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SPECIFIC PRODUCT MODELLING APPROACH FOR ALTERNATIVES IDENTIFICATION, OPTIMISATION AND ROBUSTNESS ANALYSIS

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ABSTRACT

Currently, in a context of virtual product development process, information related to the entire product life cycle has to be taken into account. In order to support that product development, the scientific community so far proposed a lot of results concerning product modelling that have to be seen as complementary in order to cover the largest product life cycle activities (functional analysis, structural breakdown, CAD model, FEM, "X" assessment, etc). The synthesis of activities 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 "first the right time" by least commitments of the initial solutions space according to experts' information synthesis.

The main result presented in this paper 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. The initial space of solutions is therefore analysed by solving transfer functions and then to asses the product's behaviour (required functions) respect to parameters range of values. This decision making process is finally performed identifying what could be the optimal solution or the most robust one.

An example based on an electrical switch illustrates the 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 achieve both individual and collaborative tasks according to a dynamic design process that aims at taking into account during the virtual product development information related to the entire product life cycle (manufacturing, assembly, recycling, etc.).

In order to support the product development, the scientific community so far proposed a lot of results concerning product modelling [1], [2] that generally highlight specific concepts as FBS [3], ICARE, multiple points of views [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 managing those models can then be use currently to support every of the entire product life cycle. Recent research works [5] [6] [26] 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 the coherency among every data related to product life cycle.

A strong link is also proposed in [7] to relate the industrial organisation model, the design process model and the product model that actually is defined as I/O of design process activities. The result of each task 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 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 objective of the paper is to present an original approach for 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 “first the right time” [8] by least commitments. In that approach the product (and the CAD model) emerges by information synthesis instead of imposing a first solution that is afterwards modified (“redo until right”). In this paper, the authors focus on two specific expert activities: functional analysis and technology selection, and optimisation and mechanical analysis.

Respect to functional analysis and technology selection modelling concepts are basically based on FBS approach. Product technical functions are first expressed and mapped to specific technological components. The mapping is fully justified owing to the identification of physical principals that formalise the behaviour of the technology respect to the required functions. Each of those three concepts 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) respect to attributes range of values. Analyses can be performed to identify what could be the optimal solution or the most robust one. 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.

Concerning optimisation and mechanical analysis the design expert has to formulate relationships among previously defined technological component (and attributes), mechanical functions (power transmission, life time, etc.) and materials property (young modulus, etc). The relationships are formalised with mathematical equations representing the mechanical behaviour of the product (deformation, stresses analysis, wear analysis, etc.) [9] [10]. Once the relationships set, an optimisation problem can be formulated and solved [11] to identify which could be the “best” solutions among the ones issued from the first activity: functional analysis and technology selection.

The final solution is then right for those two experts and has emerged according to information synthesis by least commitments. That objective could be easily enlarged to generic DFX activities which also provide information on the X ability of the product.

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 experimental analysis. The authors propose solutions based on Taguchi methods that are created according to numerical experimental analysis. Transfer functions between product parameters issued from information synthesis and behaviour are then identified by polynomial equation of more specific functions.

2 PRODUCT MODELLING CONCEPTS

During 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 objectives. 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 can not 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. The product solution emerges from the integration of the design experts constraints 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 the X'ability of the product according to specific engineering activity (mechanical analysis, manufacturing, etc.).
- Interface modelling: supports the link between experts' engineering modelling and collaborative information sharing (i.e. support for synthesis). Those models aim at supporting the CAD model emergence by least commitment.

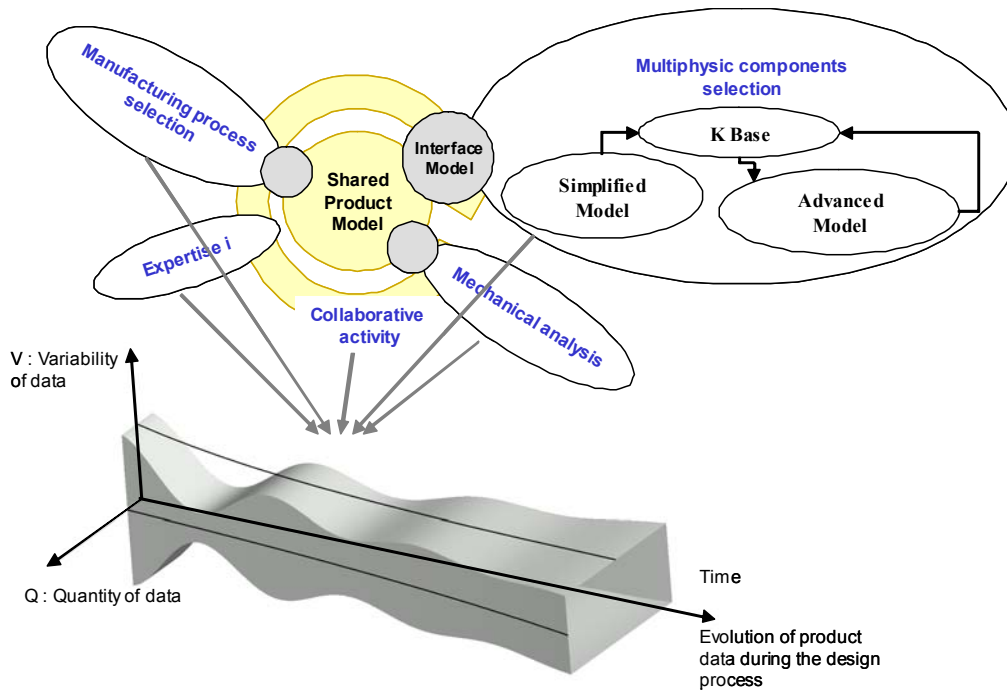


Figure 1. Overview of the Integrated Design framework

The presented design process (cf. figure 1) is based on multiple iterations of analyse/synthesis done by each design expert: the data sharing core communicates, through the right interface model, the information to specific engineering models; as soon as the expert activity is done, a specific interface model 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 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 product accurate 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 DESIGN EXPERT ACTIVITIES TOWARD DESIGN ALTERNATIVES AND VARIABILITIES IDENTIFICATION

That section describes a design activities related to components selection and how authors have specified models to foster design alternatives proposals. Other design activities respect to manufacturing process selection [12] and mechanical analysis [13] have also been proposed.

3.1 Selection and analysis of multiphysic components

Concerning the selection of technologies and the assessment of the behaviour, several models have been proposed in the literature. Triz [14] method 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 2). Bond Graph [15] model represents multi physical system through energetic flows and, thanks to its formalism, behavioural simulation can be done very early in the design process [27]. Unfortunately, there are no links between the functions and the associated technologies, and it does not provide methods to find alternatives solutions. The model could be seen as interface and simplified model (cf. figure 1). Function-Behaviour-Structure [3] method links the function, the behaviour and the structure and makes emerge different sort of parameters (functional behavioural and structural). It is a simplified model (cf. figure 1).

Based on those models the authors propose a Function, Physical Principle and Technology (FPPT) model. It is partly based on the former models and adapted to our design context (cf. figure 3).

- 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 by an energetic loss such loss is also notified in the description of the Physical Principle. [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 the physical laws can be exported to any simulation software (such as matlab) to provide a first evaluation of the chosen physical principles and technologies.

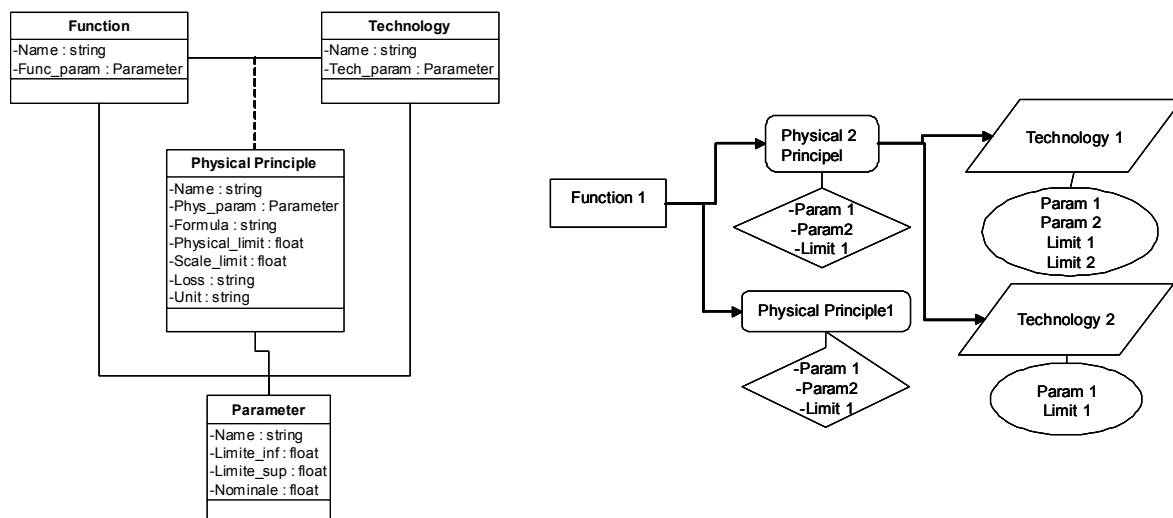


Figure 2. Model and instantiation of FPPT concepts

4 MDO AND ROBUSTNESS ANALYSIS

As explained previously (cf. figure 1), the decision making in the design process is based on a network of data coming from numerous viewpoints. As mentioned in [16], team strategies in collaborative decision making follow specific models compared to individual decision making. For collaborative systems, [16][17] highlights 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. As described in [18], four spaces¹ can be used to describe the data handled in the design process. Design consists then in the mapping between these different spaces. The main effort of engineering design is to build of the mapping between the functional requirements space {FRs} and the design parameters space {DPs}.

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 guaranty the level of performance that can be reached in use. The design should guaranty 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 identifying the following elements:

- 1) The design parameters {DPs} and the performances associated to the functional requirements {FRs},
- 2) The laws that link {DPs} and {FRs},
- 3) The “external” uncontrolled factors and their level of variability,
- 4) The variability on the design parameters and the link that exists between them and the process variables in the case of tolerances {PVs} (in the manufacturing viewpoint).

4.1 Metamodelling for alternatives analysis

Some laws are nevertheless often missing to link {DPs} to {FRs} and we then propose to build metamodels (also called subrogate models) such as described by [19]. Indeed, by using some experimental or numerical design of experiment [20], and by choosing an appropriate mathematical function, the relation between {DPs} and {FRs} can be identified [19], [21].

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.

¹ Customer (CI), Functional Requirement (FR), Design Parameter (DP) and Process Variable (PV) spaces.

4.2 MDO and robustness analysis

In addition to metamodelling, MDO (Multi Disciplinary Optimization) approach can then be useful, 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 [22] in order to build a global desirability function (Figure 3). 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.

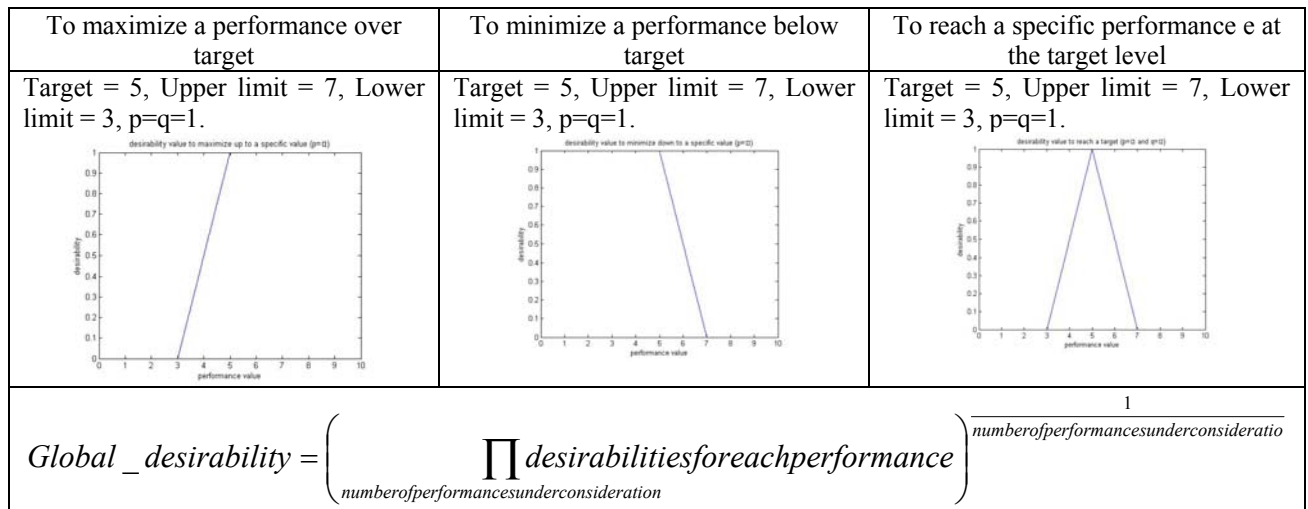


Figure 3. Few examples of desirability functions and global desirability

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 in [20], 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. 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”, this other will be called “free parameter”. Furthermore but 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.

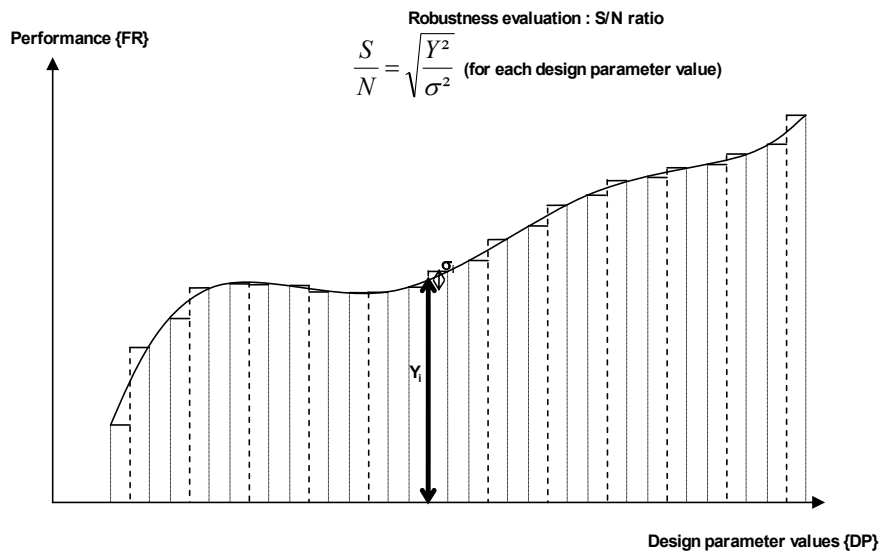


Figure 4. The principle of robustness evaluation

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 has as variables the set of “free” parameters. When it 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”[23]. One of the major difficulties is to propose relevant optimisation criteria, keeping in mind that all real problems are multi objective ones. Here finding the Pareto optimal frontier is very useful because a choice of one solution (one point on the Pareto frontier) can be made in collaboration activities.

5 CASE STUDY

5.1 Introduction

As it has been previously presented, the use of FPPT modelling enables to extract some parameters and their variability. With these parameters we are able to compute a product optimisation (MDO approach) and compute too, a robustness analysis. All these methods can be done over a lot of different products, from a simple object, a beam, to a more complicated product. In order to point up the methods and not the product we have choose a micro-switch.

[24] noticed a lack of MEMS design methods especially during the embodiment design. Switches are relatively simple systems and representative of MEMS and more generally micro-system. Furthermore, there already exists a huge variety of them, each MEMS design company bring their own products. This example is based on the switch presented in [25]. It is called a “beam switch” since a beam establish the contact via a deflection induced by actuating electrode. It uses an electrostatic strength (cf. figure 5). It’s a redesign of an existing concept. For the company it’s important to produce product where the level of performances are guaranty whatever the variability in manufacturing process, usage etc. In such design, company have to make some compromise with all the actor of the design process. We are going to show how FPPT modelling and robustness analysis can help this collaborative decision.

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 electrical 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.

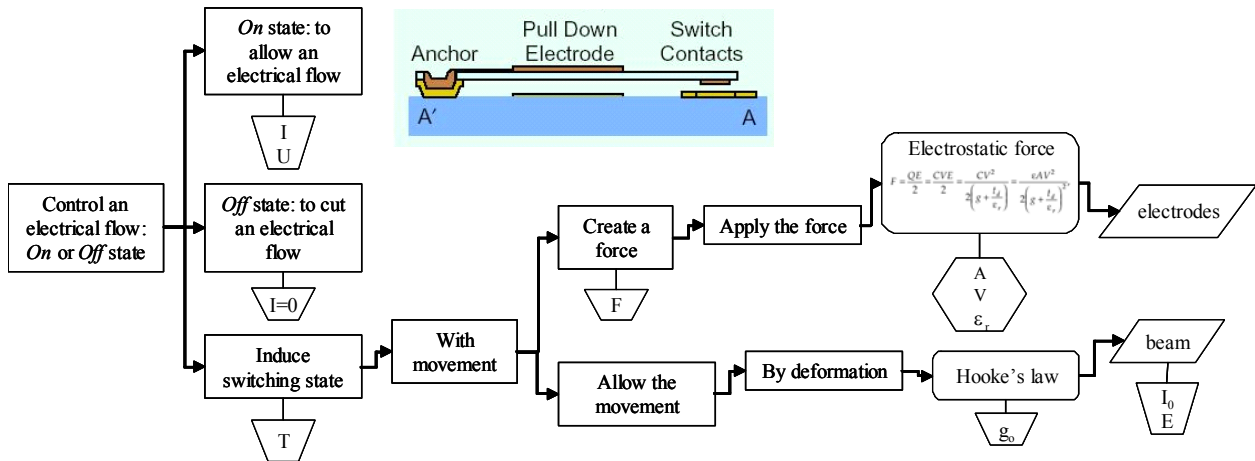


Figure 5. Part of the FPPT model of the “beam switch”

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 Interface model and representation for collaboration task

Thanks to the final FPPT model, a mapping to specific interface model based on “usage” skins (functional surfaces) and “usage” skeletons (trajectory of the energetic flows in the parts) can be defined (cf. figure 7). On a macro scale, the roughness of the skin can be defined but such notion does not exist, or can be hardly defined for the micro scale. The usage skeletons are also more described. They can be more or less constrained. Here, the unique skeleton which is strongly constraint is the bending beam. Its 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 bottom of Figure 7 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.

5.4 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 8). 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.

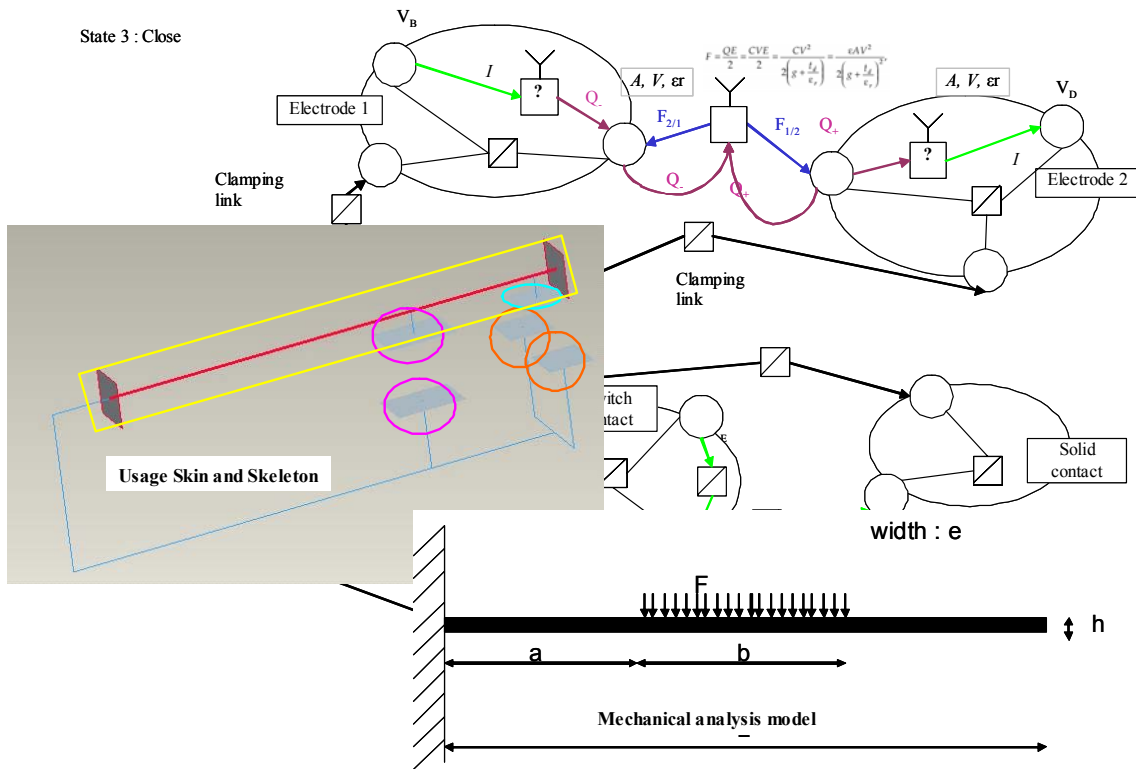


Figure 7. Interface models of the switch beam toward the emergence of the CAD model and the definition of design parameters and their variability

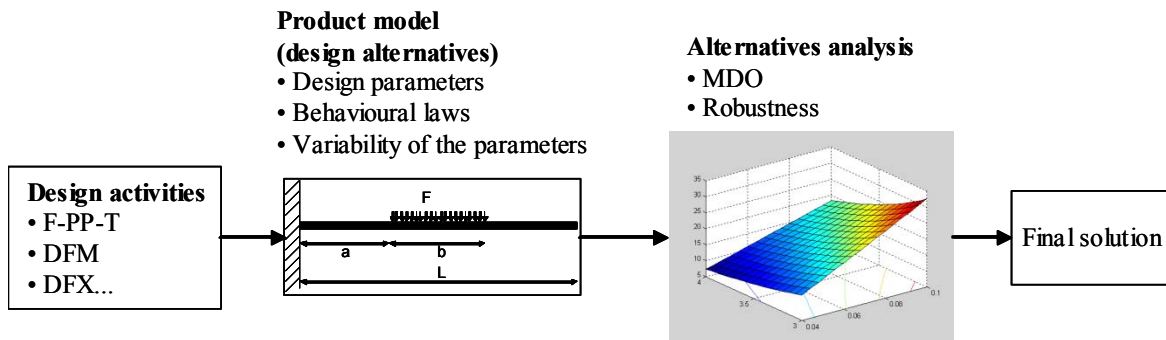


Figure 8. Representation of behavior analysis process

5.4.1 Optimisation Method

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:

$$\sigma_{\max} = \frac{6Fb(a + \frac{b}{2})}{eh^2} L \text{ and } F = \frac{\epsilon AV^2}{2(g + \frac{t_d}{\epsilon_r})^2}$$

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.

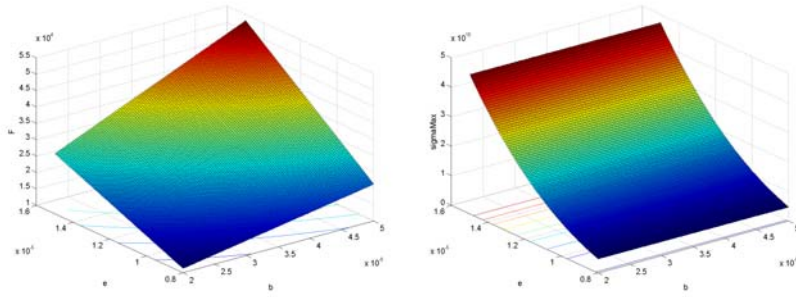


Figure 9. Response surface of σ_{max} max and F

Figure 9 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 (FRs) to be reached. So 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 to reach the performance.

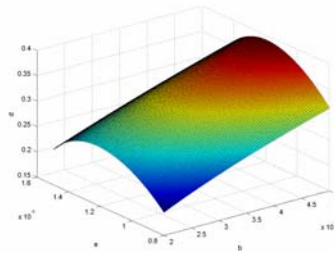


Figure 10. Desirability surface

Then the global desirability is added to the response surface (the colour in following figures). So it's possible to identify which solution is the best in order to respect the global design problem (minimize σ_{max} , maximize F). So the best design parameters values can be read for the optimization taking into account the two objectives (maximize F and minimize σ_{max}).

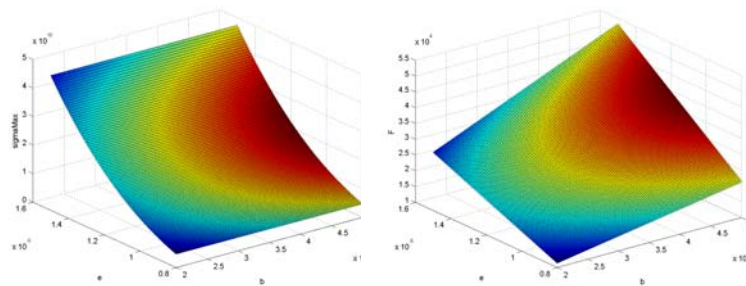


Figure 11. Response surface with desirability functions

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 principle is to build a Signal to Noise ratio, in order to maximize it. For the presented example, two Signal 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.

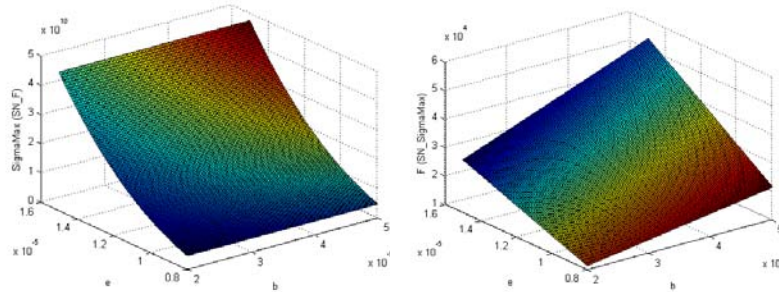


Figure 12. Response surface with S/N ratio

This example shows that the discussion for robustness seems to be complicated. Indeed, the robustness of the force F is where the strain is high; and the beam is robust for the strains in material when the F is low. We can view that these response surfaces with multi-objectives performance optimization and robustness is very useful for collaboration in design context. Because, all actors can be visualize the impact on product performances of the design parameters.

6 CONCLUSION AND RECOMMENDATION FOR FURTHER WORK

After a brief introduction of the proposed design framework, the paper presents methods and models to provides, during the product design process, design alternatives and associated parameters variability. Afterwards, robustness analysis 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 coupling specific modelling applications developed in C++ and Matlab.

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