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Corresponding Author: Pr. Lionel Roucoules, PhD

Corresponding Author's Institution: Arts et Métiers ParisTech

First Author: Lionel Roucoules, PhD

Order of Authors: Lionel Roucoules, PhD; Serge Tichkiewitch, PhD

Abstract: Engineering design is a model-based activity which describes the product's multiple perspectives. With process model, we can also lead concurrent engineering activities. Both product and process models have been largely investigated. This paper aims at describing knowledge-based heterogeneous models chained to trace the design rationale that is the fundamental requirement to afford changes management. This knowledge chain supports the progressive by least commitment convergence of the space of design solutions. This rationale allows designers to go back and forth in the decision-making process. Moreover, the progressive convergence increases the possibilities for designers to integrate new knowledge toward innovation.



Knowledge synthesis by least commitment for product design

Lionel Roucoules^a, Serge Tichkiewitch^b (1)

^a Arts et Métiers ParisTech, CNRS, LSIS, Aix en Provence, France

^b Univ. Grenoble Alpes, G-SCOP, F-38000 Grenoble, France

Engineering design is a model-based activity which describes the product's multiple perspectives. With process model, we can also lead concurrent engineering activities. Both product and process models have been largely investigated. This paper aims at describing knowledge-based heterogeneous models chained to trace the design rationale that is the fundamental requirement to afford changes management. This knowledge chain supports the progressive by least commitment convergence of the space of design solutions. This rationale allows designers to go back and forth in the decision-making process. Moreover, the progressive convergence increases the possibilities for designers to integrate new knowledge toward innovation.

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1. Introduction

The evolution of engineering design for almost 20 years reaches a situation where many persons work in a collaborative way using many software applications (CAX, PLM...) and taking into account the whole lifecycle of the product¹.

The paper first presents the main functions of an engineering design situation in order to introduce what we assume as an ideal way of designing a product. The state of the art is discussed in the second section to highlight the related work that provides adequate concepts to answer those functions. Section three details the proposal of an engineering design by least commitment based on knowledge synthesis and process modelling in order to trace design rationale and support agile design. Conclusions open the discussion toward lean design approaches and gives some recommendations for future work.

2. Evolution of engineering design, main functions and ideal motivations

Since the early 1990s, the product design has changed significantly due to changes in organizational practices (concurrent and integrated engineering [1]), due to the evolution of information technologies for engineering (PLM, ERP, CAX) and communication (CSCW), due to the evolution of the social and environmental context (ex: Corporate social responsibility, REACH regulation) and the evolution of manufacturing technologies (additive manufacturing is one of the latest examples).

Thereby, some main functions of an engineering design can be presented, as shown in Figure 1, to depict what could be the

ideal situation of lean design. With analogy to manufacturing domain, lean design aims at designing a product minimising the non-added value tasks; in other words, minimising the non-justified information that constrains the product definition. Authors talk about a "by least commitments" approach.

1. *Product modelling*. Since the design is a collaborative activity, several models² are used to represent the knowledge of the product on its global lifecycle (LC).
2. *Model integration*. Concepts from product modelling have to be linked (i.e. chain) in order to assure the semantic mapping to cover the different phases of the design [2]: requirements specification, conceptual design, embodiment design and detailed design.
3. *Data exchange*. Many IT applications are used in the design process. Therefore data extracted from modelling concepts have to be interpreted by several software applications. The syntax of the model has to be exchange among software applications.
4. *Alternatives management*. Since design projects provide several solutions and are lasting many months or years, product models are evolving. Alternatives and evolutions have then to be managed in order to trace this evolution over the time.
5. *Master design changes*. This last function is actually the final objective of what could be lean and agile design: revise the decision making and the product solution as soon as the design context is changing: new industrial specifications, evolution of the industrial context and globalisation, evolution of users' requirements, evolution of technologies, etc...

¹ In the paper, "product" is used to talk about the solution of the Product Development Process (PDP). This term can be largely understood as "system", "complex system" or multi-physical system.

² « model » has to be understood as a set of modelling concepts. We could have used meta-model as specified by the OMG but "model" simplifies the reading of the paper.

This last function is supported by the four first ones and is certainly the main objective in numerous industries that know what they do but do not master how and why they have reached such solution and then are not able to quickly answer the evolutions of the design context.

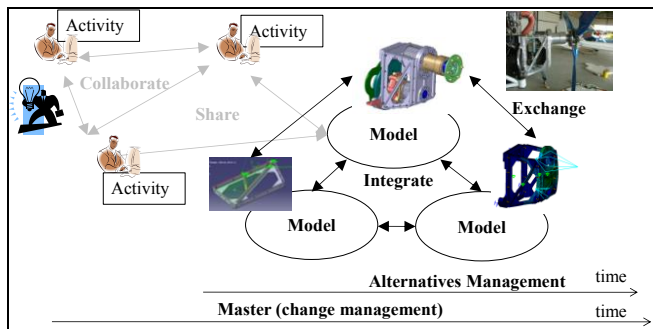


Figure 1. Main functions of ideal collaborative PDP

3. Discussions of the state of the art, main issues and objective of the proposal

3.1. Concepts for product modelling

On the one hand, modelling of manufactured products and parts, which were mainly physics has become highly (otherwise completely) digital. This development, initiated in the 1970s to facilitate the modification of manufacturing tools, coupled with the large increase in processing and digital storage capacity now allows modelling and simulating the entire product design, manufacturing processes, production and assembly lines..., to assess the product's complete product life cycle. We then speak of digital engineering, virtual prototyping, which is supported by a digital environment. Such environment can synthetically, consists of authoring applications supporting the functional analysis, structural analysis solvers, multi-physical assessments, manufacturing ranges (FAO tools), geometric modellers (i.e. CAD) to manage all the product features. The different product's and supply chain's configurations and evolutions are managed throughout respective software applications PLM and ERP.

On the other hand, design process and product modelling have also been largely studied by the scientific community [3, 4] but it is also assume that those concepts are not sufficiently implemented in commercial software solutions and industrial minds [5].

3.2. Issue n°1: lack of chaining of information toward design rationale from functions to end of life

With respect to function n°1 & 2, despite the numerous product models, many conceptual semantic gaps are still remaining in order to justify the rational understanding of decision making from functions, conceptual design to detailed design. Those gaps do not allow going back and forth in the product modelling chain: why technologies answer functions? Which form features are involved to realize one function? Which form feature are really needed and constrained by functional characteristics.

In order to really master the design process (function n°5), it is fundamental to formally trace the links among each product modelling concepts. That would give the possibility to understand the decision making points and to manage every design alternatives with rationale.

3.3. Form featured centred design process: a reactive process

For almost twenty year, since the apparition of CAD software, many developments have been done to go from paper sketch to 3D digital model that provide nowadays very powerful algorithm to obtain the geometric model (i.e. Digital Mock-up) of a system and to apply analysis on it (CAM, FEA, optimization...). Unfortunately, the intellectual design activity has therefore been focused on that form features modelling and remains a reactive approach in which CAD modelling is the entry point for assessing the X-ability (ex: manufacturability) of one solution. In the same way the PLM software solutions have been largely improved but are still providing solutions based on file management.

3.4. Issue n°2: lack of knowledge synthesis toward a "by least commitments" approach

As a first conclusion, those CAD and PLM software-centred solutions then provides very good support but have impoverished the intellectual design process which has to remain a collaborative decision making process to restrain the space of design solutions with respect to LC considerations [6]. In current approach, one person called "designer" creates the CAD model that make the design solutions spaces converged toward a single solution. Therefore, the other stakeholders can only react to this solution.

3.5. Objective of the proposal

The proposal presented in this paper is a synthesis of many results that have been investigated for many years by the authors and that are put together to provide a pedagogical point of view of the design method. **This pedagogical point of view is for us very important to really go back to support a real knowledge-based synthesis design activity using benefits of concepts provided by the scientific community.**

The intellectual design process has to follow a rationale concurrent process that aids designers to think function, think physical principles, think technology, think manufacturing, think...in order to collaboratively converge towards several alternatives of solutions and associated CAD models. Every stakeholder is then considered as a "designer" since he provides information to define the space of design solutions.

The CAD model has to be kept to collaboratively visualise the solution's form features but has to be the result of LC information synthesis. Those form feature are created "by least commitments" taking into account the minimal knowledge from every concepts of product model. As shown in Figure 2 [7], as far as the constraints are minimal, as far as the space of design solutions is large and improves innovation capacities.

It is also important to separate the creation and management of the available space of solutions and afterwards to assess this space with industrial performances (ex: delay, cost, quality...). The first stage of creating this space of solutions is followed by seeking processes to find the "best" (i.e. optimized) one in a given specific industrial context. As far as this context or the functions are changing, as far as new technologies are developed, the space of design solutions has to rapidly evolve and to provide adapted and perhaps new solutions. That is what authors call agile design approach (function n°5).

The general message that we want to highlight in this paper is then to "think differently" product design that should not be centred directly on the form feature modelling but must strongly rely on LC knowledge and decision making rationale.

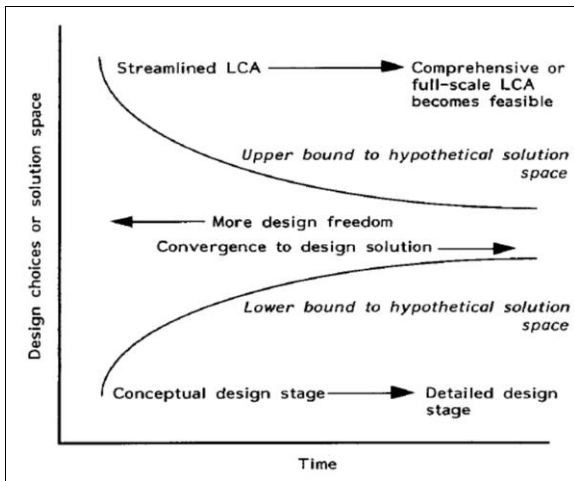


Figure 2. Convergence speed of the space of design solutions with respect to least commitments LC integration (from [7]).

4. Proposal: rationale chain of concepts in design product modelling

4.1. Concepts for semantic mapping

As far as product modelling is concerned, authors assume that it exits a lot of concepts to go from customer requirements, functions ... to form features. Many scientific works are also treating the definition of new ones with respect to certain LC phases and to specific industrial domain. Therefore the proposal aims at defining some concepts to link those already-existing ones. They will be used to support the chaining of information in a design rational way.

Figure 3 gives the main idea of this chain to let the form features emerged from both conceptual design (first stage, section 4.2) and detailed design (second stage, section 4.3).

A discussion on models interoperability is address in section 4.4 to highlight how this approach is enough flexible to use heterogeneous models in this knowledge chain.

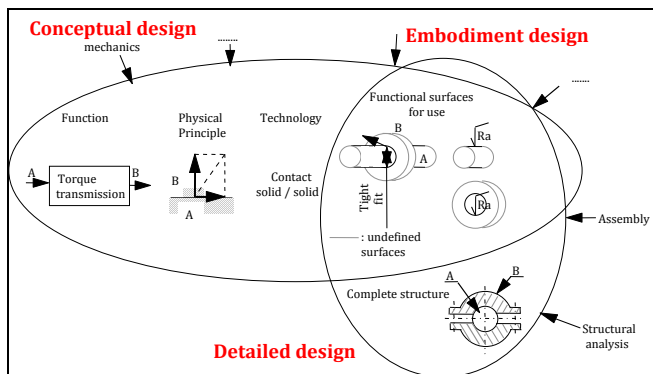


Figure 3. Two stages approach to let the space of design solutions converge by least commitments

4.2. First stage: from functions to form features by least commitment

During the design process, the first decision making concerns functions and physical principles. As introduced in the FBS model [8] this link justifies which are the functional parameters linked to physics parameter and technological parameters. In the proposal, FBS model has been stereotyped to formalize the “behaviour” concepts as “physical principles characteristics” in the F-PP-T model [9]. This concept gives rationale to understand how technological features achieve functional ones.

In that proposal, physical principles act as the first alternatives node of the decision making. This node is very important to provide “out of the box” solutions which cannot be found if designers do not think “differently”. In industrial domains, hybrid motors, photovoltaic panels... are respectively alternatives to cultural principles and provide innovations. Let us take the example of a flashlight. The main function “to light” is characterised by parameters (ex: lumen intensity at a given distance). This intensity can be realised by “electroluminescence” or “incandescence” physical phenomena. According to those two alternatives, the system breakdown can be selected. Several design alternatives also exists.

After the selection of the physical principles and technologies, this first stage delivers form features that are required to achieve the product’s functions. In order to model those minimal form features, we are using energetic flows concepts. Those flows are coming from stereotypes of Bond Graphs concepts [10] that describe what are the energetic flows transmitted in the system. These stereotypes aim at being used respectively to F-PP-T model since:

- A function is modeled as source or a transmission of an energetic flow.
- A physical principle: characterize which energetic variables are transmitted.
- A technology is associated to the system or part of it which support the transmission of the energetic flows.

Graphic representation in Figure 4 assists the designer to draw the energetic flows and explicitly highlights the functional surfaces which are the part of the system boundary crossed by a flow. This approach is closed to “Channels and Pair Surfaces” concepts proposed in [11] and reaches to the minimal required set of form features (surfaces) and energetic flows (skeletons) (cf. Figure 4)

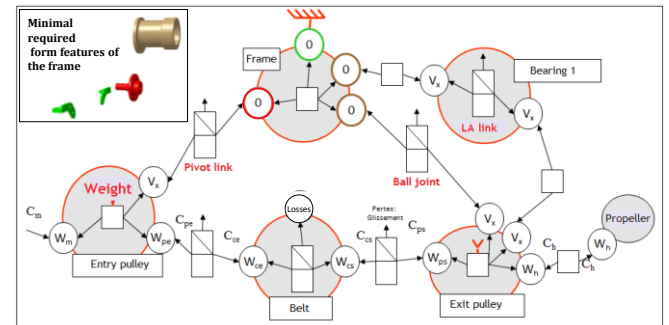


Figure 4. Graphic representation of energetic flows from F-PP-T model and emergence of the minimal required set of form features

4.3. Second stage: LC knowledge synthesis

The second stage is illustrated in this section with structural analysis and product-process knowledge integration. According to structural analysis, a four parts casing has been designed. Manufacturing knowledge can be input to create and justify the form features on the casing. Authors are calling that approach a DFM synthesis approach. Manufacturing stakeholder acts also as a designer.

This approach (Figure 5) is based on one main assumption: every manufacturing operation is based on a material flow that can add, deform or remove material. For example respectively: casting, stamping and machining. One material flow is modelled by a section and a trajectory. A sweep algorithm of the section following the trajectory creates a solid form features (i.e. volume). Details can be found in [9].

4.4. Collaborative design needs collaborative modelling and interoperability

In order to take into account all product LC phases, the proposed approach, is opened to other LC knowledge to generalize the proposal to generic FDX synthesis approach. To do so, many models can be used to model specific LC knowledge. For example [12] presents models to link product BOM, supply chain solution and material BOM to the analysis of environmental impacts.

As already presented, the authors assume that a unique model cannot be used to integrate all the LC concepts; the interoperability to set relations among heterogeneous models is then done using a hybrid solution:

- Federation level where concepts of one or several models are linked to concepts of another one [13].
- Unification level where concepts of many models are linked via a mediator model. For example a multiple-views model that is generic enough to link LC concepts [14] [15].

Using that interoperability approach, we fully implement the proposal presented in the paper. Instead of a unique 3D CAD model, the adequate collaborative environment therefore displays every CAD model with respect to each stakeholder's design intention (i.e. knowledge). Each intention is generated from LC knowledge that is translated to form features.

Those form features are justified by knowledge synthesis product modelling and are flexible enough to evolve as soon as this model changes. For example if a manufacturing plan change, form features change...

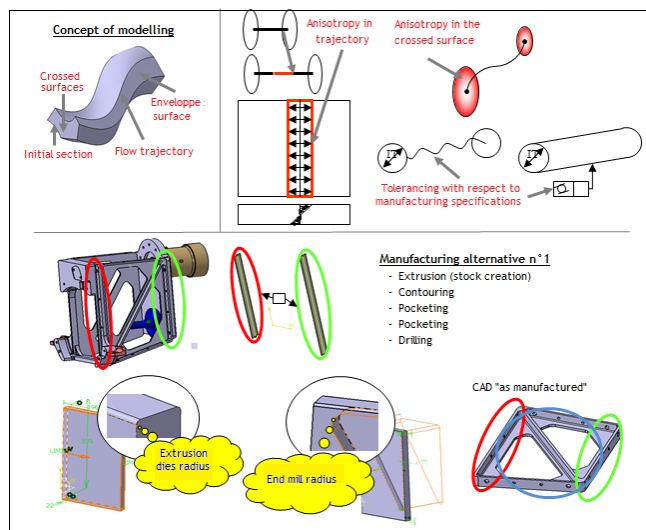


Figure 5. Overview of the second stage of the approach. Manufacturing information synthesis toward form features definition

4.4. Decision making modelling based on design process concepts

In addition to knowledge chain that allows the continuity and the justification of the final space of design solutions, it is important to extend the design rationale to decision making capitalisation. By analogy to lean manufacturing approach, the 6W concepts [16] are used to model who does what, when, where, why and how during the design process. This capitalisation supports the capacities of designers to quickly find out rationales that have been used to obtain the current solution. The saved time is therefore a good benefit to focus on innovation.

This rationale is also fundamental to identify which part of the solution is impacted when the design context changes (function 5). IDEF0 model is used to link decision making

rationale and product solution as presented on Figure 6. Details on the trace of design process modelling can be then exploited for design rationale.

5. Conclusion and recommendations for further work

The paper gives an overview of a design approach centred on Lifecycle knowledge synthesis. This approach faces current CAD centric approach considered as reactive approach. The main advantage is to constrain the space of design solutions "by least commitments" in order to trace the design rationale and to be able to adapt the design solution when the design context is changing.

This approach is currently implemented as an open modelling platform in Eclipse environment in order to enlarge its diffusion in the scientific communities. Later on the concepts that have been locally illustrated could then illustrate the global agility of the approach.

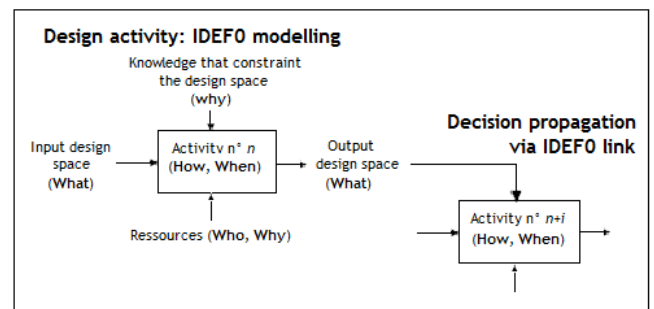


Figure 6. Design process modelling with IDEF0

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