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Experimental Plans and Intensive Numerical Aided Design

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ABSTRACT
This paper deals with new methods to optimize design and subsequent phases, notably in SMEs specialized in manufacturing. SMEs use numerical simulation to verify that the design meets the expectations of the specification, following the current traditional process: CAD model, simulation of its behavior, changes in the CAD model... This process suffers from a number of drawbacks: no overall multi-criteria vision, use of CAD software, by nature "constructive, not considering the overall objectives (even with integration of the parameters or with considering the downstream phases).
The research centre DINCCS led several projects, relying on industrial cases to consider more efficient approaches.
It is proposed to reverse this process by making intensive simulations, based on trade knowledge, before design itself. In order to plan the great number of simulations, automatically designed plan of experiences are used. We discuss the application of this approach to intensive simulations.
The stakes are crucial for SMEs, particularly manufacturing ones. Using numerical simulation (optimization) intensively, before setting the CAD model, they can get unexpected gains (mass, better use of the means of manufacture...).
The results show that the proposed approach is a very promising new way of computer aided design..
Keywords: design process, numerical optimization, intensive simulation

I. INTRODUCTION

We consider the design of a manufactured product, in any kind of firms, but particularly in SMEs. Collaborative numerical engineering is function of the situation and the strategy of the company, which can be : obligation or willingness to lower costs in a manufacturing outsourcing relationship, obligation or willingness to move from an outsourcing of manufacturing to a functional outsourcing, obligation or willingness to quickly respond to invitations to tender, willingness to share ways to progress, willingness to play a role of row 1 in subcontracting (Integrator), willingness to play a role of instructing party.

The design of a product must meet a specification that expresses, inter alia, the behavior that it must have in a given number of circumstances. SMEs, including subcontractors or OEMs are usually in one of the following cases:

- receipt of a CAD model for manufacturing: very often this model was not designed for the company's manufacturing processes and are therefore very difficult to adapt (in condition even the instructing party to accept the modifications).
- receipt of a functional specification, which describes in particular certain behaviors that must respect the product under certain circumstances. The design is therefore to achieve the whole design-manufacturing process (by the SMEs or in collaboration with the customer).

It is this second case that is the most interesting. The first case that we have already processed [1] can be taken into account by a collaborative work based on appropriate procedures. This is, as expressed above, not the most effective method, and it should be used only in cases where it is impossible to stand in the second case.

Anyway, our work (see section 3) confirm that it is essential to define methodologies for the use of numerical engineering software, for example, to facilitate the design, simulation, or manufacturing.

The simulation-optimization is going to be at the heart of the design [2], [3]. The CAD (at least in the general sense ascribed today) will be only a complementary tool certainly fundamental, especially to complete forms, but whose use should be guided by functions (parameters, design methodologies, tree of construction...) [4], [5].

The main elements which should be considered are:

-the relevance of the models used (especially for the simulation): this relevance is generally verified by physical tests.

-the taking into account of all parameters (physical quantities, materials, form...) design and behavior. It should be noted that certain behaviors are described in the specification, but that the SMEs should include their own behaviors, including manufacturing processes used (but not only).

The 'traditional' design on a CAD system is by nature constructive and non-synthetic. It is faced with the complexity of design, due to several factors:

- the number of free variables
- the number of objectives
- the number of constraints
- the non linearity.

No designer is able to take into account this complexity in most cases. Even using parameter design [6], which gives a certain flexibility of amendment, it is illusory to believe that it is possible to determine the parameters of the most suitable design, except in special cases, at the beginning of the use of the CAD.

The objective is thus to find 'better' design parameters for a given project by studying the influence of these parameters on the behavior of the product. The most common method is to evolve the value of these parameters and submit the model to an experiment (be it virtual simulation or whether by a physical test). It is of course inconceivable, except in special cases (discrete sizes with a relatively small space), to hope to test all possible cases.

It is therefore necessary to implement plans of experiments in determining and ordering tests to identify the effects of the parameters, with a synthetic approach (of the "General" settings to retail settings) on the response of the product.

II. A SYNTHETIC APPROACH OF DESIGN

Most SMEs usually follow a simple process of design using a CAD system.

2.1. DESIGN PROCESS EVOLUTION

The optimization of mechanical structures and parts is mainly, notably in SMEs, based on a « try / error » methodology [7] This approach lead to test prototypes whose design is based on the experience of the engineer.

So we find the classic stages of design sizing which are:

- The achievement of one or several CAD models from the experience of engineer which respect functional specifications, and the general environment of the structure.
- The implementation of various calculation models (static, vibration, dynamic, etc.) that assess the various design criteria of the structure.
- Several iterations to change the design in order to meet the specifications and optimize the structure.

This manual approach does not lead to an optimized model. The many iterations it can cause are costly and do not take into account the global problem (manufacturing ...)..

The disadvantages of the traditional design method can be partially addressed by the use of concepts as DFX (Design For X) : the acronym DFX (Design For X) is commonly used to refer to the work, studies or methodologies regarding the design taking into account a later phase of the life cycle of the product. The X can thus refer to manufacturing, recycling, assembly, maintenance [8], [9] ... However, this terminology, which covers a design methodology (each action design tries to take account of the constraints related to subsequent phases) is widely called into question by new means, including numerical simulation.

The project CAD4SIM [1] is dedicated to design for simulation, by setting procedures in CAD which ensure that the model is adapted to the finite element modeling and easily changeable for a parametric simulation. The CAD-CAE link became a bottleneck that requires special attention. Many works and research strive to improve this passage in focusing primarily on a good understanding of the continuous model from CAD for the finite element discretization. These works are therefore mainly applied when the CAD model is frozen and does not take into account the trade aspect (preparation of the CAD model for calculation, identifying functional area, ...).

DINCCS tries to set a general process managing the CAD-CAE link, in order to avoid discontinuities. This process is structured according to an architecture based on the work of the P4LM project [10] and associated rules of good practice to integrate knowledge related to geometry and context to prepare as soon as possible in design, best CAD model. The inductive approach of the research centre DINCCS helped inter alia to establish and test the processes and good practices on industrial cases. These rules were established as part of a thesis [Kwassi, University of Reims-Champagne-Ardenne, 2010, in french].

However, this approach runs into the multiplicity of X : well design to simulate, to manufacture, to maintain...

The numerical optimization becomes a particular activity of the numerical simulation [11]. On the basis of constraints and objectives, it allows to provide a number of solutions to a problem. The implemented algorithms give the user the opportunity to share innovative solutions. Research interest mainly to improve optimization algorithms or find new ones.

This branch is relatively recent. There is currently no work on the implementation of such tools in SMEs. They are used mainly by large groups developing their own methodologies. Offices have always faced the problem of continuous improvement of the performance of their structures to predict from the earliest stages of design forms and optimal structures of these.

One of the interests for the SMEs is to integrate their trade parameters, particularly those related to the manufacturing process, as soon as possible. The numerical simulation is an integral part of any process of industrial design. It allows to verify or validate certain concepts in a virtual manner.

As it is well known, the upstream phases of design often occupies 5% of the design process, but commit more than 75% of the overall cost of the product. Their influence is even greater when you consider that they can lead to deadlocks that are detected in the phases of manufacturing for example. To ensure that these decisions are the most appropriate possible, one can implement the design processes relying on methodologies, as discussed in this article, but also provide a human organization (project structure with experts according to trades...).

2.2. MODELLING THE TRADE KNOWLEDGE

The implementation of tools such as CAD, numerical simulation or optimization should be based on the modeling of trade knowledge. Indeed, SMEs are knowledgeable about products and processes they use (in manufacturing for example)

When we look at an optimization problem, it is important to take into account the trade. So it is suggested to use a formalized methodology to model and maintain the trade knowledge, respecting the following phases :

- detect the interesting knowledge (ontologies ...)
- extract it (human aspects ...)
- model it (structure, modeling ...)
- approve it (norms, homologation ...)
- open it (at the disposal of the users or the programs ....).

This a permanent process, the detection phase becoming a maintenance phase, verifying that the knowledge changes or not and so on ....

For example, considering the manufacture of the product (DFM : design For manufacturing), knowledge relates to :

- the characteristics of the product: its form, knowing that it may have a strong influence on the costs of manufacture according to processes ("easy" to make forms are not the same in NC machining and additive manufacturing...), material, tolerances... Generally, it is impossible to take into account all the knowledge.
- Manufacturing available resources : machines (machines for additive manufacturing, machine tools with numerical control, robot assembly, furnaces, injection moulding machines, means of transport...), tools, operators; etc. The design of products must, as far as possible, take account of these resources, or, at least, detect both easy and difficult to manufacture, the types of design that will require or not tools, those that involve outsourcing..
- Process-related characteristics: these characteristics, of course also strongly influence the design insofar as they impose characteristics of forms (for example, the spoils in forging).

Non-manufacturing technology factors are also taken into account, including the costs and deadlines.

So, it is interesting to define numerical optimization according to the trade to establish methodologies to use the best optimization algorithms depending on the circumstances (represented in the form of process methodologies). Trades identified in the work of DINCCS include stamping, forging, foundry, plastics and additive manufacturing.

It is then, by integrating trade knowledge, objectives and constraints, to simulate (optimize) to better design. Generally, regardless of the method used, the results of the simulation (optimization) is also an approximation which must be reworked by the designer. The framework is an action for better design

2.3. A SYNTHETIC APPROACH

Our research intends to define a global model which places the process module in the core of the DMU (Digital Mock-Up). Process module manages proceeds which modify the product. Our methodology is working on a hierarchical framework presented in [12, 13]. This framework allows a top-down approach by defining functions in a high abstraction level and refining them in a low abstraction level.

The 4 ‘P’s are defined according to

- Project module represents all the entities relating to the organization, the resources (human and equipment). Project module is defined in the Application Environment.
- Product module represents all information which characterizes product contents in a systematic way. A product has different representations according to the predefined abstraction levels.
- Proceed represents abstracted definitions related to a sequence of physical or virtual steps which lead to the modifications of the product.
- Process represents a succession of tasks whose implementation contributes to the modification of the product.

We then consider that to implement adapted CAE (Computer Aided Engineering) systems, we must take into account trade knowledge. It is by an integration of trade knowledge in the CAD (Computer Aided Design) system or in the specific developed software modules that we achieve our goal to improve the performance of the user. We also introduced the notion of Graphonumerical Numerical Parameter (GNP). The computer representation is ‘‘action_object (constraint/parameter)’’. A user can define a GNP like ‘‘create_hole(-through)(diameter)’’ which is the translation of ‘‘create a through hole with diameter’’ (a specific syntax has been developed for an intuitive use) [14]. This GNP is linked to a scenario which defines this GNP.

First, we study the different processes and define the ontology. Then we look at commercial tools used (or that could be used) and specific developments to do, according to our methodology and our tools.

Even if we study the overall numerical chain, to be sure not to attain a local optimum which does not contribute to a global optimum, we are mainly interested in well closed steps of the design process in which the trade knowledge modeling can lead to important gains in quality, cost or delay.

This kind of application, with a development effort between a few days and weeks, depending on the complexity of the product and data, produces significant benefits, including: quote achieving very quickly (virtually of instantaneously), reliability of choices (quote is validated by the entire chain, including simulation, and not just vaguely evaluated), if the contract is obtained, the design is "almost" already complete.

As a consequence, the formalization process (P4LM, ontology) is very interesting for the company, even if the software itself is not implemented. Many examples show that the design / manufacturing process, assumed perfectly controlled by the firm, is only very imperfectly known and often has different implementations based on operators or shadow areas. This preliminary study may make improvements, sometimes even without software development. It is important to remain attentive to the consistency of approach compared to the global numerical chain and developments to undergo software (changes in materials, new practices, standards...).

In order to work with small and medium sized firms, we have developed a collaborative tool (Adhoc Collaboration). Its description is not a purpose of this paper, but it is interesting to know that this collaborative tool (asynchronous and synchronous …) has been immediately adopted without any problem, even by very small firms.

III. INDUSTRIAL POINT VIEW

The competitiveness of sub-contractors is critical to the competitiveness of the whole chain. With some products that will be, as in automobile, outsourced to 80%, it becomes paramount. Whatever the context, the objectives of subcontractors are those of most companies in terms of quality, price and customer satisfaction, inevitable in such sectors as aeronautics and automotive. Indeed, these requirements are imposed by the prime contractors seeking more and more, for less and less expensive. In response, many SMEs have improved their productivity and obtained certifications, any collaboration sesame today. They are adapted to relocations, sometimes suggested (to put it mildly) solutions by the prime contractors for a portion of their production. It is far more difficult to change their design culture.

In order to, on the one hand show the value of our approach and, on the other hand, conduct an inductive research from real cases, about fifty industrial cases have been treated these past five years. About twenty among these fifty were concerned by an optimization (mass, delay ...). The other ones were interesting but not directly related to an improvement of the design, but were essentially concerned by the validation of the functional specification (without automatic modification of the design).

All the concerned firms are SMEs (or function as SMEs belonging to a group).

The main domains of applications belong to the design of mechanical parts, using traditional manufacturing methods (foundry, forging, NC ...) or new additive methods.

For each case, a complete study has been processed, following P4LM methodology, giving the firm the expected results. So, we base our reflexion on real industrial cases, not just experimental examples. Most of the cases are confidential, that is why we only present overall results.

It is very difficult to compare the gains, knowing that some, for example obtaining a contract, are not easily quantifiable.

We got some significant results, considering three cases :

- the integration in a specific tool of the numerical simulation and CAD system : for instance, in the study of a rear shelf of automobile, an operator can simulate a case in less than 10 minutes instead of 2 days before. In order to lead to the "best" (in fact a "good") design, it is mandatory to process about twenty or thirty experiments. Actually, the different choice of experiments are done by the operator himself. It can be imagined, it can be only done with automatically defined virtual experiments, as we propose in the next section. The other examples show earnings of the same order of magnitude in different fields (mechanics, building...). With a very low investment (some engineers days), the gain are important in terms of delay, but also quality of the design.
- the use of numerical optimization before design : All the processed cases lead to at least a gain in mass of 10% when mass was not the primary

parameter, to 40% when the gain in mass was a primary parameter.
- the specific use of trade knowledge in a dedicated system for instance, standardization of a manufacturing process (use by each of the same manufacturing method) allowed to obtain a constant quality during the production of these products. Earnings in term of implementation of the process: 15% in the realization of the production range (due to possibility to build on past experiences and from a standard range or range of a similar product). 40% in the costs quoting estimation.

It is clear that the methodology leads to significant gains in all cases treated. The lower earnings relate to gains of 10% in mass, the strongest gains are observed not only on weight gain (40%), but also on deadlines in design and manufacturing. We found no case which did not lead to a significant gain (mass, delay, quality ...).

The indirect gains (obtaining the contract, quality of the solution...) are impossible to quantify. In some cases, a comparison with competing products was made in terms of quality of the product. They all have shown a major competitive advantage.

These gains offer a considerable competitive advantage, either for the placing on the market of a new product, either for the quality and timeliness of a response to a call for tenders. They confirm experimental, often confidential, data obtained for example in the automotive field.

These General and experimental data in SMEs show the need to invest in design.

They are comparable to those obtained with more or less similar approaches (design guided by simulation) in the field of crash or aeronautics for example. In [15], [16], the authors claims that in results of their experiment, it is estimated that using simulation/design integration and knowledge management in configuration allows saving 50% time in the design process than classical approach. In [17] it is demonstrated that in the case of a stamping die (a typical case in our studies) topology optimization result has shown that 28.1% mass reduction was achieved with a slight difference of the die structure performance and blank forming quality. There are also other areas of the optimizations that do not only concern gains in mass. For example in the design of a golf club [18].

It is important to notice that the methodology also guarantees that the company will be able to manufacture in the best conditions.

IV. TOWARDS A NEW DESIGN PROCESS

4.1. INVERSE THE DESIGN PROCESS

`In general, follow a methodology of DFX type, leads to multi-criteria problems. Reverse the binding by simulating to better design seems relatively obvious. It comes then to generalize this approach by simulating the different significant life cycle phases of the product, including the 'real' phases, such as manufacturing or maintenance and "virtual", such as simulation of mechanical structure. This trend is present, even if it is often poorly formulated in LCA (life cycle analysis) in the heart of eco-design.

The multi-criteria problem aspect remains inherently inevitable. However, it seems more natural, and no doubt better to term, to proceed in this direction.

XFD is naturally easier to implement, as seen `above, to take into account the optimization of forms for example. However, LCA could rely on simulations, even (and especially) incomplete of the different phases. The fundamental difference with the optimization is that it is initiated from a correct definition of the problem. But, even without high-performance numerical simulation and taking into account the incompleteness of the problem (for instance because the incompleteness of the numerical model on which should build simulations), LCA is clearly categorized as XFD (analysis of the lifecycle to better design).

Certain phases (manufacturing, maintenance, etc) pose complicated problems to enter the framework of the XFD. This is a wide field of research to which we will return... Some approaches make it possible for SMEs to optimize their product, e.g. a topological simulation before the phase of CAD. However, these optimizations are typically mono objectives and can lead to disastrous results (for example by optimizing the mass of a piece, but by making its manufacture costly, if not impossible).

4.2. A FRAMEWOK TO OPTIMIZE DESIGN

The objective is to provide the designer all the elements (structured parameters, methodology of work...) which will enable to place him in the ideal conditions for a CAD model suitable for the verification of the specification of charges and internal stresses through :
- numerical simulation, using trade knowledge,
- intensive use of these numerical simulation guided by plans of experiments.

It would be totally unrealistic to expect fundamentally changing the operation of the CAD-simulation systems. The experimental objective given above ensures to treat cases in full-scale, allowing, on the one hand to verify that significant gains can be obtained on real industrial cases, and on the other hand, that the findings of these experiments could be the basis for a totally new design-simulation approach.

The project focuses on taking account of two aspects:
- the determination of the parameters required for the simulation based on physical tests: this is

typically to "match" a curve obtained by physical tests with the corresponding curve in the virtual model. This step is essential to ensure that trade knowledge (general and from experiments) are taken into account. In some cases (company known...), it is already modeled.

- a design based on the course of design of experiments that will validate all the parameters of the product whose the general process is as follows:

1. analysis of the specifications
2. Definition of main parameters (variables) (geometric, materials, physical testing,...) and constraints (including internal constraints as manufacturing processes, based on the knowledge...).
3. definition of experiment plans
4. (If useful) mono-objective topology optimization
5. Conduct of the design of experiments and return to settings
6. the results are the definition of parameters and a CAD methodology, which will allow to change the values of these parameters to check the characteristics of the product designed from the book loads and the internal constraints of the company. The product can then be specified precisely in CAD respecting the functions and constraints and being adaptable using the right parameters.

Finally, the geometric definition of the model of the product must rely on a Modeler sufficiently powerful and open to:

-allow easily to express constraints and freedoms (non-editable areas, free areas...).

-facilitate crossings and consistency between (CAD) geometric model and finite elements. The idealization of the model must be controlled (simplification of the model for calculation). A number of changes can be performed on the EF model and must be passed on to the CAD model.

-manage the incompleteness of the geometric definition (non defined free zones, variable settings,...).

This is to give the tools and methods to predict the behavior of the product and to make decisions.

We are therefore placed in the case of an optimization (search for the "best" product) that, except in very special cases, does not result in the best solution, but a set of solutions (Pareto front).

4.3. INTENSIVE NUMERICAL SIMULATION /OPTIMIZATION PROCESS

Innovation is therefore initially on the methodology of design by coupling innovative numerical design-simulation. It concerns all firms, including SMEs, and shows the interest of intensive simulation, on condition that it is integrated into a coherent design process giving them an opportunity to innovate the design of their products (new forms, new materials...), either to significantly optimize their products giving them a major competitive advantage.

First, it is an innovation in terms of usage of existing tools. Technological innovation which is underlying and which could be based on the results of the work of this project is of a very complex nature and application of means of considerable development. It indeed leads to put in question the current approach to design (CAD) and CAD-simulation coupling. This innovation is however addressed in this project, at the level of the geometric modeler in the heart of the design-simulation adaptations and at the level of the methodologies of use of tools (including CAD), who will seek to use as "intelligently" as possible the characteristics of current tools, generally underused. There is a paradox in CAD tools, which are not suitable for a real design, but whose abilities are generally used in a very partial way (15 to 20%).

The results of this experimental research will also serve as the basis for profound change in new generations of CAD-CAE systems. Indeed, proven methodologies and developed experimental algorithms (which will not claim to treat all cases) will give a true understanding of approaches which can be used as well in larger groups than in SMEs.

The objectives of the work are however realistic whereas a technological innovation that would be to completely recast the CAD and simulation software is out of reach. But it gives essential guidelines to understand what should be done. Future work will particularly meet this last point, which is essential to consider the new generations of software design-simulation-optimization taking into account actually loads and constraints business workbook.

V. CONCLUSION

SMEs, or even bigger firms, use numerical simulation very marginally. Often, they rely on one or two simulations for performance reasons, but mostly because it is very difficult to manually express design of experiments (planning of simulations to perform). Generally they examine only one or two parameters (for example a thickness) and do not take into account constraints associated with the manufacturing at the design stage.

Even in the case of unique parts (without Assembly or with simple assemblies), the method should allow unimaginable gains for SMEs.

The approach of our current work shows as well as the intensive use of numerical simulation is essential for SMEs, while one might think that they can settle for some simulations. Even for parts (without Assembly) designs or for new processes such as additive manufacturing, intensive simulation, with real-time answers, may prove to be very effective for businesses and lead to a profound change in operation, particularly in SMEs.

The gains that we were able to examine, without yet using new developments (computational geometry) and automatic design of experiments are very encouraging.

Without claim to lead to a standard, the project leads to a new design-simulation process that will be modeled by P4LM [10]. This new approach could also affect the relations of orders - subcontractors further strengthing the necessary cooperation from the earliest stages of design.

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