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CLUSTERING ENGINEERING DESIGN RESEARCH: A METHODOLOGICAL FRAMEWORK

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Abstract.

For a long time considered as taking place in designers' mind and being of their own ability, engineering design is an activity still badly known and understood. Since the 1990s, a lot of engineering design studies have been carried out, giving many examples of industrial practices and many models of design processes. But studies were carried out in particular industrial environments and proposed models rather difficult to generalise without description of the research approaches. So in this paper, after having characterised engineering design process and analysing Design Research Methodology proposed by Blessing, we propose a research framework which objective is to cluster engineering design researches and to make results comparable.

Keywords : Design research methodology, design methodology, design process

1 Introduction

The fundamentals of engineering design have been studied as a research activity for only thirty years. Up to this date engineering design was considered as an art where informal practices of skilful designers played a central role. Simon [1] has been the first, essentially in an architectural domain, to consider design as a scientific research object. The first studies in the mechanical domain had been published in the beginning of 1990s [2], [3]. But the new worldwide economic order imposes to get a finer knowledge of engineering design activity to optimise the industrial organisation for a real, efficient and the most rationalised possible design activity. The growing importance of the engineering design activity made more researchers interested in. As in other new fields, premium approaches are diverse, not necessarily homogeneous and often not formalised. A future challenge will be to compare and generalize their results.

The objective of the paper is to promote a methodological framework for the research on the understanding of engineering product design processes. It is adapted to research problems aiming at a double goal of proposing design methods relevant to the activity and adapted to industrial practice, and developing known, useful and used tools assisting designers in their activity. We would like to contribute to the debate on positioning research approaches in a common scale or framework making comparisons between research results easier [4],[5].

The work leans on our 15-years experience of research in engineering design. After emphasising the main properties of an engineering design process (section 2), we discuss about the Blessing's Design Research Methodology (section 3). Section 4 presents the framework proposed, then (section 5) the methodological framework proposed is illustrated by the presentation of different research approaches lead in different working environments.

2 Engineering design process is a complex activity

First of all, products are complex. An industrial product is considered complex when the management of the knowledge handled to understand an existing product is difficult or even sometimes impossible. The first level of complexity is linked to the fundamentals like physics, mechanics, chemistry, material sciences, thermodynamics, computer sciences, etc, necessary for its behavioural modelling. Acute knowledge is required, but, in some cases, these fundamentals cannot explain even elementary product properties like operating levels of wear. A second level of complexity is due to the necessary interaction between these fundamentals in the every day life of most products: mechatronical products are common examples.

Designing is a complex activity as well, because of the cognitive and social points of view. Many expert persons, so called design actors, are involved in a design process. They generally operate with various devices, methods, computer tools, and also knowledge, competences, languages, objectives, strategies and behaviours. Actors and materials are very various and heavily interact together giving a networked nature to a design process. Design is a situated activity [6] with many and different opportunistic behaviours [7]. If methods can help designers, the design process itself cannot be definitively planned initially and results from multiple adaptations due to the progress of the design problem and solution [1]. The design problem is only partially defined; It will be constructed throughout the design process simultaneously to the product definition progress [8], [9]. Functional emergence occurs [10]. Consequences of the properties of a design process are numerous. Let us notice notably the uniqueness of a design process, its non deterministic nature, the time as a main driver of the process progress.

A first possible approach for design research is to study the design process as a ‘black box’ by external variables. Considering the difficulty or impossibility to understand design activity, this type of research aims at comparing the performances of design processes submitted to different inputs or environments (methods, designer's skills, tools, etc.). Due to complexity, a first difficulty comes from the impossibility to reproduce a design process: Inputs, particularly when actor-oriented like previous experience for example, are very difficult to be controlled. A second difficulty is to clearly evaluate a design approach within a recognised frame. If a failure of a product design can be recognised, there are no elements to define when succeeded. Results on the design process are mainly captured from results on the product features. The only process parameter captured is lead-time.

A second approach states that the activity of designers can and must be studied, but like with each human activity the approach is still difficult. These studies range from laboratory experiments to in situ observations, with techniques from Protocol Analysis [11] to ethnographic approaches [12]. A good agreement between the observed design period and research time must be met impacting the nature and the quantity of data collected and processed. A main issue is to know whether results obtained from a research world may be transferred to an industrial world.

3 An existing framework for the research in engineering design

A systematic methodology for doing engineering design research is proposed by Blessing [13]. This framework is composed of four stages helping researchers to clarify their study and the methods to be used to achieve their goals. Due to time constraints, a research project generally does not address the four stages (only one or two) but a research study has to be replaced inside the whole framework. The four stages are criteria definition, descriptive studies 1 and 2, and prescriptive study. The phases are not fully sequential and some of them can be run in parallel.

Defining criteria is thought important to clearly identify the aim that the research is expected to fulfil and the focus of the research project, then to enable evaluation of the developed supports and the research results. Criteria have to be measurable. This stage contributes to the definition of the product development performance measures.

The descriptive study 1 aims at identifying the factors that influence the measurable criteria in a reference model. The method of the study has to be explained carefully to, first of all, limit inconsistencies between aim, data collection context, data analysis method and validation of the results, but also to create a frame of comparison of the results from different studies.

Descriptive studies 1 make prescriptive studies legitimate. The end is a method or a tool to improve design practices. The result of a prescriptive study generally consists of a demonstrator or a prototype to proof the concept. It contains what is absolutely necessary to evaluate the results with respect to the criteria.

The formal evaluation of the methods or tools developed in prescriptive studies is achieved by descriptive studies 2. This evaluation is made in two complementary ways. It aims at investigating whether the method or tool can be used as forecast and addresses factors as supposed. It also aims at identifying whether it really contributes to success. The evaluation focuses on both measurement of outcomes and effects of the developed design supports.

The links between the stages are important in this methodology. They guide the research progress through a targeted goal by justifying the consistency throughout the research process. By clarifying research goals and methods, it creates an interesting possibility for doing research and validating the results. The second main interest of the framework is the systematic suggestion of research methods to deal with the different stages of the research. It creates here a sharable corpus of methods for the engineering design research community in order to have comparable results.

This rigorous approach to design research appeals some remarks and open questions:

- The framework is evaluation-guided, meaning that criteria can be defined in the first stage, then guide the research procedure. If it is true that a lot of research methodologies are evaluation processes, we may think that the specificity of the design process might open other research methods supplementary to that one.
- The framework is goal-driven i.e. the goal initially exists. Its evolution is therefore possible by adaptations through iterations, in some instance similar to the iterations in the Pahl and Beitz design process model [14]. The relevance of the goal has to be proved initially and could be simplified (to become too simple may be) for getting measurable effects
- Nothing is said about the goal identification. It is nevertheless an objective of research not only to verify concepts but also to formulate them. The DRM methodology appears therefore well adapted to the verification of hypothesis. But the emergence of design research questions is not really discussed. Here, the design complexity probably induces a true complexity of design research processes that a structured methodology can hardly handle. Due to our product design research experience, we think that design process models should emerge throughout the research process.
- Concerning tools and methods, once they have been developed based on previous researches, tests in adapted conditions (experiments in laboratory or in industry) must

be carried out. The delay between the initialization of criteria definition and the use of tools seems enormous. Moreover, in many cases we met, after a period of adaptation, tools and methods were mainly used in a way different to this that was thought initially. The initial analysis of their usage was not successful due to in-use deviations. Shorter iterations are necessary.

To sum up, we believe that research in engineering design may not be limited to identifying and weighing dependences between known inputs and known (and measurable) outputs. Both descriptive models and clarification of concepts are still research objectives as well. The main objective of Blessing's framework is a construction of a research methodology to be applied on engineering design activity. It is based on a well structured functional description of research stages that finally – due to complexity - does not really guides the structure of a stage to be operated. We would like to propose not a methodology, but a framework, to be seen as a complementary point of view. Its final objective is to clarify research methodology in design but mainly today helps to cluster design researches, studies and results from a compatibility point of view.

4 Our framework for clustering engineering design research

Based on our experience of leading engineering design research and on the literature (quite poor on engineering design research methodology but rich in design studies), a framework for engineering design research methodology is proposed. The principles of design research discussed above are of course fully accepted. It particularly means that:

- engineering design research aims at supporting industry by both improving design understanding and developing knowledge for practical and industrial use,
- the methodology must propose both a guide for doing research in engineering design in a scientific way and a framework to make research results comparable.

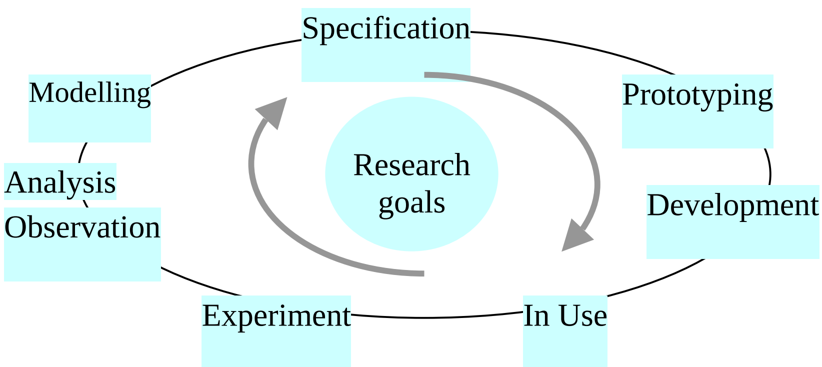

Figure 1: framework for engineering design research methodology

The elements of the framework are given in Figure 1. The coherency among the elements is given by the objectives of the research. Research goals are the drivers of the research process and are operated by both specifying methods within each framework element, and specifying the progress through the elements. Even if a natural order seems exist for the global research process (clockwise), the sequence is not so clear and some activities can be carried out in parallel or skipped in a first time to be performed later. It is these feed-backs among activities that enable to progress, to refine the goals and the results. It is particularly true between the activities of descriptive modelling and specification/prototyping. Depending on the research objectives and the material that can be collected, the entry and exit points of the research process are various. The framework suits whatever the research level considered. If a research programme must certainly address the whole activity of the research framework in order to be entirely validated, it is sure that a research project (like a PhD study for example) will address only a part of the framework elements. It is a set of complementary research projects, which put together in coherency and in perspective, will give research complete and validated.

Description of the basic elements of the methodological framework :

- *Research goals* are the origin for the research activity. They guide the construction of the objectives of each element of the framework and contribute both to select the best suited method to be applied for every element and to validate the results of every element against them. Research goals control the research process. Research goals should be clearly expressed before the research starts and would evolve throughout it.

- *Observation* of a design process (or a part of it) is a data collection phase that should be instrumented. Only data that could be observed can be collected. Methods to collect data are numerous and depend on the research context. They should be explained and justified against the possible instrumentation. Data collected are rough observed data.

- *Analysis* deals with filtering, sorting and calibrating rough data into nice data making sense from the point of view they would be used. Numerous methods for analysing data have been developed for years in different disciplines. They are dependent on domains and data types. They have to prove their relevance to engineering design. Analysis is oriented by a pre-existing typology of model feature that should refer to a theory.

- *Modelling* is the activity of proposing a descriptive and explicative model of the design process (or a part of it). The expected model must be the more general possible and at least represent a class of design processes. It could address the definition of the concepts supporting the model by clarifying the model features and detailing the connections among these features. The representation method of the model should be formal and semantically acceptable.

- *Specification* is the activity of requiring what a design method or tool, or what a support of the design process should be. It implies a strong dialogue between the person who modes and the one who implements. It addresses the functionalities of the method or tool and highlights the technical point of view. The language of specification is generally oriented towards implementation. It brings a prescriptive model of the design process (or a part of it).

- *Prototyping* is developing something that demonstrates and proves the concepts developed. Based on specifications, it gives a scientific and technical feed-back to researchers. The technology used is the most appropriate to researchers.

- *Development* is not a research activity. It is just for getting a reliable and robust prototype that could be tested in an environment different from which it was developed in. In many cases, development addresses the user interface. The technology used is the most appropriate to users.

- *In use* is the phase of the introduction of the method or tool developed into practices. It addresses how designers appropriate the tool or method and learn about it. The main interest is about the actual conditions the designers create to efficiently use it. Methods to get the right information have to be explained.

- *Experiment* deals with a design situation specifically built to be experimented. An experiment is a design situation cleaned up where relevant parameters can be handled. The way the experiment has been built and conducted (the constructed environment) has to be explained.

5 Examples of research project approaches

Literature shows that the paths through the framework elements are very diverse. An exhaustive survey has not been done. Let us explain three of them as examples in the next three figures.

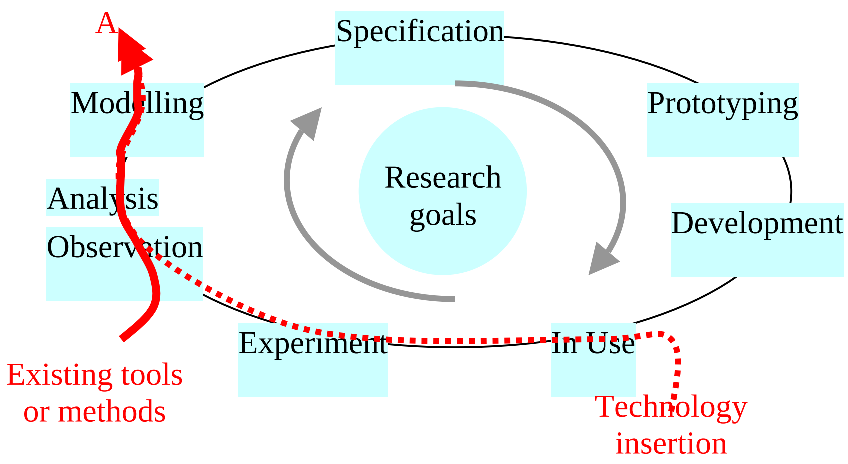

Figure 2: Route A – Sciences studies : Modelling of the activity from in-use situations.

Route "A" (figure 2) is typical to sciences studies. Starting point is how tools and methods are used in practice. The objective is to provide researchers with explicative models of the design process. A new way is to study the design process after having inserted a new technology (a method or a tool) disturbing practices and therefore creating new practices (dotted A route).

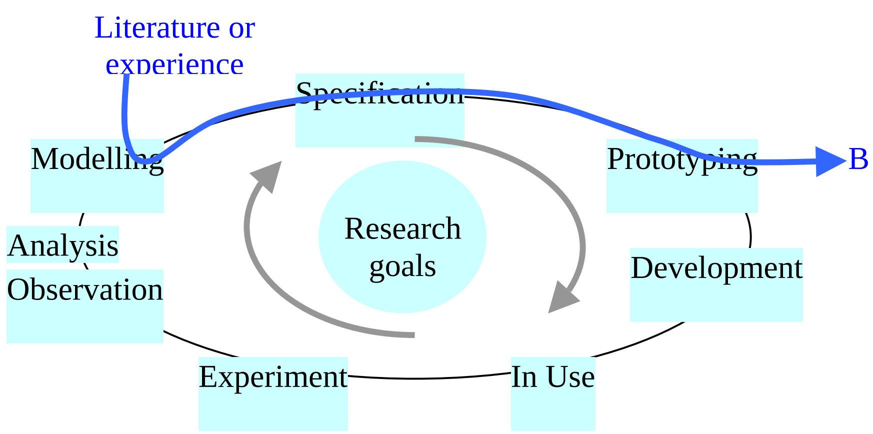

Figure 3: Route B – Engineering sciences : From model to Prototype

Route "B" (figure 3) is more for engineering sciences. Very often, elaborating a model of design process from literature or industrial studies starts the research activity. The model is then implemented in a prototype.

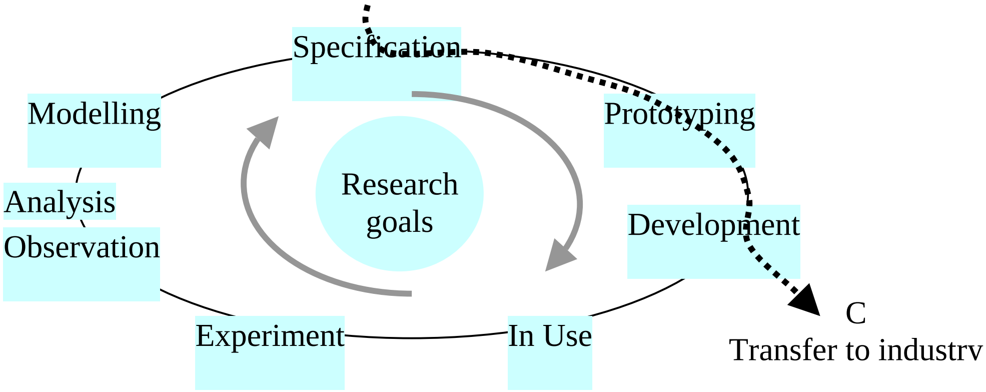

Figure 4: Route C – Engineering work : From specifications to development

Route "C" (figure 4) is engineering work. From specifications from previous studies, tools and methods are developed. The research part of this activity is often weak. This approach can be exploited only when needs have been clarified and specifications accepted. It is the route for transferring research results to industry practice.

It is easy to understand that the routes are complementary and many of them have to be tested all over to achieve usable design tools and methods. Therefore they are not sufficient in the way that each new tool or method will modify the way designers design. A loop within the research approach should then lead to new experiments and industrial monitoring to evaluate results and correct them eventually. In current design research, we have not heard about such loops.

6 Discussion and perspective

If we accept the idea that each design research is a creative, ill defined, non deterministic, unique, contextualised process, it shares with design process itself some of its essential characteristics. One of them is complexity. As a corollary, we face the difficulty – even the impossibility – to represent it in an exhaustive and simple way. In this sense, our proposal and DRM must not be seen as opposite, but complementary. Main features of DRM can be retrieved in our framework. For both, the process is goal driven even if we think important to insist more on the evolution of research goals during a research project. Descriptive Study 1 and Prescriptive Study could easily find their routes in our framework, close to routes A and B (or C) respectively. Descriptive Study 2 is a second loop. One main difference is the beginning of the design research process which is rather prescriptive in DRM. Another difference lies in a more detailed process with more items, and, above all, more compliance for use. This last point highlights an important argument: reflexive practitioners certainly need frames for representing their action as well as (more rigid) methodologies (To be honest, as individuals, we could also recognise that the design models we currently refer to may have influenced our representation of design research)

So, after having carried out research on engineering product design in many isolated studies for a long time, it is now time to try to concentrate all the research and next studies results for the understanding of a whole design process. For that, the paper proposes a methodological framework for the engineering design research activity to both

- Make each research result contribute to the general objective of understanding the actual design process and getting it better. Studies can be compared in a way that tries to isolate design activity basics, making the design project context and the nature of the design activity not in a so central place they generally get. The framework enables isolated results to be compared in a common scale to know what they really are, and to be added on in a cumulative manner to strenghten each others.
- Help defining research objectives and new studies. The framework gives the opportunity to structure the research efforts by highlighting the knowledge and results still missing. It can be used for research on the general activity and on very local ones as well.

As we would like to improve engineering activities, the framework was developed in a way to get the synergy of works on both design methods and the assisted-tools supported them. It also aims at getting research and industrial viewpoints close. They are very opposed as short term and long term results but research and industrial production fuel together the design process understanding and the willing of formulation and expression of the research and study results make them more dependent than they generally seem.

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