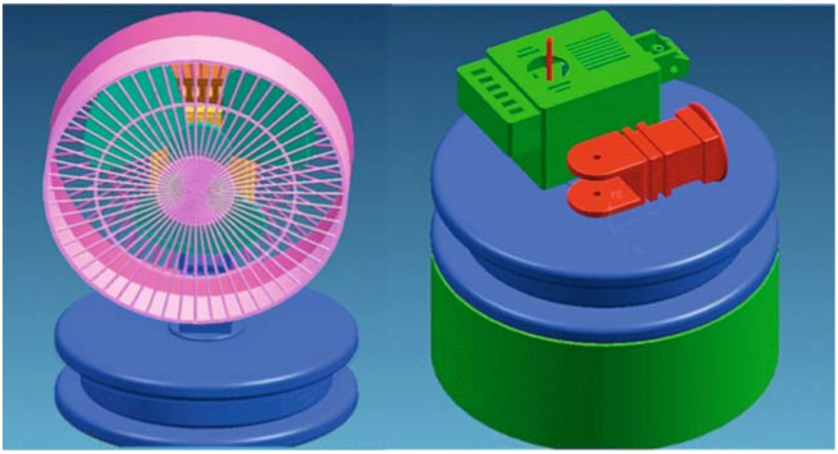


Fig. 7 First generation of table fan

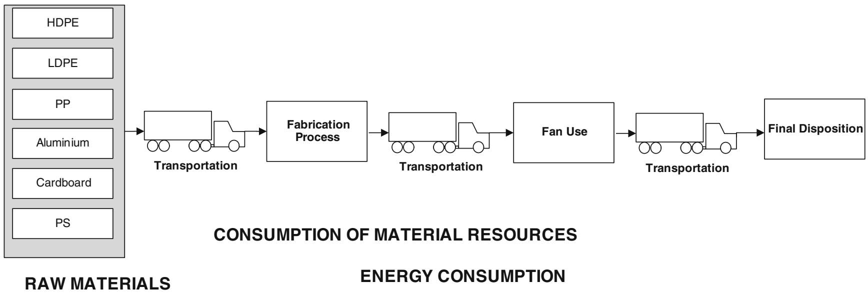


Fig. 8 System for environmental assessment

The following sections illustrate the environmental and logistic assessments to improve the performance of the product as evaluated for each iteration.

3.1.1 First Iteration-Environmental Performance

For the environmental evaluation of the first iteration, a life cycle assessment (LCA) was performed. The methodology of the life cycle assessment is integrated in an international standardized frame as specified in the family of standards ISO 14040. [14]. LCA is a methodology commonly used in environmental engineering for the environmental evaluation of products and processes taking into account their whole life cycle: extraction of raw materials, manufacture, distribution use, recycling process, and final disposition of the product. This methodology is composed by (i) definition of the system, objectives and scope, (ii) an inventory of emissions obtained by energy and material balances, (iii) a stage of environmental evaluation that takes into account a series of aspects like global warming and resource consumption, among others, and (iv) identification of improvements to the system [16]

Based on the aforementioned standards, in the practical application presented in this article the following system was defined (Fig. 8): First, raw material is extracted and processed (High density polyethylene, HPDE; low density polyethylene, LDPE; polypropylene, PP; Aluminum, Al; cardboard and polystyrene) so it can be ready for production; afterwards, it is transported to the plant, where it is transformed by means of diverse injection processes which are needed to manufacture some pieces of the fan; after this, the assemble and packaging is done; then, the fan is transported to the point of sale, from there to the consuming place, where it has a specific operational life (approximately 5,000 hours); finally it is transported to its respective place for final disposition (landfill or recycling). The developed equations for the material and energy balances, as well as for the correlations that determine the inventory of total emissions and the calculations for the relative environmental impact are available upon request.

Mass and energy balances were performed with the use of a calculus spreadsheet and GaBi 4.0, a commercial software for life cycle assessments. These activities led to an inventory of emissions, with information on the type and amount of materials and energy produced and consumed. Main results are presented in four different categories:

1. **Total**: addition of the other three categories.
2. **Fan production**: includes emissions of the extraction of the raw material, the transportation of the raw material to the plant, the manufacture of the fan and the distribution to the sale points.
3. **Fan use**: includes exclusively emissions from the useful life of the fan by the costumer.
4. **Fan disposal**: includes emissions from the final disposition of all parts that constitute the fan (including packaging material)

This LCA had two fundamental objectives: first, to determine if an emission of pollutants that was not allowed by regional law existed in the process; second, to identify the process stage in which the highest environmental impact existed; in order to direct modifications on product's design, especially on those activities associated to the highest environmental impacts.

The main indicators related to environmental impact were the following: Potential contribution to greenhouse effect (Global Warming Potential, GWP), Depletion of natural resources (Abiotic Depletion, AD) and Human Toxicity (HT). Fig. 9 illustrates the relative GWP associated to major transformation processes. As such, the X-axis represents a series of processes, such as (i) energy consumption, (ii) production and transformation of materials (LDPE, HDPE, PP and Aluminum) and the rest of processes involved in the LCA. It can be seen that the stage that contributes the most to the GWP environmental impact is the ***fan use*** by the consumer, which is basically due to energy consumption (electricity). This contribution represents approximately 95% of the total emissions related to the life cycle of the product. In other words, the energy consumption that is required during the useful life of the fan is responsible for the largest environmental impact related to the product.

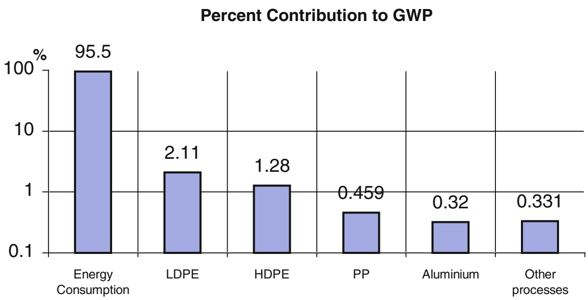


Fig. 9 LCA results for first generation of the design

As such, efforts on a new design were oriented to obtain a product of less electrical consumption, and in particular to the implementation of a new engine with lower requirements of consumption and power.

It is important to mention that other obvious changes like a design of less material would also have a positive impact. Nevertheless the LCA showed that this change represents a small percentage of the global emissions and does not justify its incorporation into the first iteration of the process.

3.1.2 First Iteration- Logistic Performance

This section presents a supply chain analysis related to the fan – from raw materials procurement to end product delivery. Weight logistic variables related to product design are presented in Table 2.

The ranking of the suppliers was obtained after performing a weighted average of the following criteria: price of raw material, average lead time, and quality of raw materials. A mathematical model was developed for this in order to understand the effect of each variable on the general ranking and consequently find the most convenient provider.

The mathematical model for the weighted average was devised as the addition of the weighted values for distance, cost and historic performance of suppliers. The resulting equations lead to a comprehensive and clear set of values that can be easily interpreted by all members in the design team. The following formula represents suppliers ranking:

$$\text{Weighted ranking} = A.f(x) + B \cdot g(y) + C \cdot h(z) \tag{1}$$

where

A = weight value assigned to distance
B = weight value assigned to cost
C = historic weight given on previous rankings.

Table 2 Logistic aspects – First iteration

General aspects		Units
Net total weight	5874	Grams
Number of parts	20	Pieces
Logistics		
Package size		
Length	500	Centimeter
Width	500	Centimeter
Height	350	Centimeter
Maximum Stacking	6	Boxes
Package weight	950	Grams
Total weight	6824	Grams
Suppliers rank	8.0	

Weighted values assigned to the constants in this work are based on current hierarchies as reported previously on Table 1. As such: $A = 0.25$, $B = 0.45$, $C = 0.30$

The functions $f(x)$, $g(y)$ y $h(z)$ were proposed in order to obtain rankings on the same order of magnitude (between 0 and 10) so they could be compared.

The function $f(x)$ decreases at a decreasing rate. Three points define the parabolic shape of this function:

1. 0 km equals 10 points (none of the suppliers reaches this value)
2. 1000 km equals 0 points (suppliers must be based within this distance)
3. 160 km equals 7.5 points (average distance considering all potential suppliers).

$$f(x) = 6.6964 \times 10^{-6}x^2 - 0.0167x + 10 \tag{2}$$

where $x =$ distance.

The function $g(y)$ is also a function that decreases at a decreasing rate. Three points define this function:

1. A cost of zero equals 10 points (none of the suppliers reaches this mark)
2. There is an asymptotic limit on 0 points (i.e., the cost reaches an infinite value)
3. A cost of $ 13.21 equals 7.5 points (13.21 is the average price).

$$g(y) = \frac{396.3}{(y + 39.63)} \tag{3}$$

$y =$ cost of raw material as given by each supplier

The function $h(z)$ is a function that increases at a decreasing rate. Three points define this function:

1. 50 points equals a ranking of 9 (currently, this is the maximum rank)
2. There is an asymptotic limit on 10 points (none of the suppliers reaches this mark)
3. 0 points equals a ranking of 0.

$$h(z) = \frac{-55}{(z + 5.5)} + 10 \tag{4}$$

where $z =$ total points based on suppliers history.

Results presented in Tables 1 and 2 suggest that logistic improving is directly related to product packaging. Thus, a series of modifications were proposed in product design in order to reduce package size and net weight.

Design improvements in terms of weight, resource depletion and energy consumption were incorporated into the fan's second generation. There was only one constraint that could not be modified: the fan's engine. The reason was that the supplier had previously negotiated a long term supply contract. Moreover, engines are provided by a qualified supplier. The new design is illustrated in Fig. 10.

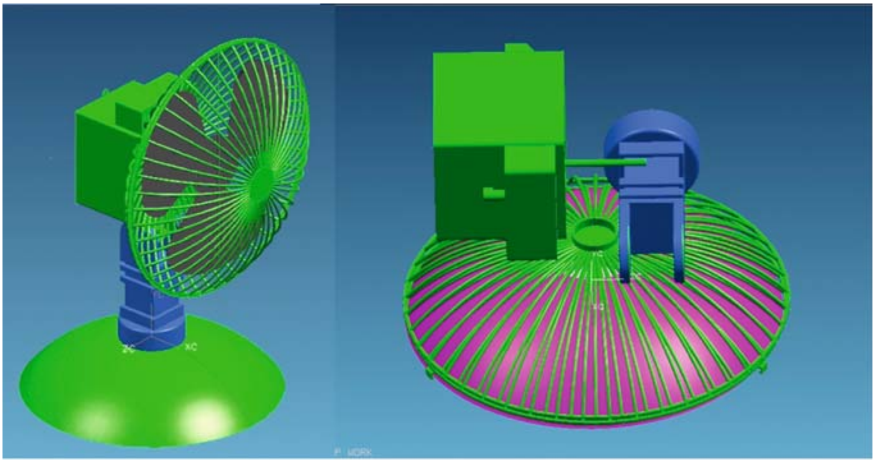


Fig. 10 Second generation of table fan

3.1.3 Second, Third, and Fourth Iterations

The new generation performed better in terms of materials consumption (resource depletion). Similar conclusions to those presented in the first generation were reached in the second generation. This is due to the fact that changes adopted in other categories outweighed environmental performance (see Table 1). Figure 11 presents the relative GWP impact of production and transformations of materials (LDPE, HDPE, PP), Fuel consumption (diesel), and Energy evaluated for the third generation of the fan design.

Logistic changes adopted for the second generation were performed. Major improvements were concentrated in four areas: package weight, fan's net weight, package's height, and stacking number. The changes on the design

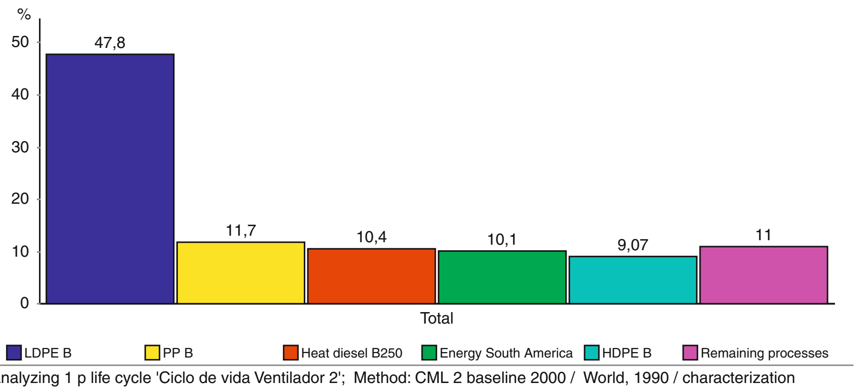


Fig. 11 LCI of the third generation of table fan, percentage contribution to GWP

Table 3 Overall improvements to table fan

Analyzed attribute	1st Generation	4th Generation	Difference	% of Improvement
Net Weight	5,915 g	4,319 g	1,596 g	27 %
Packaging weight	950 g	815 g	135 g	14 %
# stacking	6 boxes	11 boxes	5 boxes	83 %
Volume Packaging	87,500 cm^3	63,000 cm^3	24,500 cm^3	28 %
In House Fabrication	75 %	75 %	0	0 %
Pondered ranking of suppliers	7.70 points	7.89 points	0.19 points	2.5 %
Energy consumption of fan	70 W	66 W	4 W	5.7%
Equivalent emissions of CO2 (GWP)	266 kg	225 kg	41 kg	15%
Equivalent consumption of Sb (AB)	1.67 kg	1.40 kg	0.27 kg	16%

allowed for a reduction of 8% in energy consumption due to a change in the electric motor. Moreover, there was a reduction of 5% in the energy required to produce the fan, due to the changes in mass to the components.

The iterative process presented in this section was conducted until a fourth generation that compromised major attributes was reached. A final design for this product involved significant advantages such as a new record on design time, lower material consumption, lower weight and higher stacking number. Table 3 presents a comparison of total improvements along design generations. The final design is illustrated in Fig. 12.

From the results presented in Table 3, it can be appreciated that all logistic and environmental aspects assessed suffered an improvement. The most significant result from the logistics evaluation is the increase on the number of

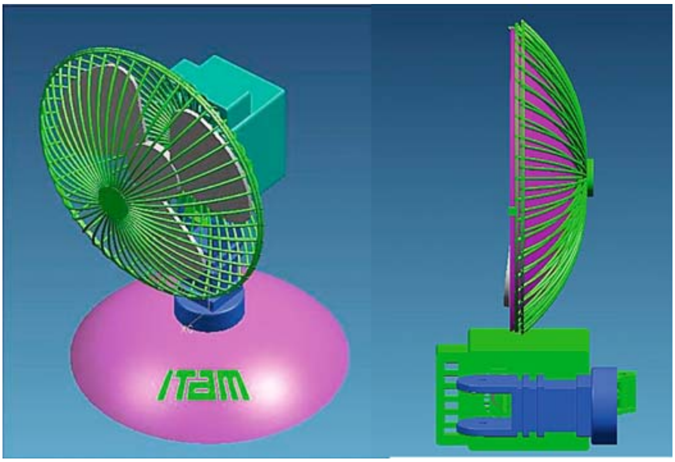


Fig. 12 Final generation of table fan

items that can be stacked for transportation, it went from 6 to 11, which represents an 83% increase. Design changes on the base and fan guards allowed for an important reduction in the net weight of the fan, as well as a reduction in material consumption to produce those parts. These modifications are reflected on a lower expenditure on raw materials, a reduced amount of energy required for its processing, and consequently a lower level of emission of GWP gases.

3.2 Case 2: Development of a Lamp for Street Lighting

The R-R methodology was also applied in the development of a *highly-energy-efficient* lamp for street lighting. As was presented in the previous section, the first step in the design process includes the definition of the mission statement of the product. The lamp mission statement declared that the product was envisioned to work either connected to the main electrical grid or (due to its high energy efficiency) in an independent manner connected to a solar panel, controller, and set of batteries.

There were several technical constraints regarding the development of the lamp: (i) the assembly of the lamp should be easy, not relying on complex technologies, (ii) the lamp should be able to be mounted on all commercial street posts, (iii) the lamp should be able to operate under conditions of low solar radiation (December and January in the northern hemisphere), (iv) the lamp should be able to stand adverse environmental conditions (humidity, salinity, wind, extreme temperatures, etc.) during its life cycle, and (v) the lamp should meet the Mexican illumination standards NOM-001.

A typical supply chain for public lighting systems is shown in Fig. 13; each member of the chain has different needs and requires different features of the product to fulfill them. It should be noted that in accord to the holistic design philosophy of the R-R methodology, all members are considered customers of the product.

According to a series of interviews with different participants of the supply chain the needs were identified as features that the product should have regardless of the technological solution. These needs were first ordered according to Table 4.

The needs listed in Table 4 can be grouped in two large categories: those related to the interaction with the lamp and those related to the performance of the product during use. A new series of interviews and focus groups were

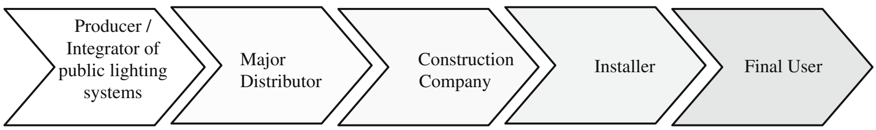


Fig. 13 Supply chain for public lighting systems

Table 4 Needs of different participants of the supply chain

	Needs
Producer / Integrator	The availability and continuity in the market of third party components should be ensured
	Parts should be efficiently stored
Major Distributor	Easy to transport
	Stock availability with the producer
	Availability of credits and discount policy
Construction Company	Financial justification of the investment
	Ensure warranty and maintenance after sell
	Meet international standards
Installer	Comfortable and rapid installation
	Avoid extra costs during installation
	Protect the equipment against rough use and accidents
Final User	Obtain enough luminescent performance compared to traditional lighting technologies
	Reduce maintenance and avoid replacements
	Avoid blackouts
	Avoid the stealing of the equipment
	Reduce the electrical consumption and the costs associated to operation and maintenance

conducted in order to further detail the needs, especially those relating to the performance of the product. These needs were ordered according to their importance, where level 3 needs are critical for the customer, level 2 needs are of medium importance, and level 1 needs are desirable features (Table 5).

Engineering requirements were developed to satisfy the needs the customer is expecting from the lamp. This was performed in a similar manner as for the table fan presented previously. Once the requirements were established, a benchmark was conducted by analyzing the existing products in the Mexican

Table 5 Performance needs for street lamp

Need No.	Need description	Hierarchy
1	The lamp is on all night	3
2	The lamp works even in cloudy days	2
3	The equipment is installed high from ground	3
4	Long life of components	3
5	Affordable prices	3
6	The illumination meets the Mexican standards NOM-001	2
7	Attractive and modern appearance	1
8	Low maintenance	3
9	Easy installation using standard tools	2
10	Detailed technical information of components	3
11	Clear manuals of operation and maintenance	3

market that were competitors to the street lamp. Since none of these solutions were satisfactory for the design team it was decided to develop a new product concept.

A product concept is an approximate description of the technology, operation, and shape of a product: this concept represents how the product will meet the needs of the customer. In order to develop a concept, it is necessary to vision the product as a series of connected functions (or sub products) that work together. The process of defining these functions is known as functional decomposition and helps identify the critical functions that the product has to perform to translate them later on into features of the product. For the solar street lamp the functional decomposition is depicted in Fig. 14.

From the functional decomposition three critical functions were identified, namely: “conversion of solar to electric energy”, “storage of electric energy” and “conversion of electric to luminescent energy”. From the definition of the product presented above, the conversion of solar to electric energy was selected to be by means of a set of photovoltaic (PV) panels commercially available. The options of PV panels available in the market vary depending on the price, conversion efficiency, light sensitivity and warranty. Several potential suppliers were identified offering different technologies such as mono-crystalline, polycrystalline, or amorphous PV panels. The selection of the best suited PV panel was not based only on the previous characteristics but also on its integration to the whole system, since it was found that although the amorphous panels provide the best energy performance, they require a larger area than the other options hence complicating the installation. Moreover, it was also necessary to

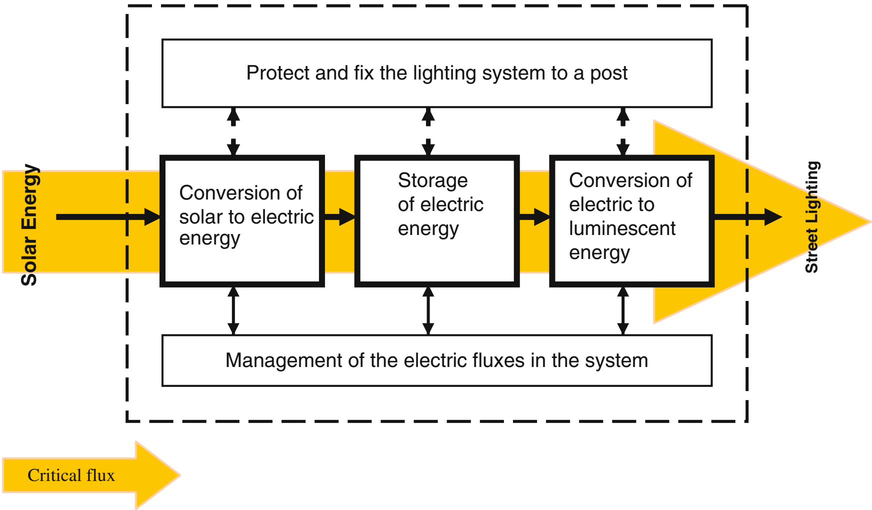


Fig. 14 Functional decomposition of the lamp

consider the reliability of the suppliers; consequently the selection was to use crystalline PV panels.

A solar powered system for lighting presents an interesting problem in terms of energy management; during daylight the PV panels will generate electric energy that needs to be stored for its use during the night. The best available technology for storing electric energy is the use of batteries; hence, like in the PV panel selection, a reliable battery was selected. The selection criteria for the batteries were the expected lifetime (directly linked to maintenance cycles) and the energy capacity. The development team decided to use sealed batteries with a large energy capacity in order to reduce wiring and connection complexity.

The third function, conversion of electric to luminescent energy, was considered critical for the development process of the system. It was found that the competitors used either gas discharge lamps (specifically sodium oxide) or fluorescent tubes. Although the gas discharge lamps offered good luminescence to energy ratio, the light emission is omni directional and distinctively yellow in color; in other words not all the light produced goes to the street surface, and it is not possible to have a good color differentiation. The fluorescent tubes do not have a good light penetration nor meet the Mexican standards for street lighting. Since none of these alternatives were satisfactory for the design team it was decided to develop a new solution based on Light Emitting Diodes (LEDS). A LED is a source of highly directional light with an opening angle of only 7°, in other words a single LED at a height of 8 m will illuminate a circle of 1 m diameter. Clearly this presented an issue since in street lighting systems the area to be illuminated is a circle of 10 m radius (314 m^2). The design team developed a solution to orient an arrangement of LEDs in a semi-spherical manner in order to cover the working area. This development was registered with the World Intellectual Property Organization (WIPO) and is sketched in Fig. 15.

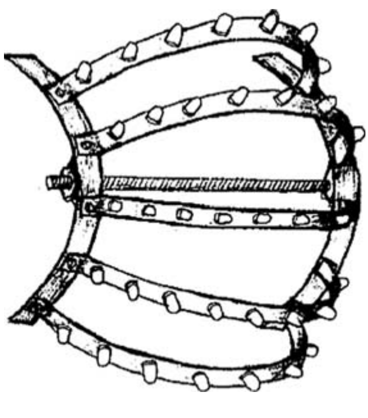


Fig. 15 Concept sketch of the orientation of LEDs (By courtesy of Grupo ECOS Innovations ®)

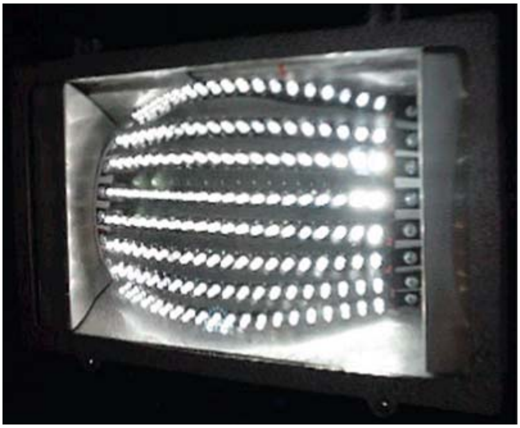


Fig. 16 Physical prototype of LED based lamp (By courtesy of Grupo ECOS Innovations ®)

The LED arrangement was mounted in a commercial enclosure to test its lighting efficiency, ease of manufacture and assembly, energy consumption, and selection of materials. This resulted in a physical prototype as shown in Fig. 16.

The R-R methodology was applied to this product concept in order to optimize its operational, environmental, and logistic performance. After 4 cycles of optimization there were improvements in the ranking of suppliers, the energy to luminescence ratio, the amount of recyclable materials in the lamp, the energy consumed during production, and the mounting arrangement for the system, among others. Due to confidential purposes, specific technical data cannot be presented in this paper.

The design was optimized to fit a cobra-head type of enclosure that presented the best protection against adverse environmental conditions (rain, humidity, dust, etc.) while improving the ease of assembly and installation. Figure 17 presents a close up of the final LEDs-enclosure arrangement.

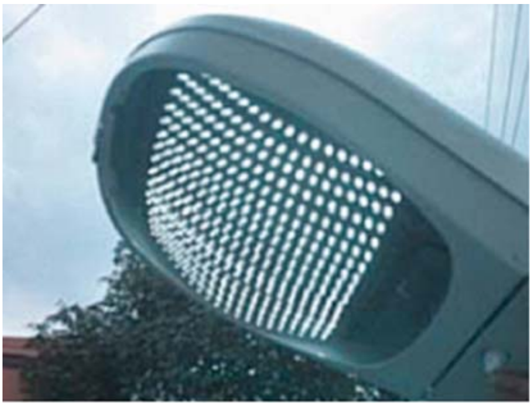
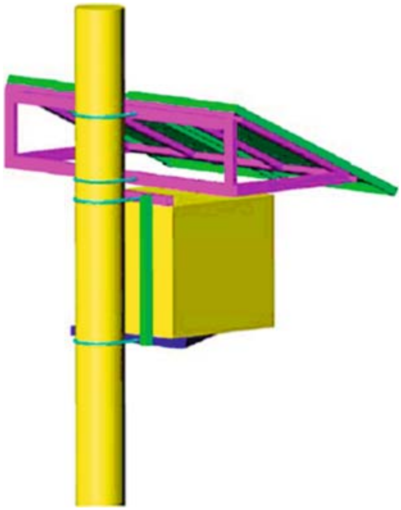


Fig. 17 Final lamp close up (By courtesy of ECOS Innovations ®)

Fig. 18 Schematic of the mounting system for the street lamp (By courtesy of Grupo ECOS Innovations ®)



Once the three critical functions were solved it was important to integrate them into a system that could be mounted into most commercially available posts. This is a design requirement since the system is intended to be used in several geographical locations within Mexico. A schematic of the mounting system is presented in Fig. 18.

The system for street lighting was selected by the government of Mexico City to be used in a linear park. More than 150 lamps were installed and have been functioning with no malfunctionings or maintenance for over two years. Figure 19 shows a view of the park.

Fig. 19 Solar powered street lamps at linear park in Mexico City (By courtesy of ECOS Innovations ®)

4 Conclusion

Developing concepts in order to satisfy consumer needs does not represent a sustainable competitive advantage. It is mandatory to innovate and generate flexible concepts within record timing and minimum cost.

Innovative and integrating engineering designs and environmental and logistic issues within a single framework represent a useful alternative to come up with optimum product designs at a faster speed than with a traditional trial and error scheme. Multivariable decision making can be accomplished with the use of constrained parameterization. Hence, as long as manufacturing, environmental and logistic interaction are expressed in terms of equations, the innovative design process is facilitated.

This framework was successfully applied into various product-process systems. A comprehensive diagram of both frameworks was presented. The main results showed that an optimized design can be achieved in the early stages of the design process, by combining computer aided tools for design, analysis, and predictions in a feed-back process loop. This methodology allows for the conception of a successful prototype in a "do it right the first time" manner. Furthermore, the mathematical framework showed trade-offs between higher inputs (electricity, steams, and steel) and lower discharge limits (considering not only the production process but also the need for a waste-treatment plant).

The conceptual design of a commercial fan serves as a means to illustrate the methodology and the advantages of a holistic design. After reviewing results from the first to the fourth iterations it is clear that design parameters vary within a range. As such, trade-offs within parameters occur, which in turn are evaluated with the QFD matrix.

The methodology was also applied in the design and development of a solar powered system for street lighting in Mexico City. Four cycles of optimization were performed resulting in improvements in the ranking of suppliers, the energy to luminescence ratio, the amount of recyclable materials in the lamp, the energy consumed during production and the mounting arrangement for the system, among others.

More specific results are available upon request. So far, the application of the aforementioned methodology allowed for the design, test, manufacture and launch in almost half the time (and 40% cheaper) compared to traditional schemes. Furthermore, the application of this methodology, which is fully based on PLM concepts, delivered a better ranked product in less time and at a lower cost. The correct application of these engineering concepts combined with PLM can be easily extended into almost any new product at its development stage.

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A Comprehensive Business Approach to Product Realization Using Service Oriented Architecture

Vijay Srinivasan

Abstract A comprehensive business approach to product realization involves tackling both business and technical issues. As business executives focus on innovation – both in products and in business models to realize these products – as a means to increase revenue and profit, they have identified collaboration and partnership with external players as keys to their success. They want flexibility and responsiveness in sharing and exchanging sensitive product information across a global network of partners, but feel that they have not yet been able to achieve their goals. A technical solution to this problem may well be provided by the convergence of three recent developments: maturity of standardized product models and processes, emergence of service oriented architecture for information sharing, and availability of middleware to implement them. This paper describes the results of a recent business and market research in identifying the problems facing business executives, and an information sharing architecture with service orientation for product realization to solve some of their problems.

Keywords Innovation · Product realization · Product development · Product Lifecycle Management · Information technology · Standards · Services Oriented Architecture (SOA) · Middleware

1 Introduction

Business leaders make tough decisions every day, usually without the benefit of all the information they would like to have. For example, let's assume that in an industrial firm the engineering department has proposed a change to a top-selling product. The change will make the product better, but at what cost? How many parts in inventory will be made obsolete? What new tooling will need to be

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designed and developed, and how long will it take? What customers will be affected, and how are they likely to respond? In short, is there more risk than reward in making the change? Such questions arise in any comprehensive approach to product realization.

Traditionally, answering these questions has required information from Product Lifecycle Management (PLM), Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), Supply Chain Management (SCM), and in some cases plant floor Manufacturing Execution System (MES). This information, however, was usually available only through complex manual data compilation and analysis. Finding the answers could take weeks, time that is not often available or that could give a competitor an advantage in the marketplace.

But profound changes in information technology infrastructures are changing this paradigm. A powerful new approach to Information Technology (IT) known as Service Oriented Architecture (SOA) is promising to break down the barriers between IT systems and applications to deliver actionable business intelligence in ways never before possible. The combination of SOA with PLM seems to be especially powerful, enabling greater insight into the business impact of engineering decisions, facilitating collaboration with external partners regardless of the systems and applications they have chosen, and leveraging legacy PLM investments while reducing the cost and complexity of deploying new or updated applications. As CIMdata recently observed, "SOA can significantly reduce a (user's) exposure to costly upgrades and deployment expenses and will preserve their tailored implementations" [1]. Moreover, SOA offers the potential for companies to empower the investment they have already made in PLM, transforming it from a tool used primarily by product engineers into a powerful business decision support enabler that allows users to react quickly to sharp changes in market direction – or to initiate changes the rest of the market must scramble to match.

To understand how and why PLM is poised to become a key driver of competitive business advantage, it is important to first understand the forces at work in the market, the forces at work on PLM, and how the two are converging to give business leaders the required power to innovate their businesses. In Section 2 we focus on the business drive for innovation. This leads to the importance of a global network of partners in Section 3. SOA is discussed briefly in Section 4 as a technical solution to the information sharing problem. Section 5 addresses the application of SOA to PLM. The resulting business benefits are outlined in Section 6, before Section 7 summarizes and concludes the paper.

2 Business Drive for Innovation

Today, Chief Executive Officers (CEOs) are concerned with the same business objectives that have consumed them through the ages, including revenue growth, cost reduction, asset utilization, and risk management. But how CEOs expect to achieve these business objectives has made a radical shift. For several years, CEOs have focused on product innovation as a driver of competitive advantage, recognizing that innovation is a means to achieving all those other goals. “We will fight our battles not on the low road to commoditization,” said Howard Singer, Chairman and CEO of Sony Corporation, “but on the high road of innovation” [2]. Jeffrey Immelt, Chairman and CEO of GE Corporation, recently remarked “Constant reinvention is the central necessity at GE. . . We’re all just a moment away from commodity hell” [3]. Ed Zander, Chairman and CEO of Motorola quipped “All I have done since I got here is focus on one word: innovation” [4].

Recently, however, their understanding of what enables innovation has changed, leading to a new focus not just on innovating products and services, but also on innovating the business processes and business models that influence the creation of innovative products. Simply put, innovation looks for new ways to make money, because old ways may not work anymore. This new focus on innovating not just products, but how products are created and commercialized, is a reaction to rapidly accelerating change. In a world where competitors can emerge overnight from anywhere on the globe and breakthrough innovation can fundamentally shift the competitive landscape, the ability to continually scan the horizon for threats and opportunities and then change directions quickly to meet or seize them has become paramount.

In a recent IBM Global CEO Study published in 2006 [5], 87% of respondents said their organizations will require fundamental change to succeed in driving innovation in the next two years (see Fig. 1). This survey population included 765 CEOs, business executives, and public sector leaders from 20 different industries and 11 geographic regions, both from mature markets and from important developing markets such as China, India, Eastern Europe, and Latin America. More than 80% said their organizations traditionally have been largely unsuccessful in managing change in the past, and only one in ten CEOs

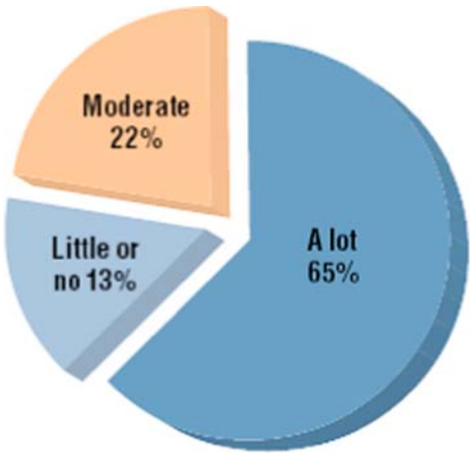

Fig. 1 Extent of fundamental change needed over the next two years

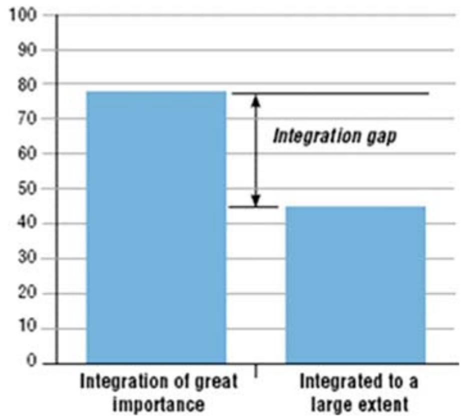

Fig. 2 Importance versus extent of business and technology integration (% of respondents)

believed their organization had the ability to respond to rapidly changing market conditions.

The CEOs also recognize the important role that the integration of business and technology plays to improve the flexibility and responsiveness of their organizations. Nearly 80% of CEOs responding to the IBM survey rated business and technology integration of great importance – but only half said they are executing at the levels required, leading to an 'integration gap' illustrated in Fig. 2. This failure is costly: 'Extensive integrators' reported three times the revenue increases of less integrated companies. IBM's own financial comparisons estimate that 'extensive integrators' grow revenues five percent faster than their competitors.

3 A Network of Partnership

In the same IBM Global CEO Study of 2006 [5], major strategic partnerships topped the list of significant business model innovations. As global connectivity reduces collaboration and transaction costs, companies are taking advantage of the expertise and scale beyond the boundaries of their organizations. They are assembling groupings of "specialized" capabilities, combining, for example, internal expertise and scale through shared services centers with the capabilities of specialized partners to create innovative business models and processes.

When asked which sources their companies relied on for their most significant innovative ideas, CEOs' responses held some surprises. Business partners were near the top of the list, just behind the general employee population. External sources are not only prevalent in the ranking of CEOs' most significant sources of ideas, they also comprise a substantial portion of the overall quantity of ideas. This trend was particularly evident among financial outperformers.

CEOs believe collaboration is absolutely critical, but there is a problem: Although collaborative aspirations were high, actual implementation was

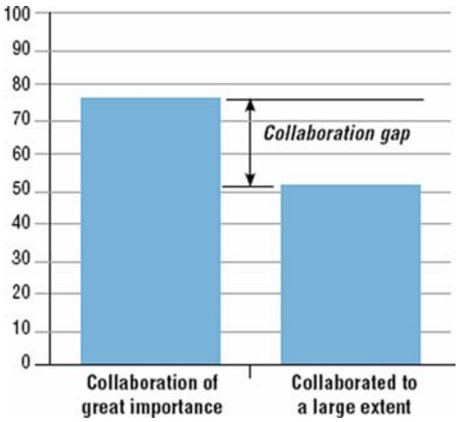

Fig. 3 Importance versus extent of collaboration and partnering (% of respondents)

dramatically lower. Only half of the CEOs interviewed believed their organizations were collaborating beyond a moderate level. See Fig. 3 for an illustration of this ‘collaboration gap’. Citing a lack of the skills and expertise needed to partner externally, many CEOs refer to partnering as “theoretically easy” but “practically hard to do”. The message is clear: whether it involves crossing internal or corporate boundaries, collaboration requires serious intent. The upside of collaboration is underscored not only by qualitative CEO feedback, but also by the financial performance of companies with extensive collaboration capabilities. The Global CEO Study 2006 illuminates the degree to which strong collaborators enjoyed healthier revenue growth and average operating margin over their competition.

The challenge of meeting these collaboration objectives for product realization is compounded by the need to operate effectively within a value network. Today, delivering the product the market wants requires cooperation among a complex ecosystem of players, from the customer-facing Original Equipment Manufacturer (OEM) to its design partners, their suppliers, and a host of manufacturers. Simultaneously, distributors and retailers join the network, delivering the product to customers and providing in-field service after the sale (see Fig. 4).

Finance and business controls govern revenues and costs. But because product development processes extend across multiple companies, much of the information required to establish these financial targets is known only by the partners, suppliers and manufacturers who design and source the components. Their activities, in turn, rely on information in systems they may not fully control, such as inventory and manufacturing scheduling. The OEM’s sales and marketing organizations, meanwhile, need visibility into all of these activities to gather market requirements and condition the market to demand the product. In short, in a comprehensive business approach to product realization, there is a dire need to share and exchange information across a complex network of partners, such as the one shown in Fig. 4, that is spread globally and whose topology can change quickly.

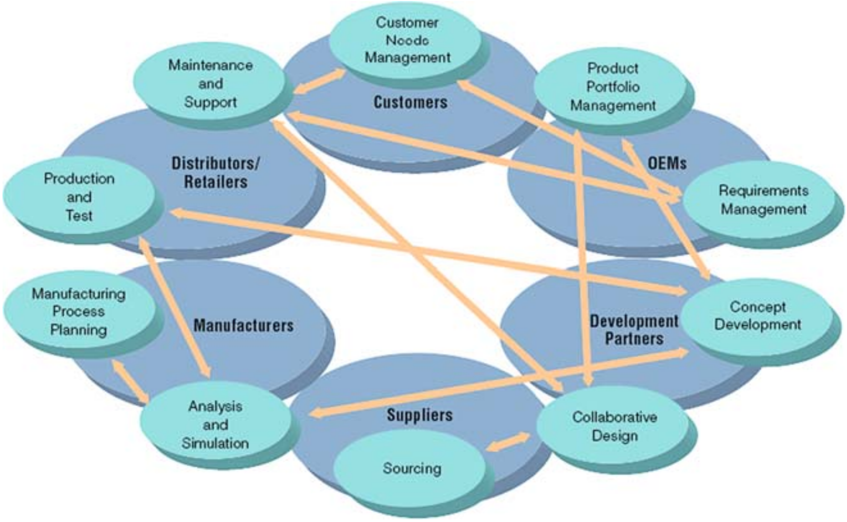

Fig. 4 Product realization takes place within a complex network of partners

The truth is that until recently, the IT tools and strategies available simply were not up to the challenge of sharing information across such a complex network of players in an efficient way. In fact, hard-wired links between enterprise applications compounded the very challenges they were meant to address. Those links were also difficult, expensive and time-consuming to build because developers had to compensate for the incompatible architectures of the systems involved. This resulted in redundant and contradictory data and a hopeless jumble of connections that were costly and difficult to manage and maintain. And when business priorities changed, changing the links could take so long that companies were late in responding to opportunities – or missed them entirely.

The way business leverages information technology must therefore change radically if enterprises are to garner the insights and achieve the agility CEOs require to respond to business conditions. Fortunately, the development of a Service Oriented Architecture (SOA) approach to building information technology systems promises to overcome the challenges of inefficient and inflexible architecture through adoption of an architecture specifically designed to accommodate rapid and frequent changes.

4 Service Oriented Architecture

SOA is an approach to enterprise computing that works in a way that resembles LEGO, the popular childhood construction toy. LEGO can be assembled into one structure today, then broken apart and reassembled into something else tomorrow. The blocks do not change, but their modular structure allows each block to play many different roles, depending on how it is assembled with other blocks.

SOA works much the same way, allowing an IT analyst to break business functions and processes into small chunks known as services and then reassembling them to support different business models and processes. Services are functions that when invoked accomplish some specific task. They expose a well defined interface, hide their implementation details, and are scalable through open standards mechanisms. Services can be used to perform a wide variety of tasks, such as portfolio and program decision support; requirements, configuration, or engineering change management; supplier and OEM collaboration; commonality and part reuse; analysis and simulation; or system integrity validation, to name a few.

These modules can be assembled together on a standards-based framework to support one business model today, and a different business model when market conditions change. SOA enables a business-centric view of the enterprise, orchestrating functions in terms of people, processes, and information. SOA allows one to integrate these services with customers, partners, and suppliers when everyone in the chain has different applications and computing platforms. See Fig. 5 for an illustration of how the information, process, and people-related issues can be organized in a framework to support the technology-business integration and collaboration needs identified by the CEOs.

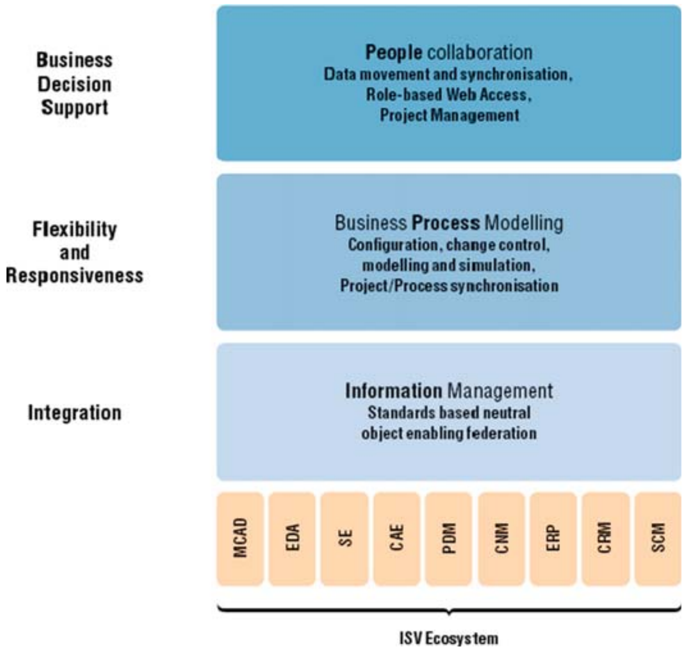

Fig. 5 A framework to support business needs identified by the 2006 IBM CEO survey

At the bottom layer of Fig. 5 are various engineering and business application developed and supported by different Independent Software Vendors (ISVs). The information generated by them can be integrated using standardized data models [6], web services, and middleware to implement them [7]. These services can be composed to provide flexibility and responsiveness in various work-flows to model and execute business processes. This results in the role-based people collaboration and provides business decision support needed at the top in Fig. 5 as desired by the CEOs.

Just as businesses are adapting to changes in the environment, so must their supporting systems like PLM. The consistent growth of PLM is proof of its ability to deliver business benefits specific to design, engineering and manufacturing, such as providing a 3D model-based development approach and enabling concurrent engineering to reduce time-to-market and development costs across a wide range of industries.

SOA is emerging as a key technology for enabling such growth in PLM. Combining PLM with SOA can deliver the flexibility vital to enabling innovation and achieving desired outcomes. This could provide the much sought-after breakthrough for integrating applications around the product realization process and breaking down the silos that traditionally have limited PLM. By integrating PLM with the rest of the enterprise, SOA can transform a formerly engineering-centric solution into a federated source of all product information, including pricing, market demand, portfolio costs and more.

Together, PLM and SOA can enable flexible, standards-based access to product information regardless of which software applications or hardware platforms are in use throughout the enterprise and out into the value network. The result is total product information visibility for product and portfolio planners, support engineers, sales and marketing – even business executives, as envisioned in the following section.

5 Applying SOA to PLM

SOA could address the needs of CEOs, delivering an entirely new approach that rises above the complexity of current IT systems to give enterprises the insight and ability they need to thrive in today's competitive reality. SOA allows organizations to more easily link and share PLM product data with information from other enterprise systems, effectively supporting approaches that require multiple-team collaboration, such as functional design, design-for-compliance, design-for-cost and service after sales.

Using SOA to combine the value of PLM and ERP, for example, allows users to understand costing and inventory levels of existing components, as well as their associative sizes and tolerances, to make better upfront design decisions. This lowers the cost to develop new products by leveraging existing components, which results in less excess inventory, fewer design iterations, and faster time to market.

By combining PLM with CRM, on the other hand, SOA allows organizations to showcase products in different configurations, allowing them to better illustrate the features in a virtual reality mode that could be highlighted in their sales initiatives. This is but one example of how product development could be tied more closely to market introduction processes. Similar benefits are available by federating PLM information with Requirements Engineering and Systems Definition, as well as with other downstream enterprise systems, such as Manufacturing Planning and In-Field Service Management.

Traditionally, most PLM environments utilize multiple applications, each of which has its own database. Each of these databases contains not just information, but knowledge about the relationships between the information – the context in which the information makes sense. When these databases attempt to share information through an enterprise PDM (Product Data Management) system, a traditional engineering tool, the knowledge embedded within the data relationships specific to each application is lost.

Attempts to overcome this limitation by integrating proprietary applications require hard-coded, difficult-to-change links. This defeats the goal of creating agile, flexible business models. This challenge is compounded when an OEM, for example, attempts to work closely with multiple partners and suppliers. Now each organization in the chain must deal not only with its own application complexity, but the complexities of its partners as well. Barriers between disparate systems make it difficult for people in interrelated functions to collaborate.

To get around these walls, people must schedule meetings, send e-mails or make phone calls to share information that cannot be shared by the organization's disparate systems. This ad-hoc system of collaboration is fraught with problems, however, including failures to include key people in critical decisions, or difficulties determining whose data to trust. This further stifles the goals of collaboration, innovation, and flexibility.

SOA-enabled PLM can remove the problems inherent in duplicating data from individual applications into an enterprise PDM system by creating a federated information mechanism that all applications access and share. Business processes exist independent of specific applications and can be viewed and accessed by all companies participating in a product realization value network. Portals provide access and visibility into all business processes relevant to particular user roles.

By eliminating traditional information silos and making vital product information visible throughout an enterprise, SOA-enabled PLM could transform PLM from an "engineering" application into a source of all product information. SOA-enabled PLM provides business decision support, increases flexibility and responsiveness and improves integration with the value chain, enabling CEOs to continually innovate their products, their business processes and their PLM infrastructures.

SOA can also create an ecosystem in which multiple solution developers, integrators and IT consultants can collaborate, replacing competition with cooperation – a profound benefit to the client. By permitting heterogeneous hardware and software to operate together smoothly through a shared commitment to open standards, SOA can deliver on the long-held client dream to mix and match best-of-breed applications to achieve a system uniquely suited to their special goals and challenges. The result is tailored client solutions for the electronics, aerospace and defense, automotive, consumer products, and fabrication and assembly industries.

6 Business Benefits

The SOA-enabled PLM approach could deliver new capabilities that would not be possible without this flexible infrastructure. These capabilities enable a comprehensive approach to product realization processes used within the entire value network. Some of the benefits of this approach were mentioned in the previous section. Listed below are a few more of the new capabilities and their benefits enabled by SOA.

6.1 Enterprise Asset Management and Service after Sales

Information systems used for enterprise asset management and service after sales track asset data including location, work, and cost history to control costs and operational condition of capital equipment. Collaboration between engineering and field services made possible by connecting mobile field service technicians to PLM and asset utilization data instantly speeds the communication of field issues back to the engineering department, allowing OEMs to identify design issues earlier, design fixes and communicate them to the field to reduce warranty claims and improve product reliability. Linking PLM data to asset usage in the field can improve customer service, account for proper asset usage, and lengthen useful life.

6.2 Enterprise Integration and Collaboration

Tools for enterprise integration and collaboration link engineering disciplines with product development stakeholders in commercial and operational functions by connecting disparate CAD and PDM systems to other enterprise systems, enabling an enterprise-wide view of product data that even extends into the partner network. When connected applications are accessed by users throughout the value network through a web-based portal, each user gets role-specific, secure access to the critical business applications they need to do their jobs. Information is presented to each user in a manner consistent with their role and in a way that they can understand. These flexible access tools help to ensure better business decision support and lower product development time and cost. Improved integration within the enterprise and into the supply network ensures flexibility and collaboration with people throughout the product realization process.

For example, Volkswagen AG has used such portals to improve productivity in its procurement department by improving access to product information. The portals have shortened order-to-delivery cycles while making the procurement staff 20% more productive and improving their ability to focus on high-value-add activities. Meanwhile, another leading OEM is using portals to streamline the communication of design changes between its own development teams and its suppliers, cutting the design/engineering cycle by more than a third, reducing development costs by 25% and replacing manual distribution of time-sensitive change orders with an automated, real-time system.

6.3 Product Performance Simulation

A modeling and simulation system simulates the behavior, flexibility and performance of a virtual product along all development stages and across multiple design partners. It includes desktop analysis/simulation plus digital mock-up (DMU) to improve product quality and shorten development time by detecting design problems early; Enterprise Simulation/CAE (Computer-Aided Engineering), which provides complex analysis and simulation; and IT Resource Optimization for Engineering, which optimizes the supporting infrastructures used to run compute-intensive analysis applications.

For example, Daimler-Benz Truck Division used mechanical analysis solutions earlier in its engineering developing cycle, improving its cycle time to product introduction by 60%. Meanwhile, a leading automaker reduced the time needed for engineers to compile their reports by employing a systematic approach to simulation data management for CAE that managed many terabytes of simulation data spread across several million files. The solution not only saved time; it also improved user confidence in the resulting data. And Magna Steyr, a Tier One automotive supplier, applied grid technology to its clash detection environment, reducing run times from 72 hours to four hours, which reduced costs, improved time to market and resulted in higher quality products.

6.4 Supply Chain Collaboration

Supply chain collaboration enables extended value chain creation and management of the virtual product into the supply chain, improving collaboration and integration through an optimized infrastructure, improving the management of data and development processes by suppliers, reducing program risk, improving business model and process innovation support, and reducing administrative costs for activities such as manual exchange, checking and data translation. Suppliers also benefit through reduced IT resource requirements, pre-defined solutions with industry templates that reduce implementation time and time-to-productivity by as much as 30% and a 10–20% reduction in overall engineering costs. Other likely benefits include a 30–35% reduction in engineering time and a 15–20% increase in profitability.

For example, to build its Falcon 7X business jet in four years rather than the traditional seven, Dassault Aviation assembled a team of 27 design partner firms scattered around the globe. The company employed a fully digital process to eliminate physical prototypes, and built a collaborative workspace that allowed all of its partners to share data online in real time. The resulting productivity gains have allowed the aircraft company to decrease its time-to-market plan by 30%. Similarly, an automotive OEM identified and eliminated bottlenecks in its collaboration processes after establishing a supplier portal as a single data exchange source with its suppliers.

6.5 Software and Systems Development

Software and system development tools accelerate and improve the design, development, implementation and management of the delivery of software and systems. To create virtually any new product today, it is necessary to synthesize the engineering disciplines of mechanical, electronic, and software development. Engineers must understand, simulate, and validate a broad set of factors that influence product success. Customer requirements must be captured, understood, and allocated to functions and system architectures, which can then be analyzed and simulated again, to enable the development of an optimal design that balances risk, cost and time-to-market constraints. Software and Systems Development integrates mechanical and electronic design to create a systems-level view of PLM applications and databases on a SOA, regardless of their engineering domain (for example, electronic-CAD, mechanical-CAD, software, hydraulics, simulation, verification) or their internal development cycles and rules. This allows for efficient reuse of system-level design know-how to drive lean, effective, global and innovative product realization initiatives.

These and other examples – such as integrated change management, product information management, and product and portfolio management – demonstrate just some of the benefits real companies are achieving or could achieve with an SOA-enabled PLM approach to manage their product lifecycle data and business processes.

7 Summary and Concluding Remarks

This paper describes a comprehensive business approach to product realization using service-oriented architecture. The emphasis is deliberately on business issues that can be addressed by such an architecture – the technical details to design and implement SOA can be found in various technical literature, for example in [7]. Some of the early successes in applying SOA for product information sharing across an enterprise can be found in [8, 9]. While much remains to be done to fully realize the comprehensive business approach outlined in this paper, these initial projects have yielded encouraging results that point to a promising future. In essence, SOA allows engineering and business processes to be built using modular chunks of software in the form of services that can communicate with each other and be used across different parts of a business. As observed recently by The Wall Street Journal "the approach can save companies time and money because the software modules can be reused and reconfigured in new ways" [10]. This is perhaps the most recent and best endorsement of SOA by the business community.

Acknowledgments This paper is based extensively on IBM's business and market research on innovation [5] and SOA for PLM [11]. The author gratefully acknowledges these sources and numerous IBM colleagues who contributed to these researches and their documentation.

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Integration of Collaborative Engineering Design Using Teamcenter Community in Mechanical Engineering Curricula

Xiaobo Peng, Ming C. Leu, and Qiang Niu

Abstract This paper presents a collaborative project conducted by Prairie View A&M University (PVAMU) and University of Missouri-Rolla (UMR) to jointly develop collaborative engineering design instructional projects, utilizing the Teamcenter Community and NX3 software provided by UGS PLM Solutions, and to implement these collaborative design projects in the teaching of two CAD courses in the Fall 2006 semester at the two universities. The collaborative design projects have been implemented in both the freshman level course MCEG1213 "Creative Engineering" at PVAMU and the senior/graduate level course ME363 "Principles and Practices of Computer-Aided Design" at UMR. This paper describes how to effectively prepare such a collaborative effort and how to implement the Teamcenter Community software. It was observed in this project that thorough communication among the team members is the key to guaranteeing the success of collaborative design. This paper also discusses the challenges in conducting a collaborative engineering design. The planned improvements for the future implementation are discussed.

Keywords Collaborative Design · Teamcenter Community · Curriculum · PLM

1 Introduction

The globalization of the economy has significantly changed the way the industries do business. Many companies have outsourced their design and manufacturing factories overseas. Therefore, global collaboration has become necessary in industry. Product Lifecycle Management (PLM) has made the collaboration possible. As defined by Grieves [1], PLM is "an integrated, information-driven approach comprised of people, process/practices, and technology to all aspects of

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a product's life, from its design through manufacture, deployment and maintenance – culminating in the product's removal from service and final disposal." With such a PLM system the members of a design team in geographically dispersed locations are able to interact with each other effectively in the collaborative design process.

One major goal of the higher education is to produce high quality students who shall have the skills working in the changing global economic environment when they graduate. Since the last decade, the CAD/CAM/CAE has been widely integrated into mechanical engineering curricula due to the demanding needs from the design and manufacturing industry. CAx has been considered as the mandatory training for engineering students. Today the growing interest in PLM in the industries has demanded college education to impart engineering students the necessary skills for collaborative design in a distributed environment.

To meet this emerging need, Prairie View A&M University (PVAMU) and University of Missouri-Rolla (UMR) have conducted the pilot collaborative project to jointly develop collaborative CAD engineering design instructional projects, utilizing the Teamcenter Community and NX3 software from UGS PLM Solutions. These collaborative design projects were implemented in the teaching of two CAD courses, i.e., MCEG1213 course at PVAMU and ME363 course at UMR in Fall 2006. The students at both universities teamed up to work on the collaborative design projects, by dividing up the project tasks among different team members. The members of each team consisted of students from both universities. This project is funded by PACE program (Partners for the Advancement of Collaborative Engineering Education).

In addition to the demanding needs from the industry described above, many research papers have reported that integration of collaboration activities using on-line tools can enhance learning, reduce the sense of isolation, increase participants' learning motivation, and improve students' social interaction skills [2, 3, 4]. From the social and psychological perspective, Hughes et al. [4] provided a comprehensive survey of literatures to address how to establish the most effective on-line collaboration. The paper summarized four aspects of effective collaboration, including: (1) getting students to understand the value of collaboration; (2) establishing comfort with the technology used in the collaborative environment; (3) building comfort and trust among students and between instructor and students; and (4) creating a rich on-line social environment.

Several universities have developed a program of collaborative design and product data management in their curricula. Purdue University has developed a framework to integrate design using CAD, rapid prototyping, team-based collaboration projects and realistic constraints and budgets in a computer-aided design and prototyping class [5]. However, their collaboration was conducted within one university. Tomovic of Purdue University [6] introduced the PLM experience to the senior design students with integration of part design, design optimization, and design of manufacturability. Georgia Tech and University of Maryland College Park implemented a collaborative product development project in their traditional engineering course using PTC ProjectLink system [7]. In 2004 and 2005, Virginia Tech and the Technique University Darmstadt jointly offered a new course on collaborative engineering and product data management [8]. The transatlantic term project was conducted using Teamcenter Community. In 2004, Brigham Young University (BYU) and Virginia Tech (VT) integrated PLM tools and collaboration into a capstone student project to design a concept vehicle. The students from three disciplines comprised the design teams to collaboratively complete the project [9]. In 2005 and 2006, BYU and VT expanded the collaborative project to a global scope with eleven other participating universities around the world. The requirements needed to either host a global collaboration project or be a participant were discussed [10]. Michigan State University and ITESM implemented collaborative student design projects utilizing Teamcenter Engineering and Teamcenter Community tools in the International Networked Teams for Engineering Design (INTEnD) program [11]. Anderson et al. [12] discussed the issues on the implementation of Teamcenter Community and collaborative environment in academia. Most of the above projects were implemented in the senior/graduate level and two-semester long courses. By deploying the pilot project, we are seeking to develop guidelines for integrating collaborative engineering design in regular one-semester engineering curricula.

This paper is organized in the following manner. First, we introduce the background of PACE program and two participating universities. In Section 3, details are described on how to establish the infrastructure for collaborative engineering design and how to implement the PLM tool Teamcenter Community. Next, the issues on implementing the collaborative project in engineering curricula are addressed in Section 4. Challenges, lessons learned, and benefits in conducting a collaborative engineering design are discussed in Section 5. At the end, the conclusion and planned improvements for the future implementation are discussed.

2 Participating Universities

Both participating institutions, Prairie View A&M University and University of Missouri-Rolla, are in the PACE program. PACE (Partners for the Advancement of Collaborative Engineering Education) is a consortium established by leading industries GM, EDS, Sun Microsystems, UGS, HP, and their global operations. Since it was established in 1999, PACE now is partnering with over forty (40) academic institutions worldwide to develop the Product Lifecycle Management (PLM) teams of the future [13]. In a cost-effective manner, PACE and its contributors provides hardware, software, training, and funding to PACE institutions to educate globally engaged engineering and design students with necessary skills to be successfully in a global economy. The software available for PACE institutions contains prestigious CAD/CAM/CAE and

PLM tools currently used by leading industries. These include Alias Maya Unlimited, Alias AutoStudio, Altair HyperWorks, E-factory Toolkit, FLUENT, LS-DYNA, MSC.ADAMS, MSC.Nastran, NX (previously Unigraphics), Teamcenter Community, and Teamcenter Engineering, etc.

Founded in 1876, Prairie View A&M University (PVAMU) is the second oldest public institution of higher learning in the state of Texas located 30 miles away from Houston. As part of the Texas A&M system, PVAMU is one of the Historically Black Colleges and Universities (HBCU) in which approximately 96% of the students are classified as ethnic minorities. Prairie View A&M University is known as one of the nation's top producers of African-American engineers. At PVAMU, the MCEG1213 course "Creative Engineering" is a mandatory freshman course in Mechanical Engineering. This course introduces students the basic knowledge of engineering drawing and computer-aided design and teaches student how to use CAD software Unigraphics NX3 for engineering design and analysis.

Founded in 1870, the University of Missouri-Rolla (UMR) has been one of the top among technological research universities. UMR was recognized as a top 50 Engineering School by US News & World Report's "America's Best Colleges," 2006. At UMR, the ME363 course "Principles and Practices of Computer-Aided Design" is offered to graduate and upper-level undergraduate students every year. This course introduces the fundamentals of computer-aided design and engineering with emphasis on geometric modeling. Unigraphics NX3 software is used by students to gain practical experience as well as to help them grasp the theories of computer-aided design.

Both ME363 and MCEG1213 at the two universities have an emphasis on developing students' hands-on experience on applying NX3 to solve engineering problem. In the old curricula of both courses, final team projects were assigned to students to design a product. The final projects aim is to provide students the opportunities to apply solid modeling, engineering drafting, and assembly skills to attack a real design problem. The projects develop in students the capabilities of report writing, giving presentations, and working as a team. Because both universities have similar final project assignments and have common interests in integrating PLM in the curricula, the integration of collaborative design in the final project has become very smooth.

3 Implementation of Teamcenter Community

Teamcenter Community (TcC) is the major tool used in our collaborative design project. Provided by UGS, Teamcenter Community is a secure encrypted platform with collaboration functionality that enables real-time synchronous and asynchronous engineering collaboration between geographically dispersed teams. As the host University of the collaborative project, PVAMU is in charge of installing the software, Teamcenter Community. The collaborative project has served as a catalyst for PVAMU to build the infrastructure to support collaborative engineering design. A state-of-the-art collaborative design lab is under development with the support of PACE and College of Engineering at PVAMU.

3.1 Teamcenter Lab at PVAMU

A "PACE Teamcenter Lab" is under development at PVAMU since the beginning of 2006. The objective of the establishment of this lab is to provide a state-of-the-art collaborative engineering design environment including hardware and software to support the education and research activities related to collaborative projects. The hardware and software are available at PVAMU including the following:

- **Hardware**
  - Two High-end Sun servers (×2100)
  - One HP large format printer
  - Twenty five high-end engineering workstations
  - Tandberg video conference system
- **Software**
  - Unigraphics NX3
  - Altair Hyperworks 7.0
  - ANSYS
  - Teamcenter Community 5.2
  - Video and audio conferencing software.

3.2 Deployment of Teamcenter Community

The Teamcenter Community (TcC) V5.2 software was donated by UGS. We obtained two Sun servers which were granted by PACE. One faculty and one technician were fully dedicated to the implementation of TcC at PVAMU. Teamcenter Community runs on top of Microsoft's Windows SharePoint Services (WSS). MS SQL Server 2000 is required as backend database for TcC. Windows Server 2003 is required as the Operating System. There are many other software and services that are prerequisite to run TcC, namely, Internet Information Services 6.0 (IIS 6.0), ASP .NET service, Microsoft Active Directory (AD), and Domain Name Service (DNS). It is recommended to separate the TcC Web Server from the Database Server. As the nature of the prerequisites is complex, it is quite challenging to deploy the Teamcenter Community.

The "Teamcenter Community Installation and Upgrade Guide" [14] has provided great instruction to the deployment and installation of TcC. In the case that trouble was met and no solution could be found in the guide, the UGS technical support has been an excellent resource in providing help. Normally we were contacted promptly by the technical person. The trouble was able to be resolved within one or two days. The implementation was relatively smooth although no training course has been taken.

Before the installation of the TcC, we needed to select the proper deployment in determining the number of servers needed and how the software should be deployed on the servers. The enrollment of two courses generally were 20∼30 students in ME363 (UMR) and 15∼25 students in MCEG1213 (PVAMU). The estimated concurrent users were under 100. Therefore, the deployment indicated in the guide [14] which can support 900 concurrent users was adequate for this project and can still provide enough room for expanding the scope of the collaboration.

Two Sun servers were configured as Web Server and Domain Controller respectively as illustrated in Fig. 1. The software installed on each server is listed as below.

- **Web Server**
  - Windows 2003 Server
  - Internet Information Server (IIS) 6.0
  - Windows Share Point Service (WSS)
  - Teamcenter Community V5.2
- **Domain Controller and SQL Server**
  - Windows 2003 Server
  - Domain Name Service (DNS)
  - Active Directory (AD)
  - SQL Server 2000.

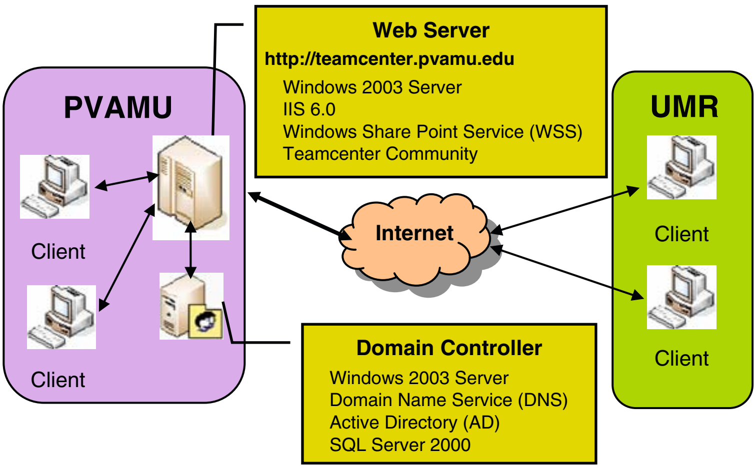

Fig. 1 Deployment of Teamcenter Community at PVAMU

It has been indicated that it is challenging to grant the access of the Teamcenter Community to the outside of the university firewall [8], [10], [12]. If there is no entry of the firewall, virtual private network (VPN) has been an alternative to allow outside user accessing of TcC. However, it has been demonstrated that using VPN has been a problematic strategy due to the blocked internet port [10]. The IT department has full control over the network setting in the academia environment. Due to the security concern, the IT normally is very restrictive on granting the entry of the firewall. Fortunately the IT department at PVAMU has been very supportive in granting a firewall entry to the Web Server when the significance of the project was explained to them.

3.3 Teamcenter Community Website

Teamcenter Community (TcC) served as central location for the collaboration and every team member were able to log in using a web browser. TcC enables team members geographically dispersed to share 2D and 3D part files, documents, and presentations, schedule calendars, post announcement and progress, and route review tasks etc. The features provided by TcC hosted at PVAMU are described in detail below.

Two layers of TcC websites were constructed for this collaborative project. The top layer was the homepage for instructors. The bottom layer consisted of websites which were accessed by student teams. As shown in Fig. 2, the instructors' homepage was restricted to be accessed by the instructors and teaching assistants. The major component of the homepage was the Professor's Announcement. The Announcement was made as a pushdown list which can be automatically distributed to all the team subsites. This was where the project assignments, tutorials, instructions, and other timely announcements can be uploaded and then distributed to all the team subsites. The "Team Subsite Links" on the homepage provided a convenient way for the instructors to access each team's webpage and monitor the progress of all the teams.

Team subsites were designed for each team as shown in Fig. 3, which were logged in directly by designated team members. It contains the following components:

1. **Professor's Announcement** – Students can get announcements, assignments, tutorials and other project related material handed out by the instructors. This is distributed from the parent site. The students can not edit it.
2. **Task Lists** – Each team uses it to assign the design tasks to specific team members and to keep track of work that each team member needs to complete. Description of the tasks, assigned team member's name, due date, status, and completion percentage are able to be tracked using this feature.

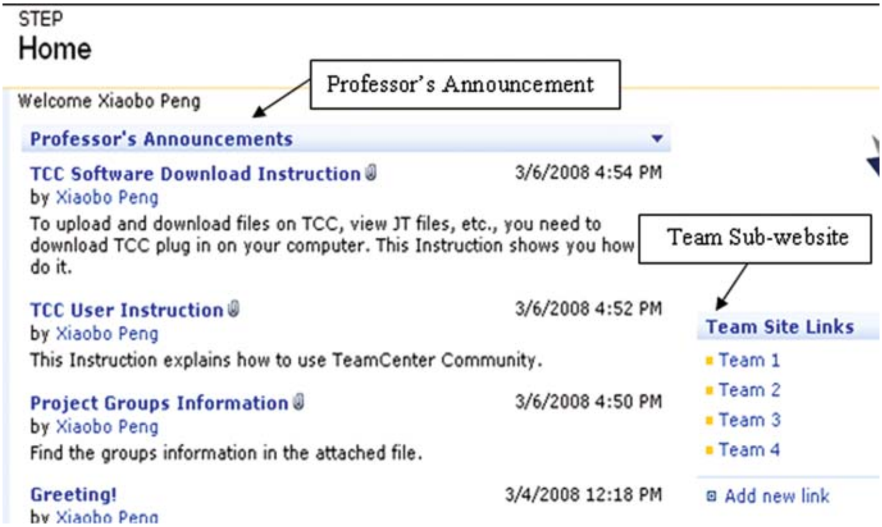

Fig. 2 Teamcenter Community homepage of collaborative project for the instructors

3. **Contact Information** – Members can exchange their names and contact information (such as telephone number, e-mail address, and living address) here.
4. **Announcement** – The students can post news, meeting announcements, and other short information which they want to share with their team members.

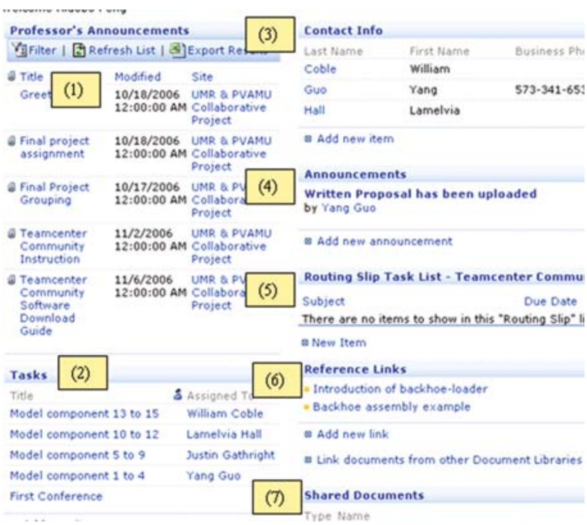

Fig. 3 Collaborative project TcC homepage for teams

5. **Routing Slips** – Routing items for approval is a powerful feature of Teamcenter Community. A team may frequently need to conduct reviews. Using Routing Slips, the user can create a Routing Slip, select documents to route, and make sure it gets to the right people for review. Team members can route items such as documents, 2D or 3D data, visual issues, or requirements to members for review and approval. When a user logs into TcC, all of the current routing slips assigned to him/her are displayed. From the list the user can open the routing slips, review the items, and take actions to either approve or reject the slip.
6. **Links** – The links are used to post hyperlinks to webpages of interest to the team.
7. **Shared Documents** – This document library is mostly used by students to upload NX3 part files, 3D assemblies, and Office documents. Users can organize different types of file by creating directories. The user can open reports, presentations, spreadsheet, PDF file etc. directly in the TcC without downloading the files to local computer. To prevent the conflict of more than one user using the same file in the library, TcC provides a "Check in/Check out" function. It is very convenient to load an assembly CAD model in TcC. The user only needs to select the assembly CAD file. All the associated sub-component CAD files will be uploaded automatically.
8. **Calendar** – Similar to MS Outlook, the calendar is used to post information about dates that are important for the team as shown in Fig. 4. One unique feature of the calendar in TcC is a workspace can be attached to an event. The workspace is a site where the team can manage the meeting agenda, minutes etc.
9. **Iseries Viewer** – It is a tool embedded in TcC that provides 2D/3D visualization, review and markup capabilities. It is enabled by the CAD-neutral JT format which can be created from all major CAD applications. Students can perform the synchronizing design, review and markup within the TcC by open the JT file of an assembly or a single CAD model as shown in Fig. 5. It is a very powerful tool for collaborative design.

3.4 Client Software Download

To fully utilize the functions of Teamcenter Community such as visualizing JT 3D models, uploading the files to the server, downloading documents, and performing seamless editing of Microsoft Office documents with Microsoft Office 2000/XP etc., the plug-ins need to be downloaded and installed on the client computers. In the public computer labs at both PVAMU and UMR, students do not have the Administrator privileges to install the software. The Administrator must be involved in this process. This caused some delay for the

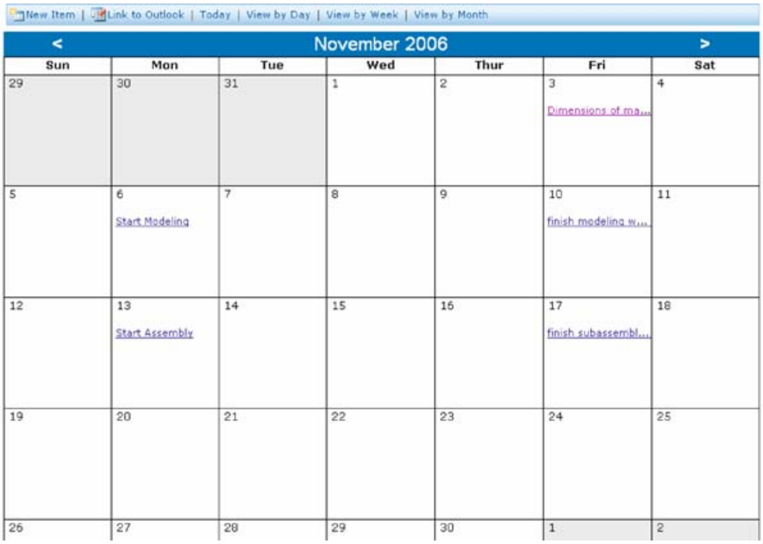

Fig. 4 TcC calendar

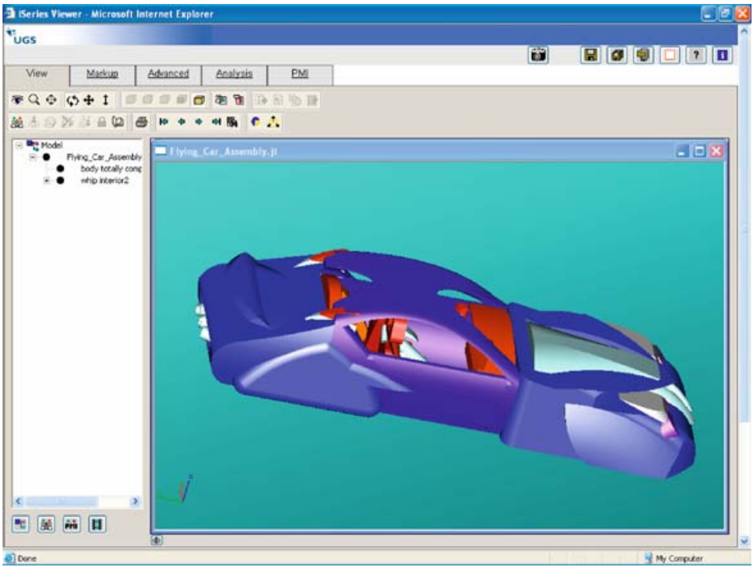

Fig. 5 Visualize 3D CAD assembly in TcC using Iseries View

student to start using TcC. Some of the students found out it was more convenient to use their personal computers.

Tutorials on how to install TcC client software and how to use TcC were developed and distributed to students. Students were trained in the class on how to use TcC. It was reported by students that most of the functions of TcC are easy to learn such as Shared Document, Calendar, Tasking, Announcement etc. Because students had little knowledge on project management, the functions of TcC related to project management such as routing slips were seldom used. Another reason was the scale of the collaborative project was small. The advantages of the using those functions did not appear appealing to students.

4 Implementation of the Collaborative Project

4.1 Collaborative Project Assignment

After the construction of Teamcenter website, the instructors from two universities designed three pre-defined topics as the final project which required students from UMR and PVAMU to team up as groups. Each group was asked to choose one design subject to work on. The final project required students to complete a conceptual design of a new product. The final design must be an assembly. In addition, the students were requested to address material selection, manufacturing concern, and cost analysis of the product. When the instructors designed the project topics, the following aspects were taken into consideration: 1) The scale of the project should be appropriate such that students can complete it within six weeks; 2) The products to be designed by students should have adequate complexity which can give students challenges; 3) The products can be easily broken down into sub-components so that team members can collaboratively complete the design. The design topics were:

- *Backhoe* – design excavating equipment consisting of a digging bucket at the end of an articulated arm.
- *Tandem bicycle* – design a bicycle to be built for two people sitting one behind the other.
- *Folding bicycle* – design a bicycle which can be folded for easy transportation and storage.

There were 22 students enrolled in ME363 at UMR and 14 students enrolled in MCEG1213 at PVAMU respectively. Each group consisted of four students. A total of nine groups were formed by one of the following formats: 1) Five groups consisted of two UMR students and two PVAMU students, and 2) Four groups consisted of three UMR students and one PVAMU students. Each group had one group leader assigned by the instructors. The group leader can make final decision when there are different opinions during the collaboration. Each team had a Teamcenter website:

http://teamcenter.pvamu.edu/collaborative/teamX (X is from 1 to 9). For example, for group one, their website is http://teamcenter.pvamu.edu/collaborative/team1.

By the time the project was assigned to students, students had six weeks to complete the project. Each team was required to submit a report and give a presentation. All the documents including NX3 part files, the final assembly file, reports and PowerPoint slides were required to be uploaded to the Teamcenter Community website. To incent students to use TcC, the active and sufficient usage of TcC was applied as one of the criteria to grade the project.

4.2 Collaboration Activities

It was found by Wegerif [15] that participants in a collaboration project are tend to be anxious and defensive to collaborate unless trust and comfort are established among the team members. It is observed in this project that thorough communication among the team members is the critical key to guaranteeing the success of the collaborative design. Various collaborative tools besides Teamcenter Community such as Video Conference, Email, and Instant Messenger etc. were utilized to assist the communication between the team members.

Teamcenter Community was used extensively by students, and was the primary means of transferring NX3 part files and data. Utilizing TcC, each group member was able to express questions and concerns, receive answers and post their completed part files. In addition, TcC allowed group members to view relevant project files and a project timeline, both of which assisted in the timely completion of the final project.

It has been suggested that an initial face-to-face meeting will significantly enhance the trust and familiarity among team members and a willingness to collaborate [4]. However, it was not feasible to have a face-to-face meeting for our students due to the time and cost constraint. On the other hand, the basic idea of the collaborative design projects is to train students to be able to collaborate with partners they never meet before. The video conferencing system was used at the initial stage of the project to get the team members from two campuses know each other and discuss the proposal. Figure 6 shows that two PVAMU students were discussing the project with team members from UMR using video conferencing. In addition to video conferencing, Email, Messenger, and Phone etc. were used by students. The instructors did not impose any use of collaboration tools or collaboration activities other than TcC and first Video Conference meeting. Different groups had different opinions on using the collaboration tools. Some groups met weekly using Messenger. Some groups did not have regular meeting. Instead they called each other when they found it necessary. There was one group that used email exclusively for exchanging ideas without calling each other. It was interesting that the communication in the groups which had

Fig. 6 Students discussing the project via video conferencing

two PVAMU and two UMR students were more active than those groups which had one PVAMU and three UMR students.

4.3 PACE Competition and Results

PACE provides student design competitions in the courses to encourage students to use digital data in the product development and analysis processes. We have integrated the students' final project presentation with the PACE competition. Students presented their projects simultaneously and interactively with their partners from two sites through video conferencing system as shown in Fig. 7. WebEx was used to share and present PowerPoint slides

Fig. 7 Final presentation competition using video conferencing

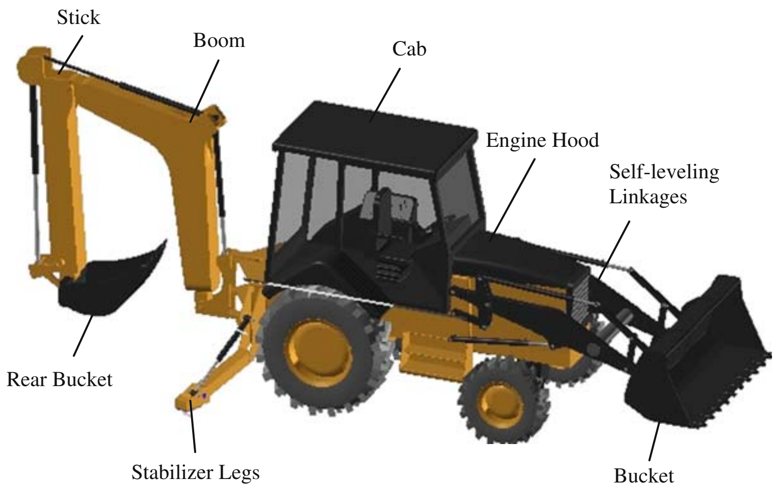

Fig. 8 Backhoe loader

simultaneously while students were doing the final presentation. The presentations were evaluated by the panel of judges based on three criteria including solid modeling and assembly modeling, report and presentation, teamwork and collaboration. The panel of judges consisted of two faculty from UMR and PVAMU, two representatives from Altair Engineering Inc. (PACE contributor), and one representative from GM. Three top teams were awarded prizes. All the students received certificates provided by PACE.

Over the nine groups, seven groups chose Tandem Bicycle as their projects. Two groups chose to design a Backhoe. Figure 8 shows the top design, a Backhoe Loader. The backhoe loader design was broken down by students into four major subassemblies, i.e., Loader, Backhoe, Cab, and Body. Each team member was responsible for creating one of the subassemblies. Figure 9 shows the Cab designed by PVAMU student.

Figure 10 shows a Miami Beach Tandem Cruiser designed by Group 4. The tandem bicycle's main functional requirement is to seat two people and have arrangements so that both passengers can pedal it. The students made some improvement on the bike to make it safer and faster, in order to market to a younger market audience. The frame was elongated to make it more aerodynamic and stable in turns. The wheels and frame were lightened by using carbon fiber. Knobby tires were put on to give the appearance of being tough and rugged, while also giving the rider the freedom to take dirt or gravel trails. The disc brakes made the bike safer in wet conditions and the handlebars were placed lower, so the rider has a more aggressive stance while riding.

Fig. 9 Cab subassembly of a backhoe loader

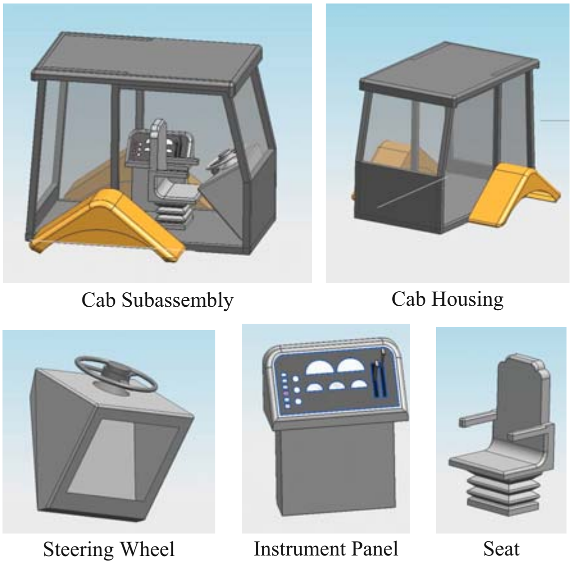

Fig. 10 New generation of Miami Beach Tandem Cruiser

5 Discussion

5.1 Challenges

Although the experiences in conducting collaborative/distributed design projects have been shared by many previous works [5, 6, 7, 8, 9, 10, 11, 12], it still remains challenging to integrate collaborative design into engineering curricula. The challenges rely on the following:

1. A solid infrastructure of PLM solution is required in order to conduct collaborative design. Teamcenter Community is proved to be an efficient collaboration tool. Its implementation needs comprehensive support of both hardware and software as described in Section 3.2. To secure the adequate manpower support and the commitment from the IT department is essential to the implementation of TcC.
2. The collaboration needs the participating universities to have common interests and to be willing to accommodate their schedule for each other. It is important to identify the answers for the following questions before initiating the collaboration: Which courses will adopt the collaborative projects? Do the schedules at the participating universities fit each other? What would be the appropriate design subjects for collaboration without adding too much overhead burden on the current curricula to the students?
3. Thorough communication among the team members is the critical key to guaranteeing the success of the collaborative design in a distributed environment. Although the scale of our collaboration is small, being conducted by students between two domestic universities, students all agree that the communication between team members is the most challenging part of the project even with many the collaboration tools available.
4. How to motivate students to be engaged in and to appreciate the collaboration project is challenging, given that engineering students already have a heavy course schedule. It was observed that UMR students were more engaged and active than PVAMU students in the collaboration. Partly it is because UMR students, who are senior or graduate students, are more mature than PVAMU students who are in their first semester in college. The format of the groups caused different degrees of engagement. Generally those groups with 2 UMR students and 2 PVAMU students were more active than groups with 3 UMR students and one PVAMU student.

5.2 Lessons Learned

Upon the completion of the collaboration projects, we have learned the following lessons:

1. Although six weeks were given to students to complete the projects which is longer than the time given for non collaboration project, students still felt the time was very limited. We should to be able to initiate the collaboration earlier next time with the TcC in operation.
2. Misunderstanding and miscommunication occurred in some teams during the collaboration. Because no weekly review meeting or progress reports were requested, the instructors did not perceive the problems promptly. This caused a delay in solving the problems. In the future, regular review meeting and progress reports should be required.
3. More training on TcC should be provided to students. The progress of the project was slowed down because students had different level of technical skills. This problem became more obvious when undergraduate freshman collaborated with graduate students.
4. Some important functions related to PLM were not used in this project such as the workflows, task distribution, and application sharing functions due to the time constraint to implement them. Application sharing allows the users to share someone's desktop with any other collaborators. By joining a visual conference in TcC, all participants can view the host's desktop and even control the remote desktop if the host transfers the control to any participant.

5.3 Students Comments

The participating students have given positive feedback:

- "To make sure that all the students were working in parallel was challenging, but by using the Teamcenter Community website, a timeline was established and adhered to fairly closely."
- "The idea of collaborating with another University is good one. Apart from sharing ideas, there is also a scope for socializing."
- "This project was a wonderful experience for us. This project helped us grow as future professionals. While doing this project we learned to trust our teammates. We polished our communication skills in a real world setting."
- "Regular and frequent communication between team members proved to be an essential component of this team's success in assembling a complete backhoe loader model."
- "In the end, teammates came to the conclusion that team work is important, but it is hard work."

5.4 Benefits

We have built a collaborative design infrastructure at PVAMU. Teamcenter Community has been successful deployed and applied in the distributed design projects collaborating by UMR and PVAMU students in two CAD courses. The benefits of integrating collaborative design projects into Mechanical Engineering curricula are:

1. By implementing the developed collaborative design projects in the teaching of CAD courses, the students learned effectively how to perform collaborative product design with different techniques and CAD systems in a distributed environment and to understand the collaborative nature of product design and related issues.
2. Because the collaborative design projects are stimulating to students, we will be able to encourage more minority students to pursue an engineering career. With the skills trained by participating in the projects, our students will be more competitive in the job market.
3. We have deployed the latest CAX/PLM technology at PVAMU and UMR. The pilot project will help us to develop guidelines and best practices for integrating PLM solutions into the design process upon completion of this project in the future.

6 Conclusion and Future Work

In Fall 2006 UMR and PVAMU have successfully integrated collaborative engineering design projects using Teamcenter Community in two CAD courses. The implementation of Teamcenter Community is described in this paper. Various collaborative tools besides Teamcenter Community, including Video Conference, Email, and Instant Messenger etc., were utilized to assist the communication between the team members. We have discussed the challenges of integrating collaborative design into engineering curricula. By implementing the developed collaborative design projects in the teaching of CAD courses, the students learned effectively how to perform collaborative product design with different techniques and CAD systems in a distributed environment and to understand the collaborative nature of product design and related issues.

It was observed that students lack skills on communication and project management which are critical to the success of collaboration. We will expand the collaborative design projects by incorporating project management fundamentals into the design process. Dr. Benjamin Dow from Engineering Management and Systems Engineering Department at UMR will bring his expertise on project management to the collaboration and lead his students in the collaborative engineering design projects. The students from two disciplines and three different classes will team up to work on the projects. The students of each school will be provided basic project management instruction and incorporate these fundamentals into the design project using Teamcenter Project. The software's capabilities allow the design teams to break down complex design projects into specific tasks, assign resources, and manage the workloads of the resources. This project is funded by PACE program as well.

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