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PRODUCT MODELLING FOR DESIGN ALTERNATIVES SELECTION USING OPTIMISATION AND ROBUSTNESS ANALYSIS

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ABSTRACT
In a context of virtual product development, information related to the entire product life cycle has to be taken into account at the earliest possible stage of the design process. In such integrated design approach, the information synthesis of each design activity provides new information concerning the product and is expressed to provide new data that have not been already defined or to constraining already-defined ones by a reduction of their alternatives and of their range of values. The final solution is defined as the convergence "right the first time" by least commitments of the initial solutions space according to experts' information synthesis. In order to support that product development process, the scientific community improved product modelling to take into account product life cycle activities (functional analysis, structural breakdown, CAD model, FEM, "X" assessment, etc).
The main result presented in this paper is an original approach that could help designers to define product alternatives at the earliest stage of design. Then, this approach could help to progressively reduce the space of solutions excluding non optimal or non robust ones. The space of solutions is therefore analysed by solving transfer functions and then by assessing the product's performance (required functions) with respect to set values and variability. This decision making process is finally aimed at identifying what could be the optimal solution or the most robust one.
An example of an electrical switch illustrates the use of those tools: management of product models, multidisciplinary optimisation and robustness analysis.

Keywords: FBS, DFX, MDO, robustness, decision making

1 INTRODUCTION
In a context of concurrent and integrated design, several expert designers have to manage both individual and collaborative tasks according to a dynamic design process that aims at taking into account the entire the entire life cycle of the product (manufacturing, assembly, recycling, etc.) during the virtual product development information.

In order to make product development more effective, the scientific community has, so far, proposed a lot of solutions concerning product modelling (Krause and al. [1], Kjelberg and al. [2]). Those solutions generally highlight specific concepts as FBS (Gero [3]), ICARE, multiple points of views (Tichkiewitch [4]). Besides the proposal of different concepts, those models have to be seen as complementary in order to cover the largest product life cycle modelling (functional analysis, structural breakdown, CAD model, FEM, "X" assessment, etc).

Several software applications that manage those models can be currently used to support every steps of the product development process. Recent research works from Noël and al. [5], Yoshioka and al. [6] and Rueckel and al. [7] have proposed reference models to support the interoperability among all those specific models. They are generic enough to set relationships among concepts and then provide a really good solution to keep the links and the coherency among all the data related to product life cycle.

A strong link is also proposed by Roucoules and al. [8] to link the industrial organisation model, the design process model and the product model that is actually defined as I/O of design process activities. The result of each task provides new information on the product and enables either to provide new data that have not been already defined or to constrain already-defined ones by reducing their range of values. The final solution space can therefore be defined as the convergence of those ranges of values according to expert information synthesis.

According to that context, the aim of the paper is to present an original approach to information synthesis during the virtual product development process and more specifically during the conceptual and embodiment phases. That approach is centred on design expert synthesis. Activities are processed to reach a product solution "right the first time" (Kim and al. [9]) by least commitments. In that approach the product (and the CAD model) emerges from information synthesis instead of imposing a first solution that is afterwards modified ("redo until right") [10]. In this paper, the authors focus on one specific expert activities: selection of multiphysic technological components. Nevertheless, other design activities related to manufacturing process selection (Skander and al. [11]) and mechanical analysis (Krikeb and al. [12]) have also been proposed in order to be used during the collaborative and simultaneous design process (cf. figure 1).
Figure 1 shows how the two activities are connected (get and set) to information from the shared product model that manages design alternatives (parameters, range of values for the parameters and variability around the possible values, behavioural laws). Then designers use different methods (MDO and robustness) in order to analyse those alternative solutions to select the final design solution.

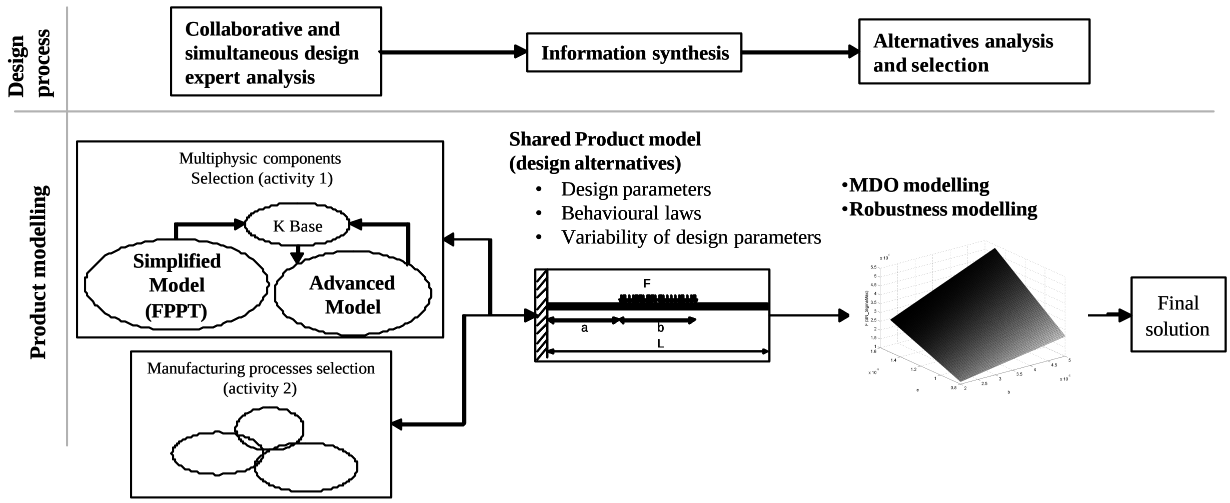


Figure 1. Representation of design process and product modeling

With respect to functional analysis and technology selection, modelling concepts are based on FBS approach. The technical functions of the product (F) are first expressed and mapped to specific technological components (T). The mapping is fully justified owing to the identification of physical principles (PP) that formalise the behaviour of each technological component with respect to the required functions. Each of those three concepts (F-PP-T) is moreover characterised with functional, physical or technological attributes represented with a range of potential values and tolerances. The boundary of those values expressed physical or technological limits over which the mapping is not available. Those initial data related to functions, physical principles and technologies are then processed to define the potential solutions space.
That solution space is afterwards analysed by solving mathematical laws related to physical principles and to assess the behaviour of the product (required functions) with respect to the range of values of the attributes and taking into account the variability on the values. Analyses can be performed to identify what could be the optimal or the most robust solution. The main result is to provide adequate tools to the designers in order to first define potential product alternatives at the earliest stage of design and then progressively reduce the space of solutions skipping non optimal or non robust ones.
Methods such as Multi-Disciplnary Optimisation (MDO) or Robust design can be used to evaluate the level of satisfaction of a design solution with respect to a set of functional requirements. In this paper, these methods are not used to find *the* best solution, but to identify the compromises that should be discussed among experts and should lead to choices. In other words, they provide graphical

representations that enable the experts to identify opposite impacts of parameters changes on functional requirements, and, thus, to define a good global solution.
First, the product modelling concepts that enable the collaboration and the data sharing are proposed in order to manage the technological alternatives and the variability. Afterwards, the way to use MDO and Robust Design methods is presented in order to identify collaboration need in the design process. Finally, the proposition is illustrated on an example that shows the feasibility of the proposition.

2 PRODUCT MODELLING CONCEPTS

For the last fifteen years, the design process has turned into a collaborative and a simultaneous process. It involves plenty of different engineering experts who must communicate, exchange pertinent and understandable information. This complex process is still the subject of improvements and full of research goals. One of the limits of the current approach is the importance of the 3D geometry provided by CAD software. Design experts have to work with an initial CAD model but cannot really participate to the emergence of the solution. Moreover the information flow is often broken: it is difficult to justify the design rationale (who, why, when).
The collaborative and integrated design approach that is presented in this paper supports the product solution emergence by least commitment and actually considers the geometry as the final result of the design process [10]. The product solution emerges from the integration of constraints of the design experts and allows the continuation of the information flow. To assist engineers in deploying that design approach, information modelling is presented in three main categories (cf. figure 1):

- Collaborative information sharing: manages, protects the data and allows the different designers to share and access the pertinent and reliable information as soon as they are available.
- Experts' engineering modelling: supports data of the design solution to assess X'ability of the product according to specific engineering activity (mechanical analysis, manufacturing, etc.).

The presented design process (cf. figure 1) is then based on multiple iterations of analysis/synthesis done by each design expert: the data sharing core communicates with the information from specific engineering models; as soon as the expert activity is done, experts return the data into the data sharing core.

2.1 Collaborative information sharing

The data sharing core shares information related to three domains:

- Product information: results of the design process.
- Design process information: organisation of activities and resources.
- Industrial organisation information: definition and leading of projects and performance indicators.

It manages and sets relationships among information from the different design expertises. It is then possible to notify potential conflicts and warn the concerned experts. Then those involved experts will start the discussion to find a solution.

2.2 Design experts' engineering modelling

Figure 1 also presents how can be detailed expert activity in the global integrated design framework:

- Simplified models support data to allow rapid analyses of the expert activity (DFX concept) in order to propose a large number of alternative solutions as soon as possible in the design process.
- Advanced models are made for accurate product analyses and to find the "best" solutions among alternative ones. They usually need more time and information than the simplified ones. They are therefore used later in the design process.
- The knowledge base represents any kind of knowledge (ex: books, computer database, own experience, etc.) used by design experts to find solutions respect to specific requirements.

3 THE DESIGN EXPERT ACTIVITIES, THE DESIGN ALTERNATIVES AND THE SHARED PRODUCT MODEL

That section describes the design activity related to multiphysic components selection and how authors have specified models to foster design alternatives proposals.

Concerning the selection of technologies and the assessment of the behaviour, several models have been proposed in the literature. Triz method (Terninko [13]) links the functions to the technologies, but is not integrated in a product model. It does not propose formal (parameters) justification of the choice (least commitment) and is not link to behaviour simulation methods. It could be assimilated to the proposed knowledge base (cf. figure 1). Bond Graph model, from Thoma [14], represents multi physical system through energetic flows. Thanks to its formalism, behavioural simulation can be done very early in the design process (Schweiger [15]). Unfortunately, there are no links between the functions and the associated technologies, and it does not provide methods to find alternative solutions. Function-Behaviour-Structure method from Gero [3] links the function, the behaviour and the structure and makes emerge different sort of parameters (functional behavioural and structural).
Based on those models the authors propose Function, Physical Principle and Technology (FPPT) model a simplified model (cf. figure 1). It is partly based on the former models and adapted to our design context (cf. figure 2), in order to manage the choice of different technologies.

- A Function describes what the product is designed for. It comes directly from functional analysis. A Function can be decomposed in two or more Functions or be redefined in order to refine its description. Some parameters are attached to it.
- A Physical Principle (i.e. physical law) is the link between a Function and a Technology. It has parameters which come from its definition. It might also have some limits: due to the scale or due to another physical law. A Physical Principle can be an energetic loss. Such loss is also notified in the description of the Physical Principle. Grabowski and al. [16] had proposed the use of physical principle in the design process.
- Technology realises a function trough a structure. Some parameters are also linked to it. They come from the behaviour and the structure of the technology. The technology might have some limits due to the scale or the technology itself.

The role of the different parameters (functional, physical and technological) is to allow behavioural analyses at the beginning of the design process, when no geometry is available. Parameters and physical laws can be exported to any simulation software (such as Matlab) to provide a first evaluation of the chosen physical principles and technologies. In such an approach, physical or mechanical behaviours are easily assessed as far as mathematic formulation is known. That is the case of really simple and uncoupled phenomenon or at very early stage of design when strong hypothesis are done. In more complex situations, behaviour has to be identified from design of experiments using numerical or experimental analysis. This method (Roy [17]) has been chosen by the authors for identifying a mathematical model (such as polynomial equation for instance, or more specific functions) of the behaviour. We then propose to build metamodels (also called surrogate models) such as described by Simpson et al. [18]. Indeed, by using some experimental or numerical design of experiments (Roy [17]), Fowlkes et al. [19]), and by choosing an appropriate mathematical function, the relation between design (technology and behaviour) parameters and functional parameters can be identified (Simpson et al. [18], Meckesheimer et al. [20]).
Using the physical laws or the metamodels, some decision can be taken in order to find the best design parameters decision in order to fulfil the whole functional requirements. Then, based on the FPPT Model, the level reached for the performances can be shown using response surfaces for the possible values of the design parameters.

As we have seen in this section, the FPPT models enable to generate parametric alternatives (at three levels: functional, physical and technological). But designers need to choose one of these alternatives. In order to improve the decision-making in this design environment, taking into account the compromise with all parameters and the variability of them, highlighted by the FPPT model, two methods are proposed: the MDO and robustness design methods.

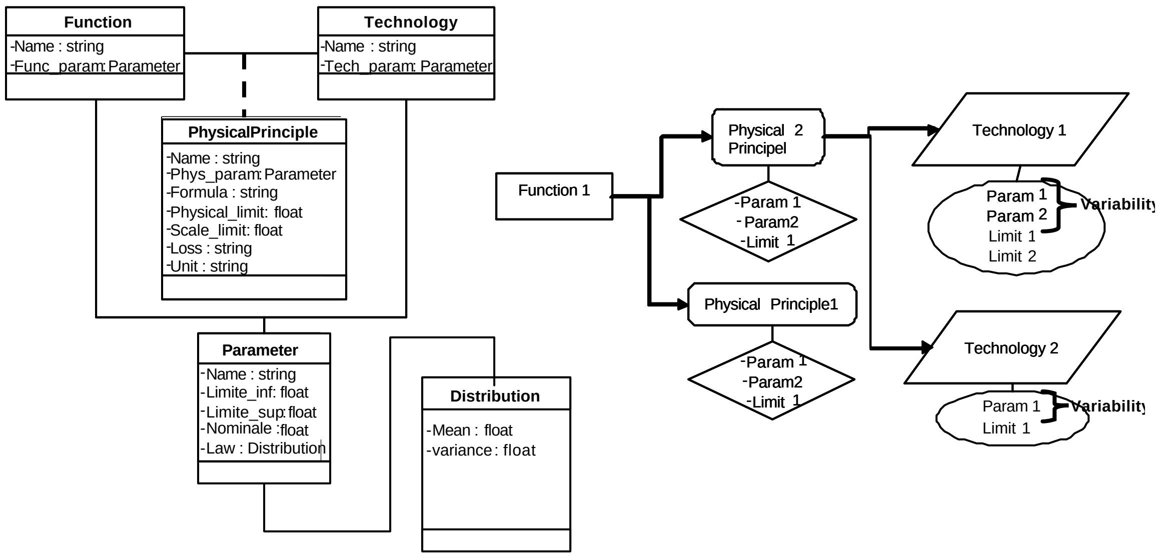


Figure 2. UML Implementation and model of FPPT concepts

4 DECISION-MAKING BASED ON A PRODUCT MODEL TAKING INTO ACCOUNT THE VARIABILITIES

As previously explained (cf. figure 1), the decision making in the design process is based on a network of data coming from numerous viewpoints. As mentioned by Grabowski et al. [16], team strategies in collaborative decision making follow specific models compared to individual decision making. For collaborative systems, Grabowski et al. [16] and Ullman et al. [21] highlight the need of decision support systems and the ideal decision support system are:

1) Support inconsistent decision-making information
2) Support incomplete decision-making information
3) Support uncertain decision-making information
4) Support evolving decision-making information
5) Support the building of a shared vision
6) Calculate alternative ranking, rating and risk
7) Suggest direction for additional work, what to do next
8) Require low cognitive load
9) Support a rational strategy
10) Leave a traceable logic trail
11) Support a distributed team

In this section, we will focus on the way to support decision making taking into account the uncertainties on the design parameters and their impact on the functional requirements (performances) to be reached in a multi viewpoints approach.

The uncertainties are linked with different factors. Some uncertainties are related to the undecided design parameters. Other ones are due to the quality provided by the process chosen for the manufacturing and can be expressed as tolerances. At least, some features of the environment can affect the product behaviour and that implies that the design parameters can not be all controlled (the temperature, the way to use, etc.). Then the consideration of these uncontrolled factors variability during the design process enables to guarantee the level of performance that can be reached in use. The design should guarantee the performances of the functional requirement list whatever the variability due to the design parameter, to the manufacturing process or to the uncontrolled environment of the product. The design is then robust.

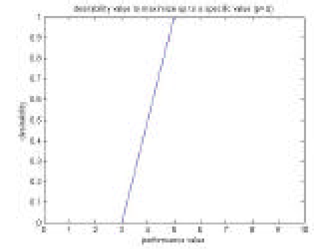
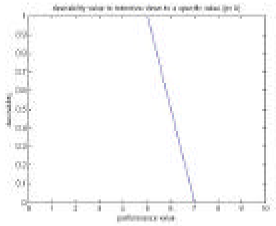
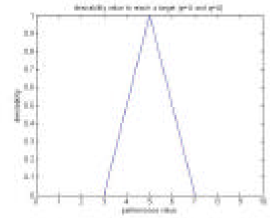
Then, to take decision in the multiple-viewpoints environment previously described and to take into account the undecided parameters, tolerances and uncertainties, it requires to identify the following elements:

1) The identification of the design parameters {DPs} (of technology and physical principle) and the functional parameters,

2) The laws that link the identified design parameters to the identified functional ones,
3) The "external" uncontrolled factors and their level of variability (as complement of the simplified model with some external parameters of the shared product model),
4) The variability on the design parameters and on the process variables in the case of tolerances (in the manufacturing viewpoint).

4.1 MDO and robustness analysis to identify the collaboration needs

Knowing the parameters, their variability and the law between them, MDO (Multi Disciplinary Optimization) approach, and in particular the desirability functions (also called preference functions or utility functions) can be used to evaluate, in a global approach, the best values for the design parameters. It should be noticed that the MDO techniques, at this first stage, are not used for optimization purpose but to provide global data in the whole design space for decision making. The desirability functions represent the level of satisfaction associated to each value of the performances to be considered. The desirability takes a value between 0 for a bad value to 1 for a desired value. The desirability for each performance are combined and defined as proposed by Del Castilo et al. [22] in order to build a global desirability function (Figure 4). In the multiple-views environment based on the FPPT model, the data of the global desirability level associated to each design parameters value can be added (as a colour data – figure 10) on the surface responses that represent the performances with respect to design parameters. A good level of the observed performance can be a bad global level of satisfaction on the whole performances.

To maximize a performance over target	To minimize a performance below target	To reach a specific performance e at the target level
Target = 5, Upper limit = 7, Lower limit = 3, p=q=1. 	Target = 5, Upper limit = 7, Lower limit = 3, p=q=1. 	Target = 5, Upper limit = 7, Lower limit = 3, p=q=1. 

$$Global\_desirability = \left(\prod_{numberofperformancesunderconsideration} desirabilitiesforeachperformance \right)^{\frac{1}{numberofperformancesunderconsideratio}}$$

Figure 3. Few examples of desirability functions and global desirability

When the sources and levels of variability are estimated, the design of experiment method is used to evaluate the sensitivity of each variability on the performances levels. Using the Taguchi method described by Fowlkes et al. [19], the variability (described in the FPPT model) are introduced as noise factors in the design of experiment. The robustness of the design solution is then estimated by the level of the signal (design parameters levels) to noise (variability levels) ratio (Figure 4). This ratio can also be added on the response surface as a colour data to be able to evaluate for a set of design parameters values the robustness of the design solution.
All these treatments on the data provided by the FPPT model enables a collaborative decision making, taking into account uncertainties, that can be used for risk evaluation in the project management viewpoint. It also enables to use global criteria on optimization and robustness to evaluate the quality of the proposed design in the decision making process.

At the second step, MDO is used for optimising the design space. It is then viewed as an n-dimensional space of parameters (assuming that this parameter may have discrete or continuous value). We must also consider a set of relations (implicit or explicit, equalities or inequalities) linking this parameters coming from physical laws or metamodels. These parameters can play different roles (functional, physical and technological) and some of these parameters come from functional requirements so their value is fixed by some requirements specifications. That kind of parameter will

be called “data parameter”, the others will be called “free parameter” (their value has to be defined and is not provided). Furthermore they also have some variability around an average value.
In order to achieve the analysis stage, it is necessary to “instantiate” a design solution by determining a correct value for the set of “free parameter”. Then, this design solution will be used in collaboration activities (cf. Figure 1) and be submitted to the other expert.

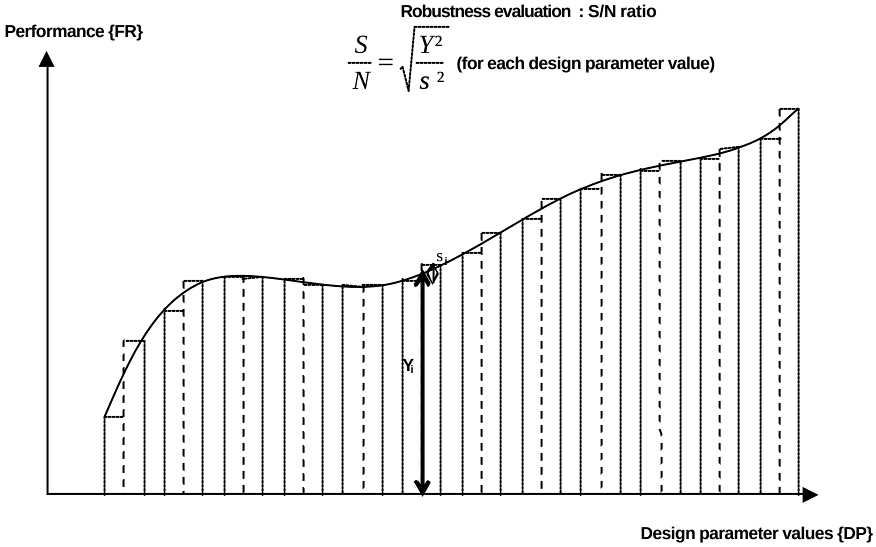


Figure 4. The principle of robustness evaluation

Usually the number of “free parameter” exceed the number of equalities relations (explicit or implicit ones), in this case multi disciplinary optimisation method are very useful to “instantiate” such design solution. The optimisation problem is build with the set relation (equalities or inequalities), and the variables are the set of “free” parameters. When it is possible, it is useful to decrease the dimension of the problem by simplifying the equalities relations. For large problem some decomposition technique can be applied in order to address some “sub optimisation problem” Papalambros [23]. One of the major difficulties is to propose relevant optimisation criteria, keeping in mind that all real problems are multi objective ones. Here, the graphical supports provided by MDO and Robustness analyses are used in order to support the experts collaboration in order to discuss about the more satisfactory solution in a global approach. In some case, Pareto frontier can be provided to find the best solutions.

5 CASE STUDY

5.1 Introduction

As it has been previously presented, the use of FPPT modelling enables the extraction of parameters and their variability. With these parameters, we are able to compute a product optimisation (MDO approach) and a robustness analysis. All these methods can be done on a lot of different products, from a simple object, like a beam, to a more complicated one. In order to point up the methods and not the product we have chosen, to redesign a micro-switch as a case study.
De Grave [24] noticed a lack of MEMS (Micro-Electro-Mechanical Systems) design methods especially during the embodiment design. Switches are relatively simple systems and are representative of MEMS technologies. Furthermore, there already exists a huge variety of them. In fact, each MEMS design company brings its own products. This example is based on the switch presented by Rebeiz and al [25]. It is called a “beam switch” since a beam establishes the contact via a deflection induced by an electrostatic strength (cf. figure 5). This strength is produced by two electrodes.
For the company it’s important to produce product where the level of performances are guaranteed whatever the variability in manufacturing process, usage etc. In such design case, companies have to make some compromises with all the actors of the design process. We are going to show how FPPT modelling and robustness analysis can help collaborative decisions.

5.2 Multiphysic components selection

5.2.1 FPPT modelling

The starting point for technologies selection is the functions that the final product must fulfil. The three main functions are:

- allow an electrical current
- not allow an electric al current
- switch between the two previous functions

To allow or not an electrical current through the switch, the physical principle is the conductivity of materials. So the associated technology just concerns the properties of materials. Two functions have emerged from initial switching function. The first one is that a movement must be possible. This function is done via a deformation (Hook law), the technology concerns the geometry and the material of a beam. The second function is that strength must be applied in order to have movement. It will be an electrostatic force created by electrodes. Figure 5 shows part of the FPPT model.

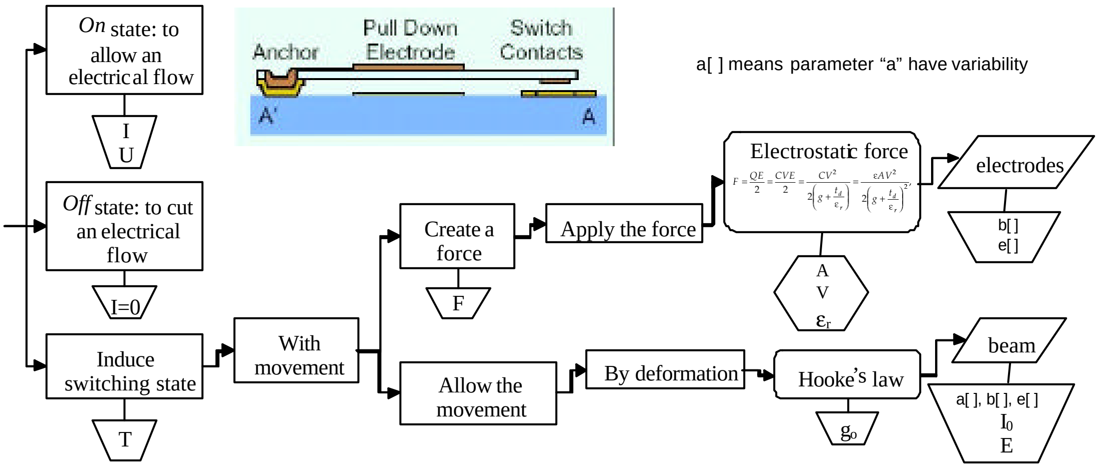


Figure 5. Part of the FPPT model of the "beam switch"

Trough this model, the different parameters appear and can be manipulated, exported. They can have variability or a range of value. They come from the different expert work: a designer might not have completely restraint the design (range of value), a manufacturing will always create variability on the manufactured shape (especially for MEMS manufacturing).

5.2.2 Shared product modelling for collaboration task

Thanks to the final FPPT model, a mapping can be done to provide information and an initial 3D solution to other expert activity (cf. figure 6). The problem is so far described with a central beam which deflection is imposed by surfaces 1 and 2 (electrostatic force). Surfaces 3, 4 and 5 then assure the electric conduction of the switch. On a macro scale, the roughness of each surface can be defined but such notion does not exist, or can be hardly defined for the micro scale. The beam definition will be driven by equations in order to have the right behaviour for the final solution.

Here it is interesting to find the different valuable solutions of the parameters of the beam depending on the deflection (mechanical analysis modelling). The figure 6 shows a basic representation of the problem and some parameters, among the other parameters there are the material, the high and the width of the beam.

5.3 Behaviour analysis for decision making process

Behaviour analysis of the *Beam Switch* can be done at several stage of the design process. Each analysis then takes into account of more or less information depending on experts' knowledge (cf. figure 1). At earlier stage of design one analysis can, for instance, be performed to assess the principle/technology solutions.

From multiphysic components selection and respect to variability and design parameters range of values, each analysis provides a response surface that represents the assessment of each functional requirement (FR) (cf. figure 1). For the same solution, different analysis (i.e. response surface) can also be calculated concerning specific FR related to experts' point of view: manufacturability, sustainability, etc. For each of them the optimum must be found.

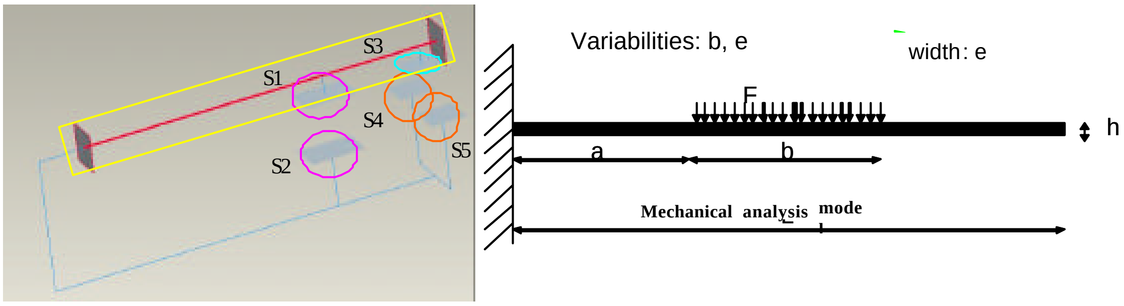


Figure 6. Shared models of the switch beam toward the emergence of the CAD model and the definition of design parameters and their variability

5.4 Optimisation Method for collaboration need identification

The optimisation process enables to find the best alternative solutions depending on the design priority. However, in order to optimize, the mathematic laws which link the different design parameters and the responses must be known. As stated previously, we can determine these laws by the mean of a metamodel design of experiment or by physic laws. For this example, the formulas are the following:

$$s_{\max} = \frac{6Fb(a+\frac{b}{2})}{eh^2}L \quad \text{and} \quad F = \frac{eAV^2}{2(g+\frac{t_d}{e_r})^2}$$

Where σ_{max} is the maximum for the strain in the beam and F is the electrostatic force need to create contact. The optimisation problem consists in minimizing the strain in the material and to maximise the electrostatic force F.

First the response surfaces of σ_{max} strain and F force are plotted. The influence of two design parameters (b, e) which are in the two responses is studied.

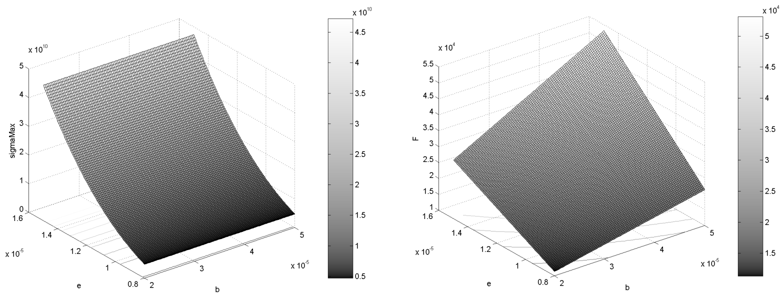


Figure 7. Response surface of s_{max} max and F

Figure 7 shows the two response surfaces depending on the two design parameters, namely e and b. The first parameter e represents the width of the beam and b represents the length of electrode. If the e value is increased, the strain level decrease (what is going well with the strain minimization) and the admissible force level decrease (what is going against the force maximization). In other words, improving one performance (the strain) with increasing e values has a bad influence on the second performance (the admissible force). In a multi-viewpoints framework, the data about the influence of a data modification should be given to the designer taking into account the whole performances to be reached. In order to deal with the decision we apply an MDO optimisation using desirability function. The level of the global desirability is calculated for each design parameter value and is added on the response surface function of b and e for reaching the performance point.

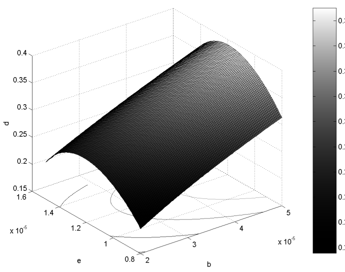


Figure 8. Desirability surface

Then the global desirability (figure 8) is added to the response surfaces (σ_{max} and F), as shown in Figure 9. So it's possible to identify which solution is the best in order to respect the global MDO problem (minimize σ_{max}, maximize F), for the e and b values that provide the higher level of desirability. So the best design parameters values can be read for the optimization taking into account the two objectives (maximize F and minimize σ_{max}).

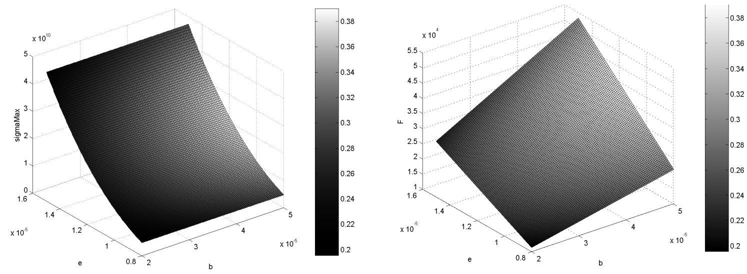


Figure 9. Response surface with desirability functions

In MEMS, the manufacturing process implies great variabilities. In order to guaranty the level of the performances whatever the variabilities on the design parameters are, the robust analysis method is used as explained in section 4 of this paper. Indeed, it could be more relevant to have fewer performances but to be sure of this level.

The main robust principle is to build a Signal to Noise ratio (SN ratio), in order to maximize it. For the presented example, two Signals to Noise ratios are built, one for the strain, and the other one for the force. These Signal to Noise ratios show the robustness of the performances taking into account the variabilities on b parameter (b is the length of electrode). That's why, analyzing the response surface with the adding data of signal to noise ratio on the other performances can be useful to find the best compromise between optimization and robustness.

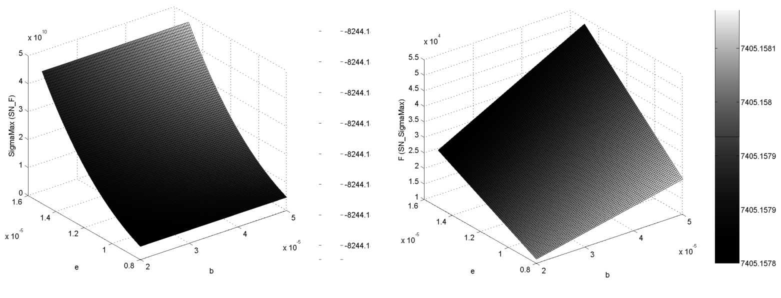


Figure 10. Response surface with S/N ratio

This example shows that the discussion for robustness seems to be complicated. In Figure 11, the robustness of F (maximum level of S/N on F) is obtained for a low value of e and a high value of b. The robust solution is not the best solution previously provided by MDO. It is the same conclusion for ensuring a robust low level of the maximal strain. This kind of divergences can be identified to warn the experts who are modifying the design parameters e and b and who are interested in the force level and the maximal strain level on the detected conflicts. This is particularly interesting if one expert is working on the force level and an other one on the maximal strain level. The background detection of divergences can enable the two experts to identify the collaboration need via a warning.

6 CONCLUSION AND RECOMMENDATION FOR FURTHER WORK

After a brief introduction of the proposed design framework, the paper presents methods and models which provide, during design process of the product, design alternatives and associated parameters variability. Afterwards, the analysis of the robustness based on desirability modelling is used to run the making decision process. Further research work concerns the consolidation of the current results on more complex case studies. That consolidation has obviously to be based on software demonstrators. Solutions are then expected to couple specific modelling applications developed in C++ and Matlab. The illustration shows how to use the proposition and an implementation should be achieved in order to test the point of the detection in a PLM context.

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