PLM-based Approach for Design Verification and Validation using Manufacturing Process Knowledge

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ABSTRACT

Out of 100 hours of engineering work, only 20 are dedicated to real engineering and 80 are spent on what is considered as routine activities. Readjusting the ratio of innovative vs. routine work is a considerable challenge in the product lifecycle management (PLM) strategy. Therefore, the main objective is to develop an approach in order to accelerate routine processes in engineering design. The proposed methodology called FabK consists of capturing manufacturing knowledge and its application towards the design verification and validation of new engineering designs. The approach is implemented into a Web-based PLM prototype and a Computer Aided Design system. A series of experiments from an industrial case study is introduced to provide significant results.

Keywords: Design for Manufacturing, Knowledge Management, Concurrent Engineering, Product Lifecycle Management.

1. INTRODUCTION

The process of developing a new product, from design to manufacturing generates important amounts of data and information [1] and relies on the experience gathered from the development of previous projects [2, 3]. This knowledge, kept by a limited number of "experts", is not necessarily captured for future use, which translates into time-wasting and project delays. Knowledge management (KM) and feedback loop information issues become essential for productivity and responsiveness improvement during the product development process. This paper focuses on a Product Lifecycle Management (PLM) based approach for design verification and validation by introducing manufacturing process knowledge.

This main concept is based on enabling experts to gather knowledge from previous engineering experiences and store it in an interactive, intuitive database. The database will allow the introduction of manufacturability analyses in the early Request for Quotation (RFQ) phase. Information resulting from these evaluations will improve compliance with all the company's business rules related to lifecycle aspects of the product, especially manufacturing ones (manufacturing constraints, standards, etc.).

Between 60 and 80% of components used in products manufactured by Original Equipment Manufacturers (OEM) are subcontracted [4]. Automotive companies bring different experts to check the product's manufacturability from the earliest stages of the product development process but, due to their unavailability (geographical or time related), this approach can be considered as ineffective and can lead to delays and additional costs. Integrating business rules related to manufacturing constraints, costs and materials could improve the designers' efficiency by incorporating a Design for Manufacturing (DFM) approach in the broader context of Concurrent Engineering and PLM into their work. A flexible DFM verification method would allow the employment of experts' experiences with the possibility of continuous updating and adaptation to each new project as their design evolves. As a result, a robust design and its related manufacturing data are obtained and retransmitted in record time and the solutions found for each project are kept for future reuse.

2. INDUSTRIAL CASE STUDY

These assumptions were carried out within the Research and Development department of a Tier 1 automotive supplier. The proposed approach is positioned in a scientific context where the ultimate goal is to generate semi-automatic, robust and optimized product models, respecting all manufacturing process knowledge and knowledge gathered from project memories [3] and expert know-how [2]. Once identified and treated through multi-objective deterministic and/or meta-heuristic optimization tools [5, 1], this knowledge will help obtain sets of optimal parameters [1] respecting the design and manufacturing rules. These sets of parameters, coupled with parametric three-dimensional CAD models, semi-automatically generate different optimal geometry configurations (Pareto frontier solutions) that respect the knowledge retained by the company and the particular requirements its customers' specifications.

More precisely, this approach is tested out throughout the design lifecycle of a key product manufactured by the automotive supplier, as a means to validate and extrapolate it for other products and situations. One of the major manufacturing processes within this company is extrusion blow molding. This tried and tested process carries with it great amounts of personal and experience generated knowledge that is not systematically transcribed for future use. A proper knowledge capture methodology and its implementation into automatic design tools could foresee considerable time and quality gains for the development of new projects. The process will start with a set of customer's requirements, pass by the generation of generic simulation processed models, and end with their validation for use in further phases of the design lifecycle, validating the use of a collaborative tool for manufacture-oriented product development [6].

3. RELATED WORK

Design For Manufacturing

Integration issues related to lifecycle aspects in the product development process highlights needs in data, information and knowledge management. As result, Design for X (DFX) and PLM approaches are considered as key enablers to the reduction of time and effort in new product development [7, 8]. Zhao and Shah [9] established a basic structure for a domain independent DFM shell and later built up on it for sheet metal and injection molding processes. Mahesh *et al.* described a generic distributed and collaborative tool for virtual manufacturing [10], in which Computer Aided Manufacturing (CAM) information is relayed between all levels of a manufacturing chain. De Martino, Falcidieno and Haßinger developed an intermediate feature-based modeler infrasstructure [11] in order to map the product development process with downstream engineering processes (CAE Computer Aided Engineering). All these research works aim for the integration of design rules and lifecycle engineering knowledge via different methods such as feature-recognition approaches, hierarchical step-by-step systems or process planning agents approaches that establish best practices by feature recognition. The integration of manufacturing process and geometric verification rules is a way to incorporate lifecycle aspects with the creation of robust “first draft products” that will be later on updated and adapted by the designer to conform a definitive geometric definition.

Evbuomwam and Anumba carried out a generic life-cycle framework for construction [12] that sets out a comprehensible and complete interaction for users throughout the product development process and the use of any and all design tools and techniques, which give out a rough preliminary form for this research. Huang *et al*. worked on a structured methodology to bring DFX concepts and constructs into a Web based form [13]. This methodology tries to balance out pragmatism and formalism in its approach. However their models rest simple without going into much detail involving model geometry or function.

Ahmed and Godbout [14, 15] both established an empirical context for the identification of relevant information and its transformation into knowledge assets that can be later mined in automatic DFX life-cycle approaches. Sanchez and Molcho [16, 17] developed structures for manufacturing knowledge use, the Intelligent Reasoning Assistant (IRA) and the Computer Aided Manufacturability Analysis (CAMA) respectively. These structures focus on bringing the knowledge out of the manufacturing floor and into the hands of via the use of rules and post process analysis. Malhotra takes this notion even further and establishes a meta-modeling framework, MetaSimModel [18], a knowledge-based decision support environment that aids in reusing multi-application and multi-domain knowledge models that can be accessed through in a flexible manufacturing environment.

This literature survey will help shape the second part of the FabK methodology, the closing off of the DFM loop, so products designed through this methodology will keep the knowledge base up to date for future use and product development.

Knowledge Management

The Knowledge Valorization and Acquisition (Knova) - Inductive Synthesis & Craft and Application Management (in French ‘Synthèse Inductive & Gestion des Métiers et Applications’ – Sigma) is a methodology centered on the management of knowledge in routine engineering, first set out by Serrafero in 1988 [3]. It proposes a series of steps to extract the knowledge retained by a company, be it on documents or by different ‘experts’, so that it can be formalized into craft compendiums. These compendiums gather all the knowledge related to the activity or process researched into a structured and easily readable document. This sets a basis for further interaction and the possibility to export it into knowledge databases and interactive forms.

Knova-Sigma describes generic knowledge taxonomy that encompasses all levels of knowledge, from total absence to absolute certainty, coupled with different stages of cognitive maturity [3] that will not necessarily intervene within the FabK methodology. The objective of the proposed work is not to go into the cognitive details uncovered and established by Serrafero but to build up on his basic capitalization techniques and orient them towards a scientific/industrial project.

Out of all the methods for knowledge extraction present and described by Knova-Sigma, the four principal axes are the more heavily used by the FabK methodology. The business process, the business expertise, the business vocabulary and the business experience [19] are the specific elements that will aid in capturing the downstream activities knowledge, form and structure it and present it during the new product development phases.

4. FabK METHODOLOGY

For the proper implementation of such an approach, some functional requirements for the methodology are needed to enable it to be as generic as possible:

1) Assess the technical feasibility for every new concept.
2) Submit an efficient and effective feedback loop for manufacturability issues in a verification approach that corrects/updates the concept to conform to the means of production planned.
3) Give experts an effortless means for rule and knowledge storage.
4) Allow the analysis for business rules and manufacturability at all stages of the product development process (detailed design, production stage), not only to the RFQ phase [9].

The idea behind FabK is to advance product/process knowledge from the latest phases in the lifecycle of a product all the way to the RFQ phase. Even if the methodology is transversal with regard to the whole product development process, it is on the RFQ and conceptual design phases when manufacturing knowledge that would influence the product will be the most beneficial and would have the greatest impact (as seen on Fig. 1).

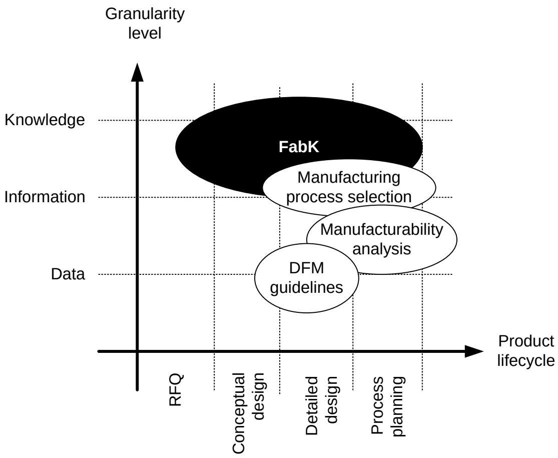


Figure 1. Map of approaches related to DFM techniques along the product lifecycle and granularity levels

4.1 Knowledge capitalization – KNOVA lifecycle

The expert's need for a method to capture and store the company's knowledge defines the first part of the methodology.

This stage starts with the application of Serrafero's knowledge acquisition methodology [19]. The KNOVA methodology determines how to transform a company's tacit knowledge into a properly framed knowledge summary, comprising business knowledge in five granularity levels:

- the business of a company (e.g.: Automotive manufacturing), decomposed into process fields (e.g.: plastics, machining ...),
- a business field (e.g.: plastics) composed of process domains (e.g.: injection, extrusion ...),
- a business domain (e.g.: extruded air conducts, injected intake manifolds...), decomposed into process proficiencies (e.g.: design of extruded air conducts, design of their manufacturing processes...),
- a business proficiency (e.g.: design of extruded air conducts), composed of process knowledge (e.g.: the section area of an air conduct). Process proficiencies constitute the different knowledge summaries in a company,
- a business knowledge is the elementary component of a knowledge summary.

The KNOVA methodology goes through several steps, the "10 C's", from the creation to the growth of knowledge, that allow for the gathering and storing of a company's knowledge and know-how. Through the use of project memories, knowledge can be further digitalized into a PLM system where they can be called on to perform verification functions.

4.2 Product/process knowledge capitalization

The context for the application of the proposed methodology requires the use of a PLM system integrating engineering modules such as Product Data Management (PDM), CAD systems and so on [20]. The PLM system chosen for implementing the proposed approach is a Web-based PLM prototype called ACSP (in French "*Atelier Coopératif de Suivi de Projet*"). This Web-based environment has been developed at UTBM since 1996 to enable synchronous and asynchronous cooperation between the members of product-process design projects [21, 22].

The main feature of the ACSP system is its data, information and knowledge management capabilities. The ACSP allows them to be capitalized in order to be disseminated, shared and reused [20]. Moreover, this knowledge can be exported as exchange files (Extensible Markup Language - XML) and reused by software such as MS Excel and CATIA V5.

Expert product/process rules issuing from the KNOVA methodology can be capitalized into the PLM system and reused for new product development. Based on the multiple domains (Project/Product/process/Usage) and multiple views/viewpoints model [21], ACSP allows experts to transcribe their knowledge and users to operate independently throughout the methodology. Once stored in a database, these "rules" can be later exported in the form of scripts.

The use of the PLM system also allows the storage of functional specifications for each product, by filling various associated geometric parameters and indicators (strength, cost, etc.) as well as the results of other product development phases of such as calculations, modeling, testing or the manufacturing process (Fig. 2). The designers directly involved must update all the information related to a product throughout its product development phases. The classified storage of design specifications on the design/process database, along with a permission to modify system facilitates their subsequent exploitation in all the concerned stages [23].

4.3 Design-verification-validation loop

During this creative phase, the designer takes into account many rules set down by experts. During early stages of the product development process, verifying the compliance with each of these rules becomes very important. Success is defined by the company's capacity to generate a product that meets the customer requirements and is simultaneously in line with the different business rules established by the company, according to the manufacturing process chosen.

The storage and access to pertinent design rules allows the designer to incorporate them from his earliest designs and build his design concept in a robust manner. The semi-automatic verification of the design at hand through the export of knowledge in script form and its implementation in the CAD system (e.g. CATIA V5) can reduce the manual verification time spent by the designer and the expert. This routine process is amplified when neither shares the same geographical location nor workload [24].

Through the cooperative work of CAD system and product experts, basic product geometries are constructed from the predefined expert rules. This model can be fed into an optimization tool which will accept the functional requirements for the new product, balance out possible scenarios and give out a new preliminary concept that the designer can take over and further adapt according to other, non-preconfigurable, design and functional requirements [1]. Further on the loop, the designer can call upon other established "expert rules" based on these non-preconfigurable design characteristics. These rules can be exported via scripts and the concept in hand will be evaluated for its conformity. This step further validates the design's conformity with the established product/process withheld by the company and alerts the designer in case of drifts from the rule.

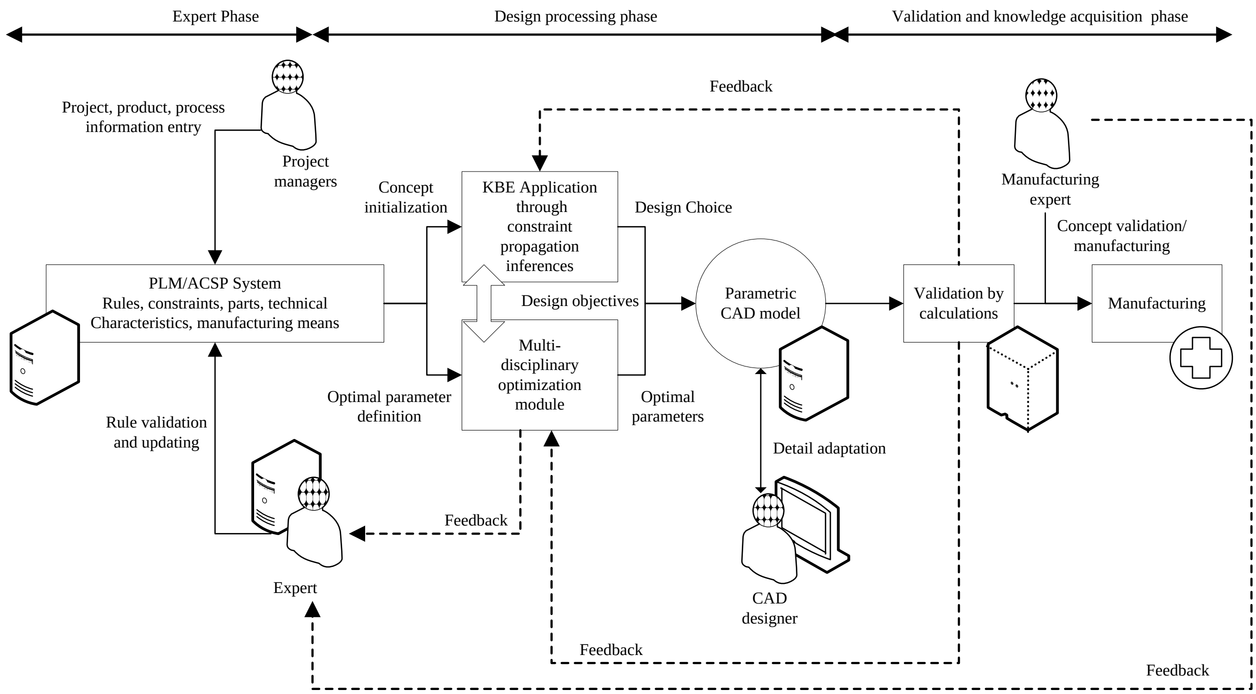


Figure 2. FabK Methodology

Before running the models through the optimization tools, various criteria must be satisfied, so several constraints and objective functions are defined in order to improve the part quality and process reliability. A future article will describe the development of an optimization cycle which will allow for the minimization of the cost and defect “objective function J” and give the best results in terms of geometry accuracy of the generic model. The optimization problem used for this experimentation is based on the Response surface method. This method consists on the construction of an approximate expression of objective and constraint functions starting from a limited number of evaluations of the real functions using a numerical design of experiment.

The main idea is to approximate the objective and constraints functions through a response surface. In order to obtain a good approximation, two methods will be used we used. The first one is based on diffuse approximations and the second one is the Kriging interpolation [25]. In these methods the approximations are computed by using the evaluation points by design of experiments around the locus, where the value of the functions is needed. To minimize the approximate problem the SQP algorithm or GA will be used. These methods will feed of rules and parameters set up by experts and project managers through an optimal parameter definition (Fig. 2) and give out optimal sets of parameters to build a generic first draft of a new product.

The flowchart of the adopted optimization strategy is presented on figure 3.

5. INTERACTIVE RULE ADHESION VERIFICATIONS

A practical implementation of expert rule verification requires the interaction of the various actors involved in the product development process. The product architect, responsible for the functional design of the product, defines the product key characteristics according to the customer requirements and the knowledge generated from experience in terms of materials, components, etc. Then the various operations necessary for manufacturing, as well as the general architecture of the product, are defined.

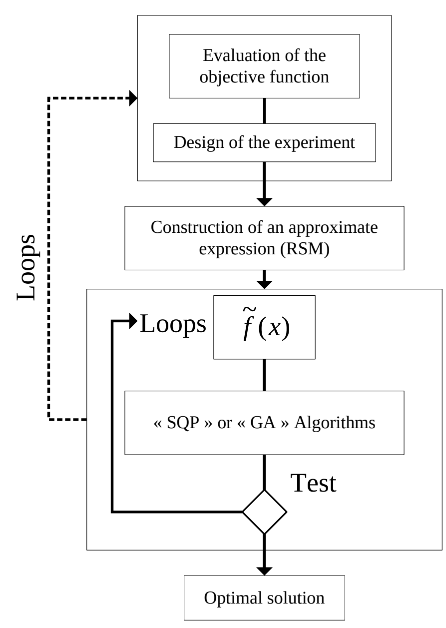


Figure 3. Multidisciplinary optimization module

5.1 Automatic verification by script definition

Once the manufacturing operation choices have been made, knowledge and business procedure constraints are defined for the new product development. Depending on the downstream manufacturing process chosen geometric rules such as thicknesses or section areas (for extruded air conducts) or height, length and depth of interpenetration (for plastic soldering on an intake manifold) are set out, to be given values by the customer requirements sheets or internal knowledge and are fed through the PLM system (Fig. 2).

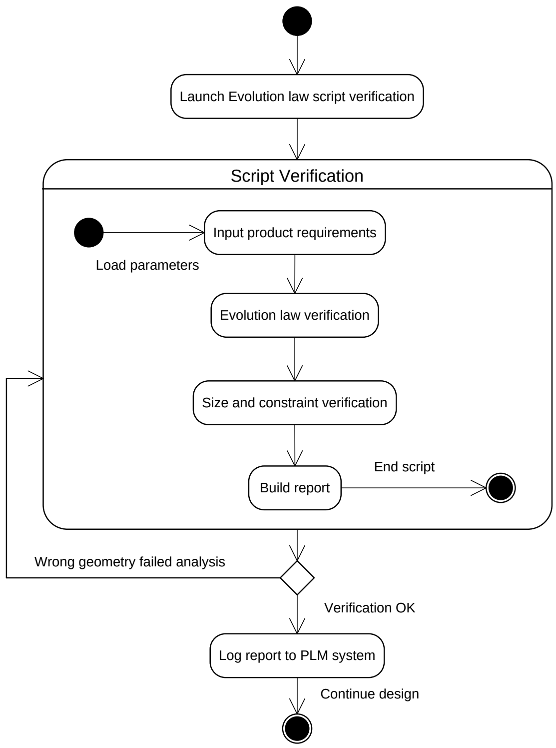


Figure 4. UML state diagram describing the specifications for evolution law script verification

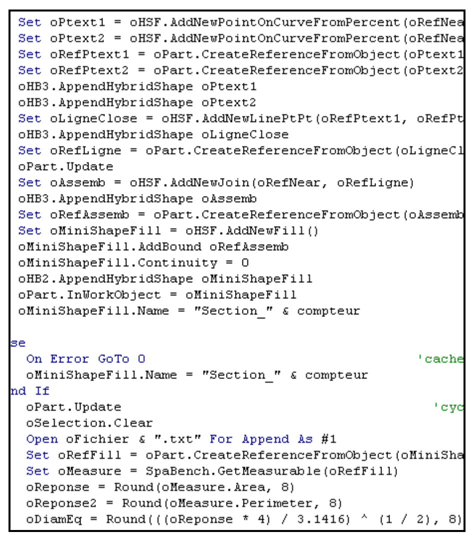
The next step carried out by the designer is to start modeling phase of the desired product with his CAD system. During this stage we can draw on other geometric modeling methodologies to better manage the concurrent and knowledge-based functional design of the product [1]. The methodology used adds a preliminary step to the geometric modeling to establish a product architecture (skeleton based modeling) linked by parameters, which guarantees a better monitoring and subsequent modification of the 3D model [26]. This parametric model is constructed keeping in mind the rules specified by the customer in his specification sheets and the internal knowledge of the company already catalogued within the PLM system. This parametric and robust "first draft model" already respect the rules and requirements for its proper manufacturing.

However, all the parameters identified for the product cannot be predefined beforehand. Depending on the characteristics of the product to manufacture, there are parameters that can be modified (see ignored) by choice of the designer without the 3D model being necessarily erroneous. By exporting their settings and then using a script linked to an expert rule (Fig. 4), the designer may, at any time, verify the compliance of his concept with these rules and justify his choice in case of deviation.

5.2 Script process

Figure 4 explains in a state diagram the procedure for calling a verification script during the product development process, especially in RFQ phase. While designing his product, the user can call the script at any time and verify his current work. The script loads the preregistered parameters to be looked for, asks the user to input the parameters pertaining to the current case in study and verifies his work. Once the verification finished, a report is made and a comparison with the pre-established constraints is made. If the product passes, the loop closes, the report is sent to the rule database and the script finishes. In case the requirements are not fulfilled, the designer is advised to work on his concept and run the verification again [16]. This same procedure can applied for other rules to be verified to verify that all geometrical models conform to the rules and parameters established for them.

In the case of an air intake circuit for a car engine, the customer's functional specifications establish the length of the line, the amount of fluid to transport and its speed and a footprint or size to comply to. Due to the evolving nature of car engines, all these parameters cannot be defined beforehand, but they can be verified *post fact*. The same theory works for soldered plastic intake manifolds; the method and industrialization departments predefine the different geometries needed for the interpenetrating parts, but due to the variability of the products that are developed they cannot be constructed beforehand. The CAD designer constructs his concept following the rules established, but has to run a verification to validate them afterwards.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Set oPtext1 = oHSF.AddNewPointOnCurveFromPercent(oRefNea
Set oPtext2 = oHSF.AddNewPointOnCurveFromPercent(oRefNea
Set oRefPtext1 = oPart.CreateReferenceFromObject(oPtext1
Set oRefPtext2 = oPart.CreateReferenceFromObject(oPtext2
oHB3.AppendHybridShape oPtext1
oHB3.AppendHybridShape oPtext2
Set oLigneClose = oHSF.AddNewLinePtPt(oRefPtext1, oRefPt
oHB3.AppendHybridShape oLigneClose
Set oRefLigne = oPart.CreateReferenceFromObject(oLigneCl
oPart.Update
Set oAssemb = oHSF.AddNewJoin(oRefNear, oRefLigne)
oHB3.AppendHybridShape oAssemb
Set oRefAssemb = oPart.CreateReferenceFromObject(oAssemb
Set oMiniShapeFill = oHSF.AddNewFill()
oMiniShapeFill.AddBound oRefAssemb
oMiniShapeFill.Continuity = 0
oHB2.AppendHybridShape oMiniShapeFill
oPart.InWorkObject = oMiniShapeFill
oMiniShapeFill.Name = "Section_" & compteur

se
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  oPart.Update                                        'cyc
  oSelection.Clear
  Open oFichier & ".txt" For Append As #1
  Set oRefFill = oPart.CreateReferenceFromObject(oMiniSha
  Set oMeasure = SpaBench.GetMeasurable(oRefFill)
  oReponse = Round(oMeasure.Area, 8)
  oReponse2 = Round(oMeasure.Perimeter, 8)
  oDiamEq = Round(((oReponse * 4) / 3.1416) ^ (1 / 2), 8)
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Figure 5. Coding of expert rule via script into CATIA

The designer constructs his 3D part model proposition taking into consideration different criteria such as the customer's part environment constraints, the product's functional requirements, among others. Once the 3D CAD construction of the part is done, the designer can export the customer's other functional requirements from the PLM system in the form of a script (Fig. 5 shows an example of a script once coded into CATIA), which will enable him to verify that his concept properly responds to the imposed constraints. Using some basic geometry (generic models) the script verifies the concept, identifies relevant information, compares it with the prior values in the functional requirements and collects the results to be interpreted later.

5.2 Verification results

The results allow the designer to validate that his 3D model fulfills the demands requested (or locate possible errors) and, in case of deviation, they provide evidence to justify the reasons for his choice (for example deviations from the established norms due to environment restrictions or finite-element calculation findings). The advantage of this method is that it allows the designer to instantly check his work and complete the archives of the product with the direct result of his design choices. These archives will later serve to save time when making design decisions and when reviewing the manufacturability analysis of a new product. Figure 6 shows resulting information from an evolution law verification script which enables the designer to check the model. If the behavior of the law does not correspond to his expectations or to the established rules, he is advised to modify and correct his model.

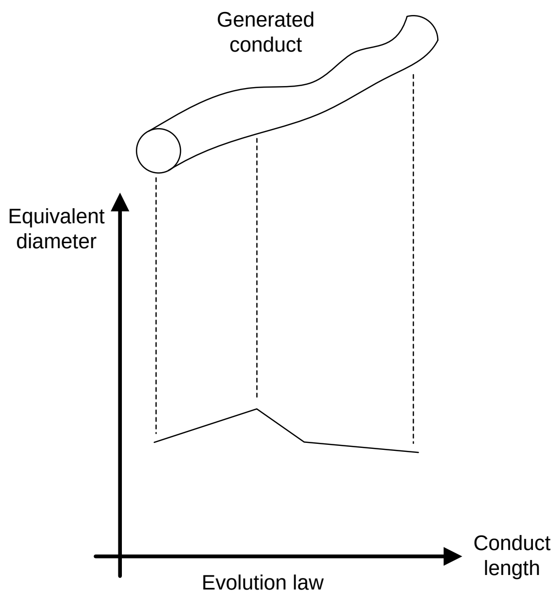

Figure 6. Evolution law verified on a generated conduct

6. INTEGRATION OF ASSEMBLY ISSUES

To realize a true integration of manufacturing aspects into the product development process, assembly issues have to be tackled. Boothroyd and Dewhurst have proposed a methodology of Design for Manufacture and Assembly in order to verify and optimize the product design depending on the type of manufacturing process and related criteria [26]. However, this method works on detailed product geometry and does not support integration aspects in the early product development process. Besides, the difficulty consists of considering two opposed objectives, on the one hand, Design for Assembly approach enables to simply the product structure by merging or eliminating product components, and in the other hand, Design for Manufacture provides some part features to facilitate parts manufacturing. In such a way, merged parts will create some manufacturing difficulties, therefore result in missing a true coherence between the both aspects. That’s why, the future objective will provide a consistency model in which manufacturing and assembly features will be related. This model will highlight the need to work on skeleton geometry in order to integrate as early as possible manufacturing and assembly issues into the product development process, especially in the product context of PLM [7].

7. DISCUSSIONS AND FUTURE WORK

The main step that has to be carried out is to close the loop in between the rule-validated geometric models, the downstream engineering activities and the knowledge database. The eventual interest of the methodology is to link the parameters that drive the geometric models with a multi-constraint Knowledge-Based Engineering (KBE) application and an optimization algorithm such as stochastic methods (genetic algorithm) [27], Gradient methods (SQP, BFGS) [28], or other methods such as the Response Surface Method [29] to improve the design quality and decrease the cost and time.

By linking the parameters with the KBE application and optimization tools, not only the concept can be improved to correspond with the client’s demands, but the rules that generate these parameters can also be actualized. This closing off of the design loop can guarantee the validity and durability of the method. Being able to keep itself up to date, through interaction and updating by the different experts concerned, the rules can keep up with the different developments in the field, be it advances in the manufacturing procedures, changes in materials, changes in standards or the application of other innovating procedures.

8. CONCLUSIONS

This research is angled towards providing the Research & Development department of a company with methodologies and tools in order to accelerate their product development lead time by identifying their detained knowledge and applying it from the early phases of the product development process. It shows the importance of forethought to avoid complications in downstream stages of a product’s design/manufacture, the significance of constant verification and of capturing the knowledge withheld by the company for the products they develop.

This robust design, based on known parameters, from the early product development process allows us to consider reducing the designers’ routine activities by two [30]. A reduction from the 80% of time spent on routine work is a welcome improvement for a R&D department. This principle opens up several interesting perspectives [31] with implications in the domain of generation and semi-automatic concept verification (Verification, Fig. 2), in a parametric geometric CAD system (CATIA V5, NX6, etc.) by incorporating engineering rules that fulfill functional requirements embedded in a PLM system.

The KNOVA-Sigma methodology, through a first document-centric application, has already yielded some results and several interesting to note manufacturing process rules. These rules are going through a second cycle, validating and enhancing them, so they can be implemented towards creating not only a proper knowledge rule base (useful for the R&D department where this research is being carried out), but also a methodology for extracting and capitalizing this sort of manufacturing process knowledge.

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