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SUPPORTING OPTIMIZATION OF COMPLEX PRODUCT DEVELOPMENT PROCESSES THROUGH SIMULATION: A CASE-STUDY OF THICK FILM HEATERS DEVELOPMENT PROCESSES

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ABSTRACT

This paper presents the work we carried out to investigate how to optimize the processes of development of complex products by incorporating finite elements analysis (FEA) and simulation as a design concepts analysis and optimization technique. As a case-study, the processes of development of thick film heater (TFH) subassemblies in a selected TFHs supplying company were explored. The principal challenges we dealt with were twofold, namely: (1) how to optimize the processes of development of TFH subassemblies through FEA and simulation, and (2) how to sync and optimize the TFHs supplying company's and the original equipment manufacturer's (OEM's) development processes. ANalysis SYStem (ANSYS) was used as the FEA and simulation application in this case-study. An empirical study on how some previously executed practical TFHs development processes unfolded was carried out. Practical TFHs design and optimization tasks were analyzed, and a suitable workflow scheme was subsequently created, and its feasibility investigated. The derived workflow scheme is generic in the sense that it accommodates a wide range of FEA and simulation applications, and its applicability is not confined to the processes of development of TFH subassemblies only. The significance of the reported work also lies in the realization of a systematic approach for selecting FEA and simulation application whilst taking into consideration technical, business, and social factors. The overall benefits for a company resorting to using the derived workflow scheme to optimize its product development process include competitive advantage over its competitors, high-quality products at a lower development cost, and more flexibility for its customers.

1. INTRODUCTION

Simulation is a powerful tool for analyzing and designing complex products. It enables the designers to test complex product design concepts without having to resort to using actual physical prototypes, thus significantly reducing the development effort, time, and costs. In the work described in this paper, we focused specifically on simulation in the form of finite elements analysis (FEA). FEA and simulation entail dividing a given domain into a set of simple domains dubbed finite elements—see e.g., [1] and [2]. FEA and simulation techniques are inheritably multidisciplinary and cross the boundaries of various disciplines including, for instance, mathematics, physics, engineering, and computer science. Typically, either (1) a continuous virtual model is divided into finite pieces widely known as 'elements', and laws of nature, e.g., laws of physics, are applied on a generic element, and the results are then recombined to represent the continuum, or (2) a differential equation representing the system is converted into a variational form, which is approximated by linear combinations of a finite set of trial functions.

The motivation to introduce simulation in the form of FEA into a product development process usually is to reduce the development time and therefore costs. The potential of virtual simulation tools in the form of FEA particularly in improving new product development (NPD) performance, including highly innovative product development, is widely acknowledged. FEA makes it possible to simulate the behavior of a product through numerical techniques and allows approximation of the solution of a problem without the need to develop a physical prototype and can thus save time, especially in NPD; and may also change the entire development process in a company—see, e.g., [3]. FEA can also be a platform to test new possibilities, to analyze cause-effect associations among various design parameters in virtual environments, and to improve the designers' insights on products that might otherwise not be directly observable. This might, for instance, trigger creation of new concepts or novel and more efficient ways of working.

FEA and simulation techniques have a wide range of applications, and enjoy extensive utilization in various areas including structural, thermal, and fluids analyses, and can support the designers in a wide range of complex product development assignments. In practice, FEA and simulation also typically serve as an aid in optimization in a wide range of applications. For instance, in the medical field, DeTolla et al. [4] used a FEA and simulation technique in optimizing implant design and placement of the implant into the bone, while using FEA and simulation in engineering product design and optimization is a standard practice, and FEA and simulation tools are nowadays incorporated in many Computer-Aided Design (CAD) systems—see e.g., [5]. There are, of course, other myriad application examples in the literature. It is, however, claimed in some literature that there has been very little transfer of knowledge and new technologies from research and development companies to industrial companies that use this knowledge or new technologies—see, e.g., [6] and [7]. In general terms, knowledge and new technologies transfer between the two is limited, collaboration is limited, and there is still a lack of relevant knowledge reaching the end-users [7]. How best to incorporate FEA and simulation into the product development process and how to eliminate uncertainty on investing in FEA and simulation through systematic selection of application are some of the challenges that some product developers often face. We dealt with these issues in our research, and we specifically focused our investigations on companies that supply parts or subassemblies to original equipment manufacturer's (OEM's). Therefore, we also partly attempted to address the challenge of syncing and optimizing the supplying company and the OEM's development processes.

The investigations specifically focused on: (1) studying the existing parts supplying company and OEM development processes with a view to identifying areas of improvement and incorporating FEA and simulation techniques into the workflows, (2) exploring how and where to incorporate FEA and simulation techniques into the workflows, and (3) redesigning the workflows and incorporating FEA and simulation techniques into the development process. We investigated how to incorporate finite elements simulation to enable effective analysis and optimization of the designs of thick film heater (TFH) subassemblies (see Figure 1) of consumer products in a case-study company that supplies these sub-assemblies to OEMs—see also [8]. The development processes of the TFH assembly supplying company and OEMs are highly intertwined and interdependent (see Figure 2). What was specifically needed was an efficient workflow scheme for developing TFH subassemblies—which take into account market, user, technology, and other aspects of consumer product development. We used TFH subassemblies as case-study products to explore how best to incorporate FEA and simulation as techniques for enabling effective analysis and optimization of designs of complex products. New TFH design concepts were modeled and analyzed by using FEA and simulation techniques to determine their behaviors under various operating conditions, and this allowed for early refinement of concepts prior to realization, when changes are typically inexpensive. It has been demonstrated that FEA and simulation techniques can be incorporated into TFH development workflows to support analysis of TFH design concepts, thereby saving time and money by reducing the number of prototypes required. Apart from new TFH concepts, FEA and simulation techniques can also be used in analyzing existing malfunctioning TFHs or TFHs that require improvements, and in this way quick reengineering or modifications can be done at a reduced cost.

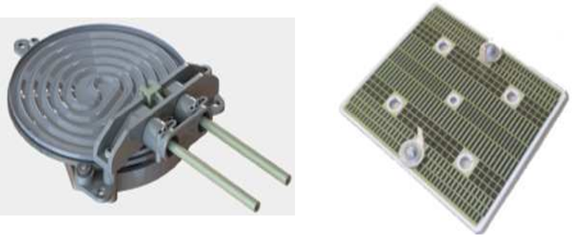

Figure 1 Examples of TFHs subassemblies of consumer products

We present the work we carried out to address the challenges described above and to answer the research questions stated in the subsequent Section. The paper is structured as follows. We first analyze the research problem and challenges, and describe our research approach in the following Section. We then describe the investigations and present the results, i.e., we describe the case studies we conducted to explore the feasibility of introducing FEA and simulation procedures in the case-study company, discuss how FEA and

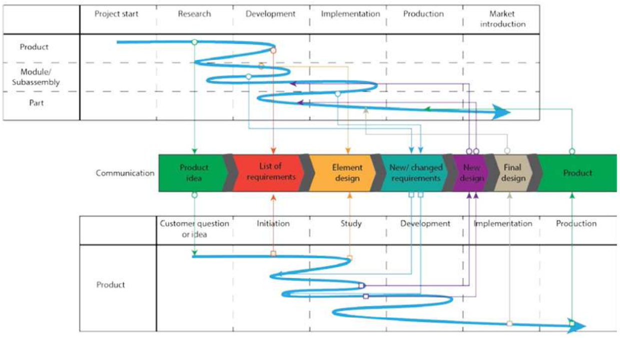

Figure 2 An example of coupled part supplying company and OEM development processes

simulation can best be incorporated into the case-study company's TFH concept development workflows, and then present the workflow scheme which incorporates FEA and simulation. Afterward, we present the approach we devised to support objective and systematic selection of FEA and simulation applications. We finally briefly discuss the research results and present the broad general conclusions of our findings.

2. PROBLEM DEFINITION AND RESEARCH APPROACH

It is a common practice to develop some products collaboratively by involving multiple companies to develop and supply components or sub-assemblies of the products. In other words, the components or subassemblies are co-designed with the OEMs. One of the principal challenges here is how to come up with an efficient and structured workflow for developing the product. As an attempt to address this challenge, investigations have been conducted at a company in which TFH sub-subassemblies are co-designed with OEMs without following a structured workflow which incorporates FEA and simulation techniques. In developing TFH subassemblies, the case-study company typically takes the specifications from its customers (i.e., OEMs) as they are, and uses highly iterative ad hoc manual analysis procedures to develop and analyze TFH subassembly concepts. That is, for each TFH development project, the end-product specifications are formulated first by the clients (i.e., OEMs). Then, a number of specific requirement specifications such as power requirements and appearance or forms are formulated, and these, along with factors such as manufacturability (i.e., manufacturing process) and cost, are considered as the TFH design concepts development processes progress. This typically entails going through a number of physical prototyping and testing cycles.

Although in many cases this approach has worked well, some of the solutions have not been optimal, the development processes have often been excessively iterative and lengthy, and there have been some cases in which some products had to be taken off from the market. The precise reason is difficult to explain, but inefficient workflow and lack of thorough TFH concepts analysis have probably contributed to this. As for the case-study company, the problem lies particularly in the processes of development of the TFH subassemblies, which presently entails using physical prototyping techniques to analyze and test design concepts. Also, a dearth of in depth understanding of the needs of the final products and those of the OEM in the case-study company often causes the TFH subassemblies to be structurally designed and optimized to meet only a subset of the requirements cataloged by the client (i.e., OEMs) without considering the global use and interactions of the end-product. Overall, the current practice is somewhat flawed and the eventual consequences include longer TFHs development times and higher development costs.

Therefore, apparently the case-study company needed a structured and efficient workflow for developing TFH subassemblies for consumer products produced by various OEMs. This workflow should embed and address all aspects of the TFHs and should help to optimize the processes of development of TFH subassemblies. One of the main challenges in devising a suitable workflow scheme was how to ensure that the scheme would help the developers to take into consideration various aspects, i.e., market aspects—identifying, understanding, and grouping different types of market-oriented aspects which may influence the processes of development of TFH subassemblies; user aspects— identifying the target group of the end-product and how their expectations, e.g., regarding the TFH subassemblies, namely, size, forms, heating rate, power consumptions, and so forth should be addressed within the TFH development interval; and technological aspects—studying the technologies and approaches presently used in developing TFH subassemblies and identifying new potential technologies and approaches and the roles that they may play in optimized TFH development processes. A workflow scheme that meets the above-described needs was lacking in the case-study industry. One of the principal tasks was therefore to develop a suitable structured and efficient workflow, and using practical case-study TFH subassembly development assignments to verify its applicability.

In short, we attempted to answer two principal questions in the research reported in this paper, namely, (1) how can the process of development of TFH be optimized through FEA and simulation, and how to efficiently incorporate FEA and simulation and to sync the supplying company and OEMs development operations? and (2) how to objectively and systematically select a suitable FEA and simulation application? We selected a case-study company, which designs and manufactures TFHs for consumer products producing OEMs. Apparently this case-study company has not incorporated FEA and simulation procedures in their workflow to date despite the fact that FEA and simulation techniques were developed several decades ago and have been adopted and used by some practitioners for quite some time. We therefore attempted also to answer some specific research questions such as why is it that the case-study company has not incorporated FEA and simulation procedures into their workflows despite the availability of these techniques for quite some time? How analysis and testing is conducted in case-study company? What is analyzed or evaluated in TFHs design intervals and how this is accomplished? What techniques are presently used, and how effective are they? Which features and characteristics differentiate or liken the case-study company to other TFH supplying companies? Which aspects of FEA and simulation are generic and applicable to TFHs? In this work, the term 'workflow' means a set of relationships, associations, or mappings between the development activities in a TFH development project, from the beginning to the end of the development process. The development activities are related by different types of relations, and may be triggered by external events or by other activities. The eventual deliverable of the reported research was a verified structured workflow scheme, which specifies a set of relationships between the development

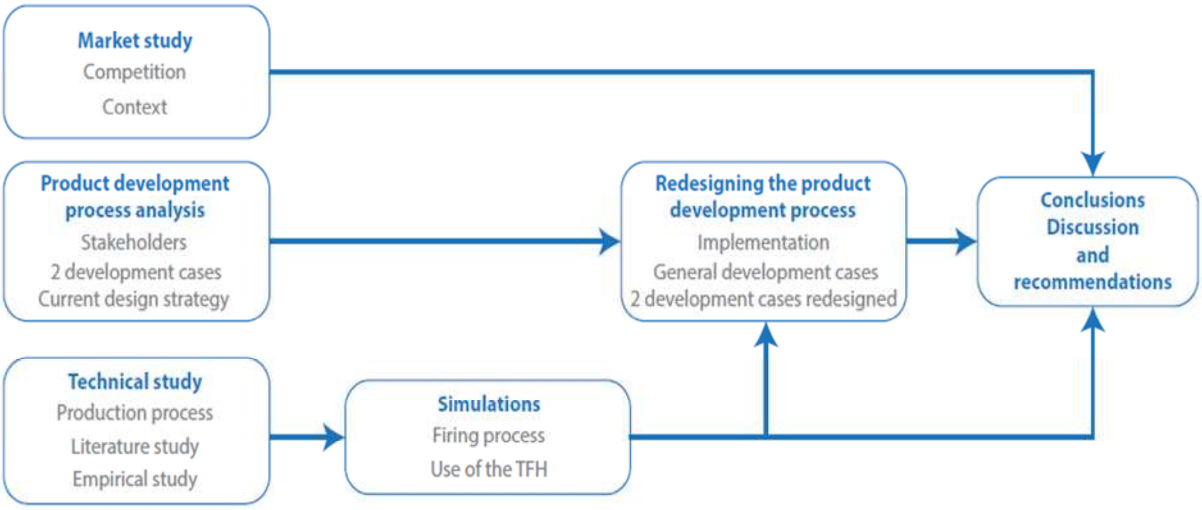

Figure 3 The research approach

activities of TFH subassemblies development project. The significance of this work lies in (1) creation of an adaptable FEA and simulation-based workflow scheme, which provides a systematic way of developing and analyzing TFH concepts, and (2) in developing a systematic approach for selecting FEA and simulations application whilst taking into consideration technical, business, and social factors.

Figure 3 depicts the approach we followed in the research presented in this paper. Market study, process analysis, and technical study helped us to formulate the requirements for the workflow scheme. The existing consumer products that use TFH subassemblies were studied and possible new TFH technologies were also investigated with a view to understanding the prevailing TFH subassemblies development processes; and based on this, a suitable workflow concept was conceptualized. Real-world FEA and simulations were also carried out to explore and to familiarize with what it takes to perform actual FEA and simulation for TFHs, and to experiment on how to incorporate FEA and simulation into TFH development processes. The task of redesigning the TFH development process entailed using the generated requirements as the basis for developing a concept workflow scheme. FEA and simulation case studies were also carried out to demonstrate the potential and the applicability of these techniques in the framework of the proposed workflow scheme. The idea was to uncover and to address the problems that might be encountered in using the workflow scheme.

3. INVESTIGATIONS AND RESULTS

In this Section, we describe the investigations we carried out and present the results of the research. We first introduce the case-study company and describe its TFH development processes and practices in the following Subsection.

3.1. The Case-Study Company

The case-study company was founded eight decades ago. It specializes in producing heating element subassemblies for commercial products. It specifically uses porcelain enameling techniques in the heating elements of consumer and industrial products. The case-study company distinguishes itself by delivering customized entire heating element subassemblies for consumer products known as thick film heaters —abbreviated as TFHs in this paper. TFHs are used in many domestic appliances, including for instance, in public coffee machines, domestic water boilers, and steam ovens. In this case-study company, the customers (who essentially are the OEMs of products such as coffee machines, domestic water boilers, and steam ovens) are often actively engaged in the processes of designing TFH subassemblies. Structurally, these TFHs are somewhat complex subassemblies, typically consisting of stainless steel plates, porcelain enamel layers, and printed electrical circuits (i.e., the heating elements) protected by a glass layer placed over the circuit. The design requirements specification for TFH subassemblies often vary, and the requirements are defined by considering the consumer product on which the subassembly will eventually be installed on. Such requirements state or specify, for instance, the required structural appearance of the TFH subassembly, the heating rate, and the target cost. Other specific requirements such as applicable standards or brand image of the OEM company in question are also taken into consideration in designing TFH subassemblies. TFHs are generally more expensive than the competing heating technologies, but offer benefits that other heating solutions cannot, such as compact size and high energy efficiency. These benefits allow designers of consumer goods, e.g., to design more energy efficient products.

The case-study company's current development process consists of four principal stages, which are: initiation, study

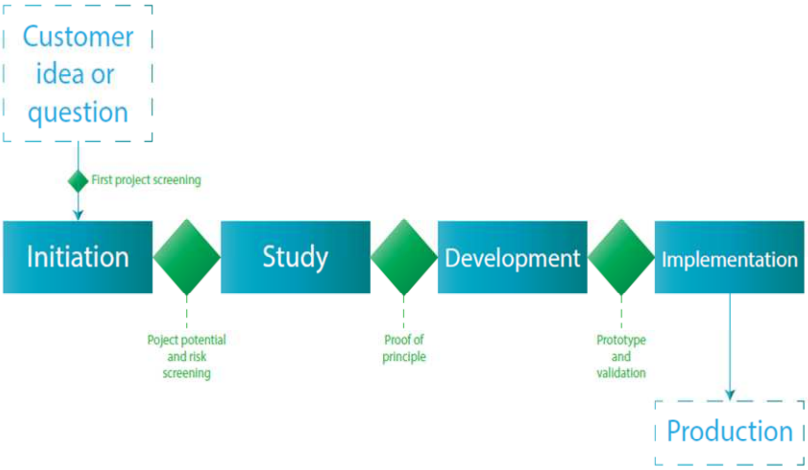

Figure 4 The existing process of development of TFH at the case-study company

(i.e., exploration), development, and implementation (see Figure 4). Typically, several design iterations (which entail using physical prototyping and testing) are needed, especially during the study and development stages in order to obtain an acceptable design concept. Overall, the current process of development of TFHs at the case-study company requires extensive physical prototyping and testing, and involves numerous iterations, which consume valuable time and resources. The case-study company wants to improve the current TFH development process by reducing the number of iterations, thereby shortening the projects execution durations. One of the key requirements in the consumer goods market is shortening of the product development duration. OEMs are typically expected to shorten the time needed to introduce new products into the markets. The case-study company, as a supplier of TFHs to these OEMs can contribute to this by shortening its own development time, i.e., shortening the time required to deliver new TFHs to an OEM. What is needed is an improved workflow, with a reduced number of physical prototyping and testing cycles. The sought after workflow scheme should allow the case-study company to optimize the processes of development of TFH subassemblies, e.g., to reduce the number of manual tasks, or help to avoid the unnecessary steps or processes.

3.2. Exploration of the Possibility of Incorporating FEA and Simulation into the Case-study Company's TFH Subassemblies Development Processes

An analysis of the case-study company's TFH development process was conducted, and based on this, measures to decrease the TFH subassembly development time were proposed. Different technical possibilities have been analyzed to determine in what ways the TFHs development processes and workflows can be improved. It became apparent that the most suited form of simulation for case-study company is finite element analysis (FEA)—a numerical method of approximating the behavior of a product in which a digital or CAD model of a part or product is split into a number of finite elements (also known as meshes), from which various design aspects such as stress, deformation, and temperature may be analyzed through computation of values based on the boundary conditions that work on the part or product in question. Two principal factors, namely (1) the number of iterations, and (2) the extent of repetition of the activity, were considered when deciding on whether or not to incorporate FEA and simulation techniques at certain points in the existing workflow. For this case-study company, it was determined that the interval at which the application of FEA and simulation techniques can significantly contribute to optimization of the TFH development process is the very early stages of the design process where heat spread, stress, deformation, and different geometric configuration of the TFH subassemblies can be tested without using physical prototypes, and also in the later stages of the design process where, e.g., the reliability of designed TFH subassemblies can be tested. The points and stages of the case-study company's TFHs design processes where we recommend FEA and simulation procedures to be incorporated are indicated in Figure 5.

Case studies were conducted to explore the applicability of FEA and simulation techniques to TFHs development processes. This involved using ANSYS to analyze deformation and stress in TFHs. The case FEA and simulation analyses passed through three major phases, which are: *pre-processing*, in which finite element meshes were developed by dividing the TFH geometry into subdomains for mathematical analysis—the material properties and boundary conditions were applied accordingly; *solving*, in which the FEA and simulation application derived the governing matrix equations and solved them, and *post-processing*, in which the validity of the solutions was explored—i.e., the values of primary quantities such as deformation and stresses were examined. A number of square test TFH plates made up of porcelain enamel, metals, and bonds between the two materials (i.e., between the porcelain enamel material and metal) were analyzed and simulated by using FEA method, and some meaningful results emerged (see Appendix 1). For instance, the stress and deformation, caused by the difference in thermal expansion of the porcelain enamel and metal was accurately determined. The stress analysis also showed that the porcelain enamel is most likely to fail during usage at the edges of the plates. The thin layered structure of the TFH used in case studies required large amounts of elements and high performance computing equipment was needed to run simulations. Overall, the study showed that the FEA and simulation techniques work well for TFHs and can be assimilated into the existing case-study company's workflow.

3.3. The Proposed Workflow Scheme

A new TFH development workflow scheme for the case-study company, which incorporates FEA and simulation techniques is proposed (Figure 5). It has been developed by taking into consideration the findings of the investigations and the recommendations presented and discussed in the previous Sections. Figure 4 shows the existing process of development of TFH at the case-study company. The stages of the TFH development process at which the manual engineering analysis activities need to be substituted by FEA and simulation procedures have been identified, and are shown in Figure 5. The *study* stage and the beginning of the *development* stage have been identified as the areas which TFH design concepts can efficiently be analyzed by using FEA and simulation techniques. The dimensions and power requirements of the TFHs are usually already set at the needs and requirements analysis stage, so early explorations of the feasibility of the concepts can be conducted. And any potential need for changes in the TFH design, e.g., a need for different design parameters, for instance, power requirement specifications or alternative geometry or form can be identified early in the development process by using FEA and simulation techniques and subsequently recommended to the OEM. The *study stage* and the *development stage* have been identified as the most iterative stages, where iterative physical prototyping and tests are conducted to attain proof of concepts or principles. One of the goals of the research was to determine to what extent the activities in these stages are iterative and if the existing approaches can be swapped with FEA and simulation techniques. Because of the iterative nature of the activities, there was an opportunity to optimize processes in these two stages to save valuable resources (i.e., time and money) through the application of FEA and simulation techniques. Ideally, the entire TFH can be prototyped virtually and tested under varying and unusual operating conditions through FEA and simulation. This can broaden the designers' insights into the TFHs behavior and performance, and helps to reduce the number of physical prototyping and testing iterations. It should be noted, however, that, in the end, a validation process involving physical prototyping and testing needs be conducted after FEA and simulation—because apparently not all physical prototyping and testing can be avoided. The validation step is intended to help the designers to determine the accuracy of the model used, and typically entails experimenting with prototypes and comparing the outcomes with the simulation results. What can be achieved essentially is a reduced number of physical prototyping and testing iterations. Obviously the final TFH design concepts should also always be prototyped and tested again, before sending it to the OEM for final testing on the product.

Knowledgebase (see Figure 5) plays a central role in the proposed workflow. This knowledgebase consists of experimental knowledge, heuristics, and scientific data related to the processes of development of TFHs. The knowledge in the knowledgebase originates from various sources, for instance, includes data mined (i.e., information gathered) from compiled simulation results of various previous TFH development projects, or from observed materials behavior. The knowledgebase grows continuously as new TFH development projects are executed—i.e., as new knowledge and insights continue to evolve. This knowledgebase can be used differently for problem-solving in TFH development processes; namely, through deduction (i.e., applying knowledge held in a general form directly, e.g., laws of physics, etc.), and/or through induction (i.e., applying new concepts and laws developed through experimentations). In practice, these two problem solving strategies should both be used by the designers in developing new TFHs. This knowledge helps the designers, e.g., to discover relations between design parameters and to acquire technical insights, e.g., into the functionality of the products or materials. The knowledgebase can be maintained by putting in place a structural method for acquiring and storing FEA and simulation results obtained from various TFH development projects. In this way, the knowledge in the company can continuously increase, and this would ultimately translate or contribute to improvement of TFHs. Overall, it can

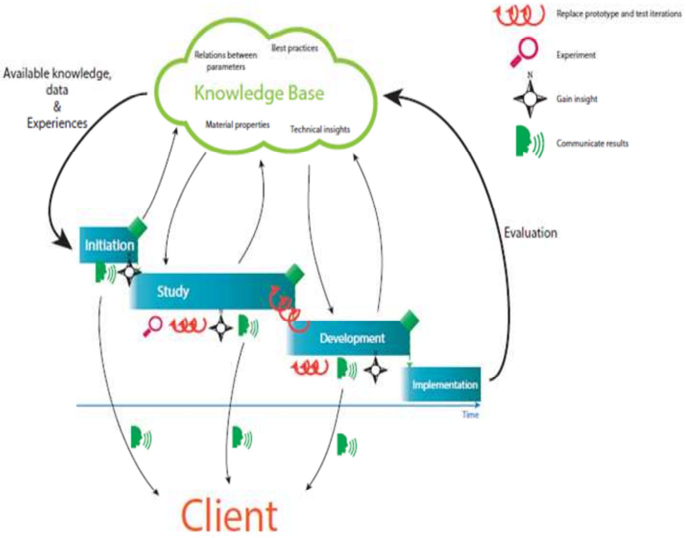

Figure 5 The proposed TFHs development workflow

be argued that FEA and simulation essentially compliment both the deduction and inductive problem solving strategy. And the incorporation of FEA and simulation techniques into the TFHs development processes is considered to be an efficient way of problem-solving which reduces design iterations and the amount of physical prototype-based experimentations.

In general terms, in order to introduce FEA and simulation technique into a TFH development process, considerations must be given to the following: (1) *economy*: from a financial or an economic point of view, the incorporation of FEA and simulation procedure into the TFH development process would only be useful if the costs of investing in and conducting FEA and simulation are lower than the costs of making actual physical prototypes and carrying out comparable tests. It was, however, practically difficult to determine how much savings can be achieved by replacing actual physical prototypes and tests with FEA and simulation; and (2) *technical knowledge*: in order to be able to conduct FEA and simulation, knowledge of engineering principles, mathematics, physics, engineering design, computer science and/or of materials science is often required. Without this knowledge, it is difficult for a practitioner to set up and successfully run FEA and simulation with a view to analyzing a TFH design concept. In some cases, for instance, essential materials properties may not always be known precisely, e.g., sometimes only a range of values is known, and it sometimes requires the practitioner to test materials in order to obtain the exact values. Apart from these two key considerations, in using the proposed workflow, it is also noteworthy that the designer should be able to identify the parameters, e.g., dimensional parameters such as the thickness of the part or any other dimension of interest that they can experiment with. Attention should also be paid to the need for having sufficient computing power in place to effectively run a simulation—typically virtual models of parts need to be broken down into a large number of finite elements which require significant computing power.

3.4. Application of the Proposed Workflow Scheme

Figure 6 illustrates how the proposed workflow scheme, which incorporates FEA and simulation techniques, can be implemented at the case-study company. A real-world assignment on development of a TFH for a steamer unit was used as an application case-study to demonstrate the applicability of the proposed workflow scheme. As shown in Figure 6, during the development of the TFH unit, several iterations were needed in a number of stages—i.e., at the points labelled 1, 2, 3, and 4, to achieve a design concept that met the requirements set jointly by the OEM and the case-study company. Apart from the preliminary explorations at the study stage—which should obviously incorporate FEA and simulation, these points were also the candidate junctures to slot in FEA and simulation procedures. Point 1 at the 'study' phase—see Figure 6, was the first point where FEA and simulation could have improved the TFH steamer unit development process. The initial design requirements originated from both the OEM and the case-study company, and some of them were derived from previous experiences in similar projects. With an initial FEA and simulation, the effects of the geometry and shape on the reliability of the TFH could be investigated to attain the understanding required in the subsequent development stages, and to establish whether there is the need to focus the analysis on certain critical points or regions of the TFH. As for cost savings, it is difficult to state precisely how much costs can be saved by introducing FEA and simulation to support exploratory design at this stage. Activities at points 2, 3 and 4, i.e., at the 'design and development intervals'—see Figure 6 were also highly iterative and inheritably tremendously routine. During the analysis of TFH concepts, numerous problems emerged, e.g., dry running conditions caused porcelain enamel material to crack, and as a result, multiple iterations were required to achieve an optimum design concept. The iterative manual activities or operations can obviously be replaced with FEA and simulation procedures. Several parameters such as porcelain enamel composition,

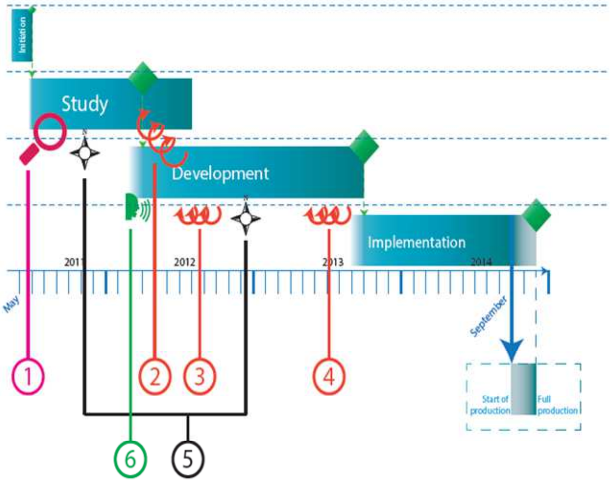

Figure 6 Using the proposed workflow in a TFH development project at the case-study company

heating track design, and material thickness, which typically require extensive prototyping and testing, can be experimented with by using FEA and simulation tools to find an optimal design solution. The experimentation may not lead to the identification of combination of parameters that would work, but rather, e.g., to the identification of a general operating temperature range that could be controlled and in which the TFH would not fail. As expected, it was established that the traditional manual procedures delay the projects—typically for a couple of months—and were highly labor intensity. Substitution of manual design concepts analysis iterations—which typically require a number of physical prototypes to validate the results, with computer-based FEA and simulation would save significant amount of time and resources. When FEA and simulation results suggest that the design concept fulfils the requirements and the designed TFH can operate satisfactorily in all known conditions, a final validation must be conducted, and as mentioned earlier, this may entail building a physical prototype and testing. FEA and simulation techniques can also be incorporated at Point 5—see Figure 6, to enable the designers gain insights, e.g., into the investment that should be made for the project or even for future projects. For instance, feasibility of different shapes, configurations of TFH, material thicknesses, or heating track designs may be explored to gain insights, e.g., into the performance and costs. And FEA and simulation techniques can also be incorporated into the workflow at Point 6—see Figure 6—to support the designers to demonstrate technical aspects of the TFH and to present design concepts to the client and other stakeholders.

3.5. Limitations

Despite the benefits described above, it is also imperative to recognize the limitations of FEA and simulation techniques. Costs of investing in the resources required for FEA and simulation are still considerably very high. Although there has been a substantial drop in the prices of commercial FEA and simulation applications and of the required computational hardware, introducing FEA and simulation techniques in the company's workflow still requires a significant investment. Furthermore, it has been shown that FEA and simulation can reduce the number of physical prototyping and testing cycles, but cannot entirely substitute them.

It is also noteworthy to point out that lack of proficiency and experience can adversely affect the outcome of FEA and simulation. For instance, an inexperienced user can unknowingly deliver incorrect FEA and simulation results. The danger here is that expensive decisions can be based upon such results. Overall, FEA and simulation applications are highly demanding tools. The users must be proficient in the relevant scientific areas, which typically include finite element method, elasticity, fluids, mathematics, and computer science. It is usually difficult for a new user to be productive in a reasonable amount of time without adequate training in FEA and simulation, and in a range of relevant scientific fields. Even the selection of a FEA and simulation technique cannot be made in a vacuum, i.e., without proper understanding of the technique and without adequate background knowledge—namely, one cannot sensibly select an application without having the basic knowledge of FEA and simulation techniques and a good understanding of the physical and mathematical basis behind these techniques. It is normally required to dedicate time up front for training or for self-help education.

4. SELECTION OF A FEA AND SIMULATION APPLICATION

There are many types of FEA and simulation applications around with various specifications. Choosing the FEA and simulation application to use is an important challenge that we also attempted to address in the research reported in this paper. The problem we dealt with here can be summarized as follows. Due to the state of influx of FEA and simulation applications, picking one application in preference to the others, without carrying out an in-depth systematic needs analysis or using suitable guidelines can sometimes be risky. A FEA and simulation application can be a major investment with considerably high degree of uncertainty in some companies. Therefore, there is a real need for a systematic method and clear guidelines, especially at the strategic level, for ensuring that a suitable FEA and simulation application is selected. Such a method should be sufficiently objective and based on specific formal or tailor-made criteria, and should guide companies or individuals to carry out thorough examination of available FEA and simulation applications rather than making hasty choices based only on highly visible attributes such as documentations, or look and feel.

Several decision-making models and selection methods are available. These include, for instance, decision-making models for selection of advanced technology—see, e.g., [9]; for selection of machines or equipment—see, e.g., [10]; for selection of system components—see, e.g., [11], and so forth. Most of the existing approaches involve techniques such as modeling a problem into multiple criteria scenario targeting specific applications or technologies; multi-objective integer programming [12]; subjective ranking; or comparing the interdependence between two or more technologies [13]. These approaches can be adapted and used in many selection assignments but none of them square precisely with the challenge of selecting a FEA and simulation technique. It is also important to note that despite the availability of formal models or methods, some literature claims that most of the selection and acquisition decisions are often ultimately made by high ranking decision makers, who normally rely largely on their knowledge, experiences, and personal judgments and biases—see e.g., [11]. We therefore propose a systematic approach for selection of a FEA and simulation application (Figure 7). Some elements of this approach are rooted in some of the above-mentioned approaches, and in the approaches we previously applied in selecting 3-D visualization devices—see [14], and in selecting computer-aided design and manufacturing systems—see [15].

According to the proposed systematic selection approach, several factors, including personal preferences as well as the application's functionality, must be considered in choosing a FEA and simulation application. The proposed selection approach requires users to take into consideration various factors, which we broadly categorized as, *technological factors* (i.e., functionality, usability, reliability, maintainability, flexibility, etc.), *strategic factors* (i.e., financial, infrastructural, and market positions of the company, etc.), and *social factors* (i.e., environmental aspects, personnel policies, etc.)—see Figure 7. Figure 7 also provides the details of the activities involved in the selection of FEA and simulation applications. In principle, this scheme guides users to first conduct feasibility study and needs analysis, and then to formulate criteria, which are subsequently used as the basis for evaluation. A feasibility study must include a multi-dimensional review and analysis of the existing alternative FEA and simulation applications; and should extend to studying various aspects of the new investment and of the FEA and simulation applications such as the economics of the new investment (i.e. whether the company can afford to invest in a FEA and simulation application), technical capability (i.e. whether an application that can fulfill requirements exists, whether the company has enough experience in using that application, etc.), schedule (e.g. whether the new investment interferes with normal business operations, etc.), organizational (e.g. whether the new FEA and simulation approach has the support of the management of the company, whether it brings an excessive change, whether the company is changing too rapidly to absorb it, etc.), cultural and societal (i.e., impact on the local and general culture in the company, environmental factors, etc.), market (i.e., analysis of market forces that could affect success of investment) and legal (i.e., making thorough legal scrutiny).

Furthermore, the proposed approach requires that the need for FEA and simulation application should be thoroughly analyzed. This must involve scrutinizing the major objectives of investing in FEA and simulation application and exploring potential problems and possible future changes. The common and easiest ways of gathering opinions and obtaining needs include interviewing the stakeholders, conducting focus group research, and carrying out questionnaire surveys. The proposed approach also requires that a comprehensive evaluation must be carried out before purchase. The consequences of investing in new technology must be investigated and the benefits and drawbacks of the envisaged investment must also be assessed thoroughly. Human aspects such as possible effects on the established work arrangements and other possible social implications of the change must also be investigated. After feasibility study, needs analysis, and evaluation; the subsequent activities shown in Figure 7 can then be carried out. Specification requirements must then be compiled based on the results of feasibility study and needs analysis, and formal and more specific selection criteria formulated. Then, a thorough review and analysis of the affordances of competing technologies must be carried out and the appropriate FEA and simulation application ultimately selected based on the established selection criteria.

As for hardware, obviously where to run the FEA and simulation application depends on the type of engineering analyses expected to be performed. Typically, FEA and simulation tasks require fast computational tools in order to achieve acceptable performance. Memory requirements are typically dependent on the code, but the more the better. Similarly, processing power is important and of the essence with respect to the performance—namely, the speed, cache, pipelining, and multi-processing are all important considerations.

5. DISCUSSION

Traditionally, simulation involves creating a physical or virtual model of a system or process and carrying out experiments on it as it progresses over a time interval. In this work, simulation in the form of FEA served as a technique for predicting how TFHs react to real-world heat and other physical effects, and the process entailed generation of models on ANSYS, i.e., generating the nodes and elements that portray the spatial volume and connectivity of the actual TFHs of the consumer products in question. The solid models created in SolidWorks were imported and used in defining geometric configuration of the model, nodes, and elements. We began with simple approximation of TFH elements and gradually refined the models as the understanding of physical effects continued to improve. This "step-wise refinement" enabled us to achieve good approximations of otherwise very complex problems. It should be noted here that a finite elements method works by breaking down a real object into a large number (i.e., thousands to hundreds of thousands) of finite elements. Mathematical equations help to predict the behavior of each element. A computer then adds up all the individual behaviors to predict the behavior of the actual object, which in our case was TFH. The models generated facilitated the exploration of how real-

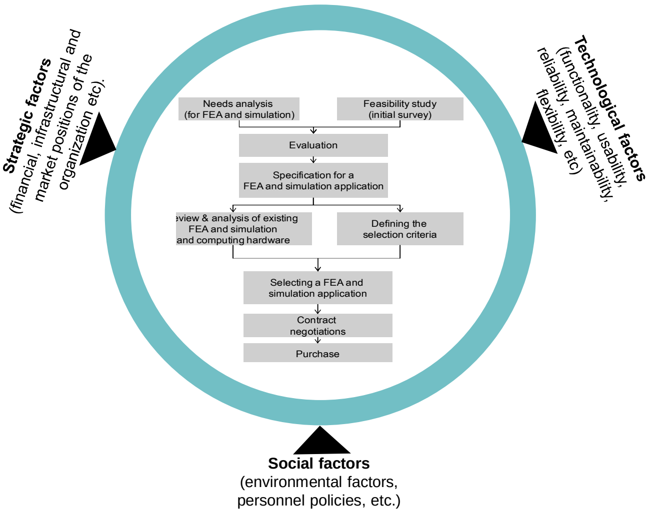

Figure 7 A general scheme for selection of FEA and simulation application (derived from [14]).

world functioning TFH would eventually perform, and allowed testing of alternative solution proposals and hypotheses at a fraction of the cost of actually building a physical TFH and undertaking the activities which the models simulate.

The advantages of simulation are widely acknowledged and have been demonstrated in this work. FEA and simulation helped to predict thermal stresses and other physical effects, deformation, performance, and showed whether or not the TFHs would work the way they were designed before building the actual TFH subassemblies. The case-study of a recently accomplished TFH development process discussed in the previous section has revealed the kinds of technical challenges encountered. It has also demonstrated that the process is highly iterative and that the total development time of a single TFH in the case-study company can take up to three years. The introduction of simulation in the form of finite element analysis into the current TFH development process, especially in the exploration and development stages, can reduce or eliminate the iterations, thereby shortening the TFH development time.

Overall, FEA and simulation provided a cost-effective means of exploring the suitability of new TFH, without having to resort to manufacturing of physical prototypes. It provided a faster and more efficient technique for verifying the design choices and helped the designer to foresee how the TFH would be like. Furthermore, it proved to be an effective communication tool, that can be used to visually show physical effects on the TFH and to explore how the TFH can be improved. Additionally, simulation provided a method for predicting the results, understanding why the observed events or physical effects occur, identifying problem areas before implementation, exploring the effects of modifications, evaluating ideas, identifying inefficiencies, gaining insights, stimulating creative thinking, and for investigating the integrity and feasibility of the proposed TFH design solutions. According to literature, problem solving in new product development typically entails deduction (i.e., application of formalized knowledge, e.g., laws of physics) and induction (i.e., e.g., application of knowledge obtained from testing and prototyping)—see, e.g., [3]. The incorporation of FEA and simulation in TFHs development processes can be regarded as bringing in an additional problem solving strategy to complement the existing deduction and induction strategies.

Despite the fact that FEA and simulation techniques were developed several decades ago and have been adopted and used by some practitioners for quite some time, apparently this had not been the case for the case-study company, regardless of the advantages stipulated above. To the best of our knowledge, this is also true for its competitors (i.e., other developers of TFHs). Many factors, including cost and lack of awareness, have contributed to this dearth of diffusion. Our recommendation is that by enhancing industry orientation (i.e., by the developers of FEA and simulation packages), and by adopting systematic processes of dissemination, the target users can experiment and understand the benefits of these technologies and be persuaded to apply them. It is also equally the responsibility of the company to explore and to constantly keep track of the latest scientific and technological advancements, and to ensure that it uses efficient engineering analysis techniques.

6. CONCLUSIONS AND FUTURE WORK

The paper has presented the research we conducted to investigate how best to incorporate finite elements methods in workflows to enable analysis, simulation, and optimization of designs of complex products. As a case-study, we explored the processes of development of TFHs. A structured FEA and simulation-based workflow scheme for developing TFH assemblies for consumer products has been proposed, and its applicability illustrated in a selected case-study industry. The proposed workflow scheme looks worthy and reasonable, and is somewhat based upon a common sense idea—and the process model is rather obvious. It has been demonstrated that, by incorporating FEA and simulation into the processes of development TFHs, a company can significantly shorten the development time, and can thoroughly explore new TFHs design concepts, and thereby improve its market position. This scheme can also be adapted and applied to other comparable product design assignments or product development companies. Only minor changes to the workflow scheme might be necessary, e.g., to accommodate minor differences between TFHs and the product under consideration. The developed workflow scheme should, however, be validated further to investigate its scope, effectiveness, and usefulness. The implications of incorporating FEA and simulation techniques into workflows also need to be investigated. To this end, since FEA is, somewhat, in many instances an industry standard, one possible way forward could be to investigate the implications FEA and simulation technique has had in several other companies—i.e., looking at the practices in similar or dissimilar companies to gain more insights into how best to incorporate FEA and simulation in workflows and into if and how FEA improves their processes.

The paper has also presented a structured method we put forward for selecting FEA and simulation applications, and discussed the key issues that need to be considered and measures that need to be taken prior to selection. The proposed approach can be of practical use for the companies planning to invest in a FEA and simulation application and can systematically guide these companies to make sensible choices by embarking on thorough analysis and evaluation of alternative applications. It guides companies to first carry out comprehensive analyses, and then to formulate multiple selection criteria, and to subsequently use these criteria as benchmarks for evaluation and selection of suitable FEA and simulation applications. The applicability of this systematic selection approach still need to be investigated.

Two principal conclusions can be drawn from the research we conducted. Firstly, implementing FEA and simulation can be considered as an additional problem solving strategy, which can reduce or eliminate highly iterative and routine engineering analysis and physical prototyping procedures. Secondly, it is apparent that the benefits of FEA and simulation go beyond time and cost savings to, e.g., allowing the designers of TFH to experiment with new and non-conventional design concepts; enabling the designers gain insights into physical properties such as internal stress development, etc., that are otherwise difficult to analyze; allowing the designers to uncover the relations between design parameters; and facilitating presentation and communication of test and analysis results.

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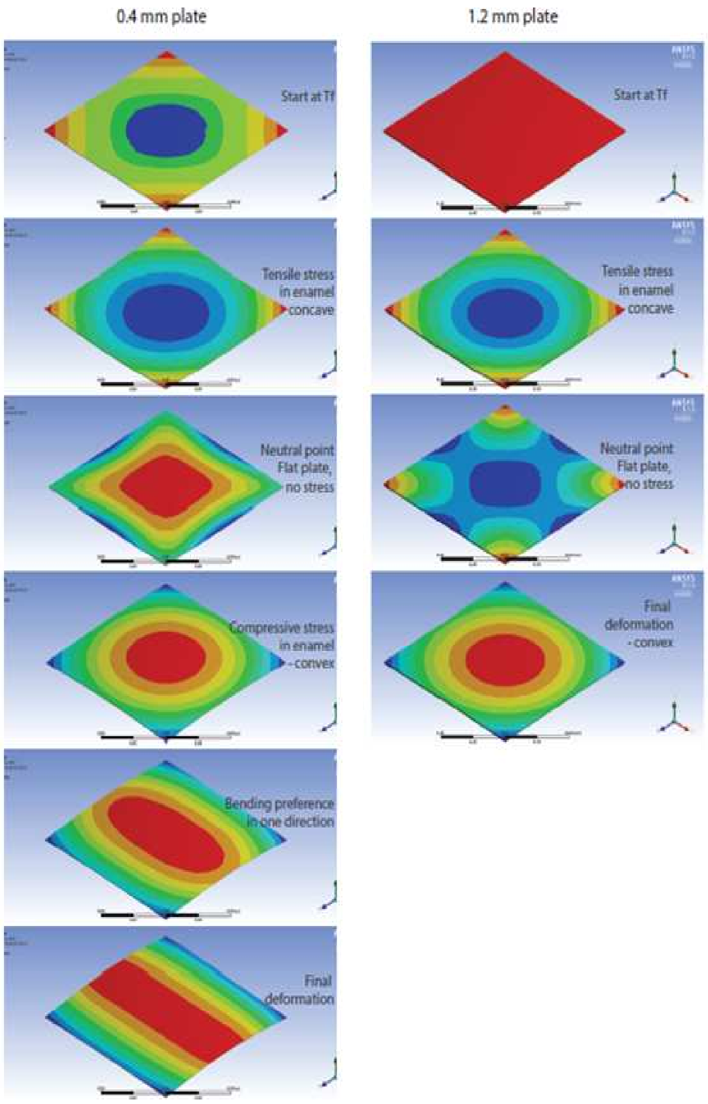
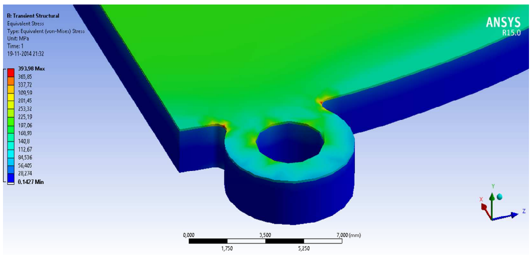
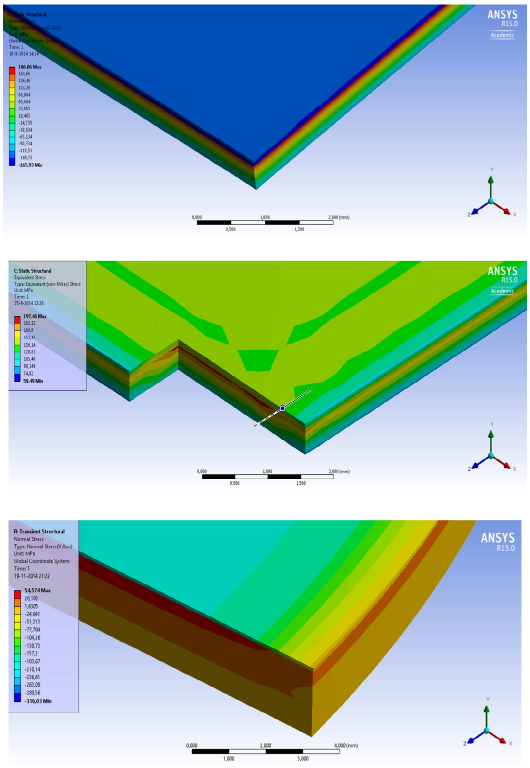
APPENDIX 1: EXAMPLES OF TFHs FEA AND SIMULATION RESULTS (refer also to [8])



(a) Simulation of deformation of test plates



(b) Stress build up at ears



(c) Stress across the thickness in an enamel plate