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VISUAL ANALYTICS FOR EVALUATION OF VALUE IMPACT IN ENGINEERING DESIGN

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Abstract. *Many traditional engineering design processes in industry have evolved, and nowadays they are supported by computational tools and methods. As a consequence, apart from the quantity of information and data, a network of simulation methods produces information at various level of detail and nature. Furthermore, human interactivity is an essential consideration when building and designing such computational systems, simply because there is a requirement to process and understand this information that is produced during an engineering project effectively in real time.*

We introduce here a Visual Analytics perspective in computational engineering design process, as well as tightening the interactive analysis of engineering data with Parallel Coordinates and Scatter plots. To demonstrate the benefits of the proposed approach we use a case study that describes the design of an aero engine component critically suffering from the operating conditions but at the same time from the change of specifications and customer requirements.

Some of the benefits include minimisation of rework through early identification of behaviour in selected Value Dimensions, as well as the ability to trade product performance (e.g. weight, minimum expected life) with internal stakeholder expectations (e.g. higher overall productivity of aircraft, low degree of aircraft modifications, faster design convergence). Furthermore, the proposed method develops the ability to identify architectural options that align with Value Creation Strategies, but also the evaluation of design options in advance of physical trade studies.

1 INTRODUCTION

These days, people perceive for granted complex engineering products, such as an aircraft, and most importantly use them in their daily routine. As a result, the requirements and specifications should meet the expectations of the customers and stakeholders simultaneously. In other words, the technical and engineering objectives that usually drive a design process, should now reflect the impact of customer satisfaction. In our example, a passenger would wish to have more leg space for comfort, better quality of air in the cabin, and cheap ticket price, and expect to be able to reach at the airport and spend minimum amount of time during security control and boarding. But how do these expectations translate to engineering performance indicators? How these metrics can be modelled? What are the relationships between such properties? We believe Visual Analytics and Big Data management can assist towards finding answers to these questions, and perhaps more importantly to create new questions that weren't thought before, but will further support the human imagination and creativity.

In an engineering design process, as illustrated in Figure 1, we start with the description of a problem, which we then need to formulate and model, often, in a computational/simulation environment. The same problem can have many model instances depending on the level of detail that is described, or even the point of view of the analysis. Each of these problem formulations are then explored, almost simultaneously through design optimisation studies, simulation and analysis tools, or similar. Before we are able to cascade this information downstream in the process for decision making, we need to collect, synthesise, and process the data.

The process to collect this data, most of the times, has a complex structure, since many different analysis and simulation tools are used during an engineering design project. Furthermore, in many cases they are located in geographically different sources.

The mere amount of aspects that need to be considered simultaneously when making decisions during product development is one of the main reasons why synthesis in engineering design relies on experienced and advanced human cognitive skills. Since the introduction of computational support, the ability to design and optimise products have made several leaps forward. As one example, the actual definition and representation of a compressor, or turbine blade is no longer possible to be defined by hand. Advances in Computational Fluid Dynamics and the following ability to optimise such designs have enabled efficiency of compressor design to advance from 9X% to over 99% in just a couple of decades. A second aspect is that to differentiate on the marketplace, success is increasingly determined by how well the product performs from multiple perspectives.

From an industrialist's perspective, we are now at a point where we no longer create a single concept with small variations of forthcoming products, but rather exploring entire design spaces using advanced computer tools. Engineers have the capability to produce more data per instance, for more variants and for more situations than ever before.

There is a need to visualise the data and more importantly to be able to interpret and understand what these data mean in a sensible way. Traditional ways of the representation of the behaviour of a design solution include the use of animations of e.g. deflection and distortion of a product (modal analysis, stress plots, etc.). Where the engineer could display results of one, or few alternatives, now is no longer feasible due to the multitude of variants and circumstances (loads) that the product is exposed to. Many aspects need to be explored for a range of alternative solutions. As a consequence, even if it is possible to generate such information, the analysis of a multi-parameter design space for many alternatives drive the need to interact and understand much richer and more complex dataset.

Hence, we need to complement other visualisation techniques to enable rich understanding of many alternatives subject to variation to many variables or aspects. This is also another major contribution of this paper.

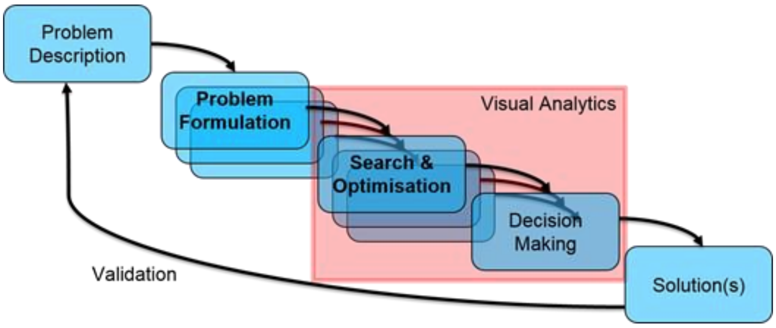

Figure 1: High level view of an engineering design process supported by visual analytics tools and methods.

2 BACKGROUND AND LITERATURE

Decision making during development is by nature multi-disciplinary, and several authors have proposed ways on how to explore design spaces in many dimensions. The MOVA framework by Woodruff et.al. [6] extended a finite dimensional design strategy to a more general framework to include multiple objectives, and compared the approach with alternative decision making strategies. Keim et al [15] summarised the area of Visual Analytics as a result from a three year European project, and concluded that assisting designers using visual analytic systems was one of the key challenges for the future.

In Figure 2 it is shown a schematic representation of a concept of how to facilitate human interactivity within the automated computational engineering design cycle.

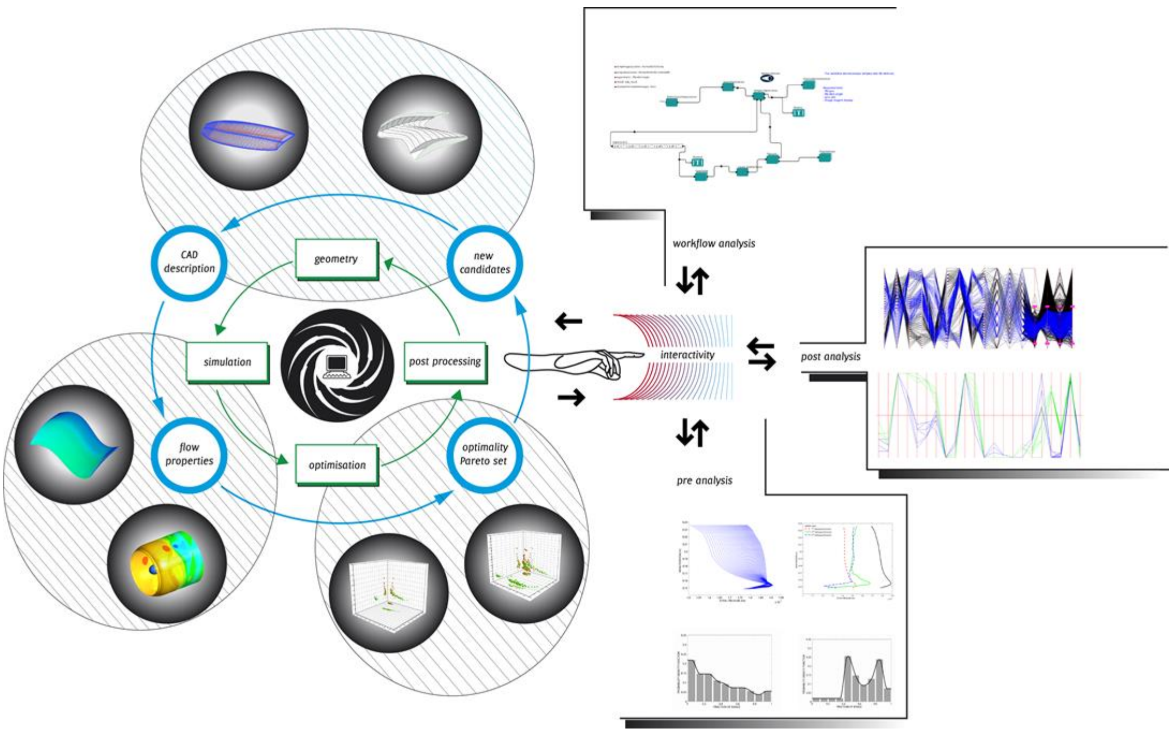

Figure 2: Schematic representation of an interactive optimisation engineering design process [10].

The automated computational design cycle is shown on the left, and at the heart of the overall process is the human, who interactively analyses the results of the process, understands the complexities and infuses this knowledge in real-time into the automated process.

Although engineering design largely relies on the use of numerical and computational analysis tools, the synthesis and insights enabling design decisions still expect design engineers to understand the breadth of the design problem. There is a human aspect on decision making where the influence of appearance and visualisation has been shown to affect decision making in design situations. The influence of colours in visualising results has been previously applied in the area of Value Driven Design [16]. It has further been demonstrated the effect of contextual information of product oriented data and observed the effect on engineering team attention to how data was visualised [14]. The ability to interact with alternatives and changing conditions, such as product requirements changes and/or preference changes are clearly emphasised.

Engineering Design is a highly iterative activity, where the definition of forthcoming products is typically matured through managing iteration and changes. Any decision support method needs to facilitate the study of variation, trading, etc. Data is typically produced in engineering tools, but also in less quantitative manner. Subjective metrics such as confidence, appearance, risk, etc co-exist with quantifiable aspects such as stresses, strains etc.

Parallel coordinates (||-coords) can support and facilitate the possibility to identify trends and relationships between technical properties and specification characteristics when these are simultaneously represented in a multi-dimensional domain.

There are platforms and frameworks under investigation and development that facilitate the human interaction and drive/guide optimisation studies. But also offer visual representation of the product in an auxiliary engineering analysis environment (i.e. Workways [12]).

3 AN ENGINEERING EXAMPLE

The initial aim and objective of this work was to identify the means to connect high level stakeholder and customer expectations and requirements to actual technical key performance characteristics and indicators. We use the Value Assessment method as introduced in [2] and expanded in [1]. Here, we only provide a brief description of the main stages of the Value Assessment process. For more details the reader should refer to [1] and [2].

3.1 Value Driven Design Methodology

A Value Assessment process can be best described within the Value Driven Design process as shown in Figure 3.

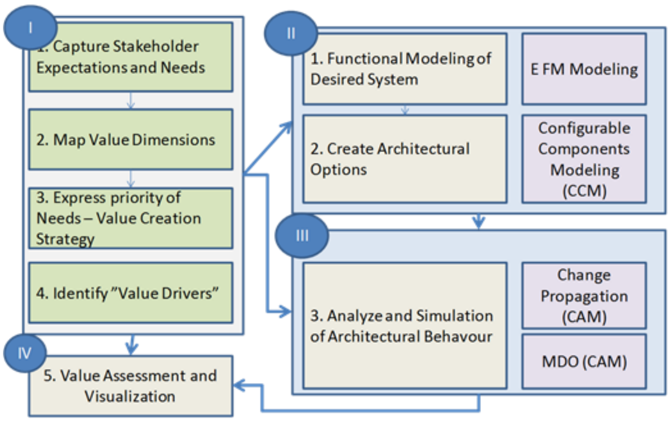

Figure 3: The four phases of the Value Driven Design methodology.

In phase I the stakeholder expectations and needs are captured and linked with Value Dimensions and Value Drivers. The often tacitly expressed expectations are organised into a Value Creation Strategy (VCS), this is the prioritised set of stakeholder needs that can be influenced in design via the Value Drivers. The Value Drivers are consequently aspects wherein it is possible to define the design parameters to explore. Typically, the breadth of information in phase I is vast. Explicit and numerically defined expectations, such as expected range or target weights are mixed with tacit and ill-defined expectations, such as being "sustainable" or "easily maintainable", "easy to integrate into a system" etc. Explicit and quantifiable modeling may not be feasible, not at least in early phases, but may still be necessary to include in decision making.

The second phase takes the VCS as input and serves to support the design synthesis stage. Searching for solutions in the design space is divided into an architectural modeling phase, in this case using an extended function means modeling approach, where the functionality of the systems is modeled and the alternative design solutions are defined. At this phase, the characteristics of the forthcoming design is modeled for all relevant candidate design solutions. One way of representing an architectural option is via Design Structure Matrices (DSM's), where the pattern of internal dependencies of design objects provides a quantifiable pattern of the architectural option (Figure 4).

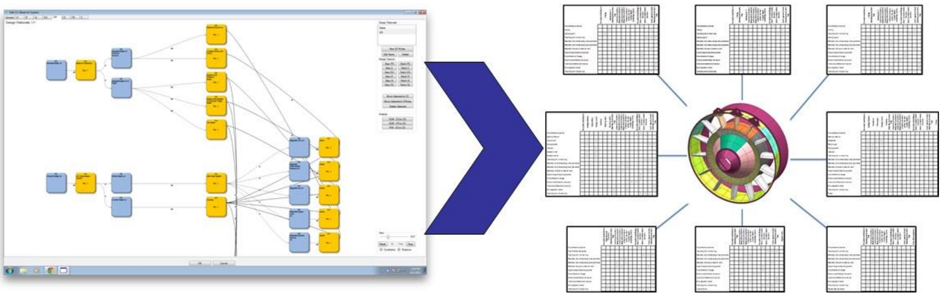

Figure 4: Through Function-Means modeling in CCM (Configurable Components Model) environment [17], alternative architectures of a RTS engine component are exported as DSM's.

The third phase introduces analytical tools that analyse the behaviour of the alternative architectures along with the evaluation of the properties identified as Value Dimensions in phase I. One efficient method to understand and explore the behaviour of the product is the Change Propagation Method (CPM) [18], where dependencies between the architectural objects are assigned with probability and impact information. Change propagation analysis then generate information of how an architectural definition reacts to changes and perturbations (Figure 5). It has been demonstrated that it is possible to define first order relations to several stakeholder needs, such as "integration ability" and "development process efficiency" [1]. Of course, more traditional methods such as Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) are also possible to be applied at this stage of the Value Driven Design methodology.

The focus of this paper is the fourth phase where the results from the simulated behaviour of all alternative architectural studies are collected and organised. Using ||-coords as a means of visualisation, the experience and intuition of the designer can be combined with the patterns discovered using analytical methods. Since multiple aspects and multiple architectural options are studied, the pattern recognition abilities of humans is used to facilitate interactive exploration and search for suitable combinations of input and output.

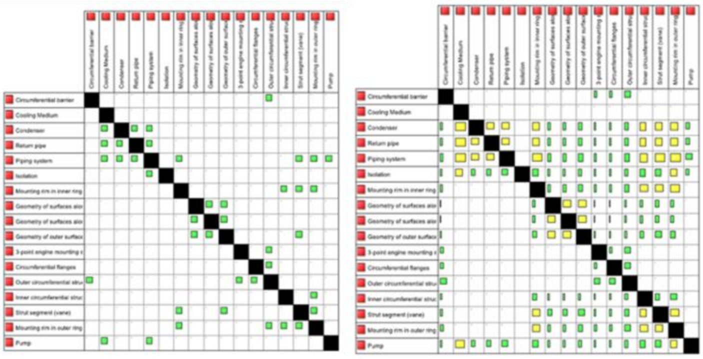

Figure 5: A DSM representation of the product and the combined risk matrix as calculated in CAM (Cambridge Advanced Modeller) environment.

3.2 A Brief Description of the Case Study

The method using visual analytics is applied onto a case study. The product studied is a sub system of an aircraft jet-engine, a rear turbine structure (RTS) as shown in Figure 6. From an applied perspective, the RTS is a tightly integrated structural component of the jet engine used to propel the aircraft and provide power to the aircraft also for other purposes. A re-engine scenario where the aircraft manufacturer wishes to upgrade the performance of the aircraft by replacing and/or upgrading the existing engine type is considered here. The engine manufacturing consortia consisting of the jet engine OEM and its design partners need to understand the new consequences and assess what design options exist that are necessary to satisfy the ambitions of the re-engine scenario.

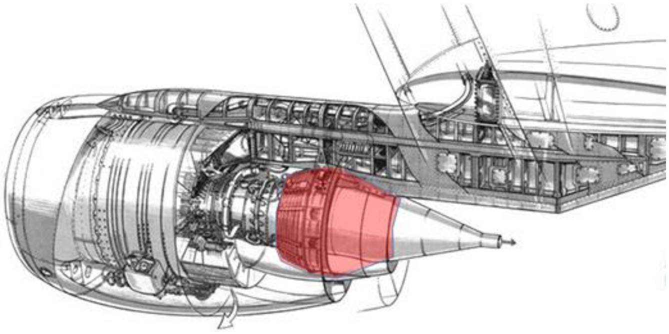

Figure 6: Re-engine scenario: turbine exit structure (*illustration from Flight Magazine).*

In the European project TOICA, the scenario is defined as a context, wherein the Value Assessment Methodology, described in [1] and introduced above has been followed. In this paper we focus on phase IV but capture portions of the dataset for clarification and to present the sources of information used when assessing value in the interactive way using ||-coords. From phase I, a range of Value information is captured, each linking Stakeholder Expectations to Value Drivers. In Figure 7 this is illustrated for the “Higher Productivity of Aircraft” Stakeholder Expectations. This expectation eventually is influenced by weight since this has a first order influence on payload, and on minimum expected life which has an equal direct influence in the operating cost of an aircraft.

Stakeholder Expectations	Stakeholder Needs	Value Dimensions	Value Drivers
Higher productivity of aircraft	Increased payload	Mission performance	Weight
	Reduced operating cost		Minimum expected life

Figure 7: Expression of generic stakeholder expectations and needs, and the mapping to value dimensions and value drivers.

Since the stakeholder expectation of "Higher productivity of Aircraft" and both of its Stakeholder Needs are attributed to the operation of the aircraft, the property of "Mission Performance" was the right classification of value dimension. Notably, there are other Value Dimensions, addressing other aspects of stakeholders, such as how costly the products are to integrate into a system etc.

The weight of a component is a good example of a Value Driver that can be assigned as a firm and quantifiable target. It can equally be related to the impact on productivity of the aircraft, since frequently is the case in aerospace that weight is given a direct relation to productivity of the aircraft. In design phases, it is equally common to formulate penalty relations in monetary terms if target weights are not met.

In a similar manner, there are relations with the expected life and the productivity of operating the aircraft. Maintenance schedules, repair and inspection costs are directly related to the satisfaction of a minimum expected life.

Both minimum expected life and weight of components are examples of quantifiable value drivers. To evaluate weight and expected life, there is effectively no mature way of analysing this impact for new alternative designs without modeling the CAD definition (calculation of volume) and making physics based evaluations using computational techniques such as finite element analysis (calculation of the stresses and strains) and some life analysis technique (such as crack propagation and/or fatigue analysis).

The actual relations between weight and performance, or minimal life and operating cost are business sensitive data and not disclosed explicitly in this paper.

4 INTERACTIVE ANALYSIS WITH PARALLEL COORDINATES

4.1 Methodology

The inputs to the interactive analysis for Value Assessment are initially the results from the functional analysis and CPM analyses, as well FEA and CFD analyses. Parallel coordinates are used to display simultaneously the results onto each value dimension in the same plot as the design variables. The architect can work interactively with the data set, and filter out architectures in several ways, either via filters on the parameters or via a graphical plot in 2D where two selected parameters are compared to each other. As the concepts are refined, more advanced modeling and analysis tools can be used to predict the behaviour or the concept.
The first step (to the left below) operate on the pre-embodiment DSM data. In this step alternative variants are down-selected, and the most promising variants are selected for further refinement. Selection of variants allow physical and parametric geometrical modeling and finite element analyses to be conducted. The same tool and interactive analysis is re-used with a richer data set. This is described to the left in Figure 8.

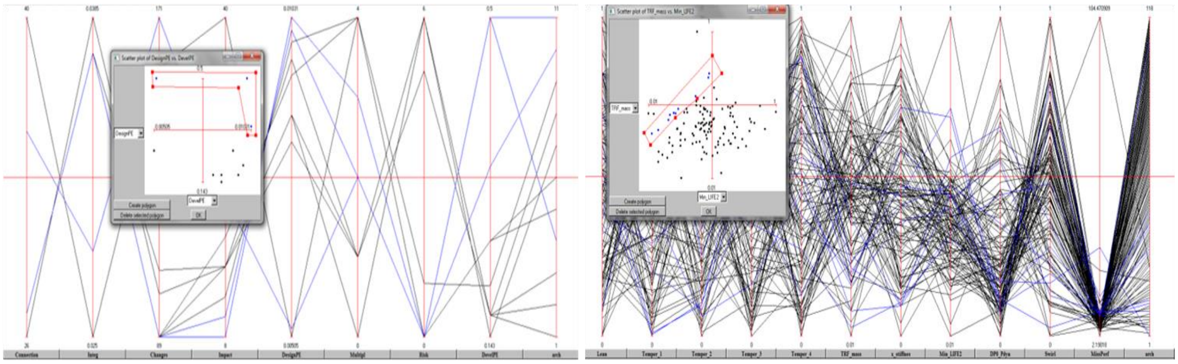

Figure 8: Parallel coordinates and interactive analysis and visualisation of impact of stakeholder needs and value dimensions enabled using multi-disciplinary analysis and design tools.

Similar examples and methods of interactive analysis can be found in [7], [8], [9], [10], [11], [12], and [13].

5 FUTURE WORK AND CONCLUSIONS

The approach presented, and the interactive way of analysing datasets was used to assess initial architectural descriptions based on DSM representations and CPM as analysis method. The same visual analytics tools is re-used as the data set is enriched through more detailed and refined models of the architectures. In particular, the visual and interactive tool has been demonstrated effective as a means to facilitate the communication between architects and different engineering design teams. The ability to link "high level" objectives through the Value Creation Strategy, to the design variables characterising the various architectures has been demonstrated successfully. Since information in complex product development typically engage many disparate competences and specialist teams, the value of communicating the expectations and technical results are decisive. The Visual Analytics methods and tools are highly suitable to combine data from different sources and of different nature.

In particular, the ability to analyse the often extensive data sets by filtering, selecting and searching for combinations of parameter values is an important feature. This is typically the task for multidisciplinary optimisation specialists, whereas through the visual analytics approach different stakeholders can analyse the datasets simultaneously. Based on this type of interaction during the development of the methods and tools in the TOICA project, engagement and critical understanding were aspects that were significantly improved.

Here we also list the identified benefits so far, and emphasis is given on further potentials and contributions in the engineering design field.

These include:

- Ability to represent many design alternatives that were evaluated simultaneously for many variables
- Aggregation of information, where dynamic navigation in resolution and underlying assumptions can be done interactively
- Analysis supported by the ability to search for better and more suitable solution areas
- Describe the logic-disciplinary development via computational tools
- Ability to combine disciplines (multi-physics)
- Ability to process large amount of data (computational power)

- Ability to automatically generate the necessary designs and their variation (design automation, KBE, etc)
- Differentiation in business by tailoring and customising products and services (i.e. more variations and aspects ageing)

But also other enabling means to support decision making:

- Impact of component performance to global performance
- Identify meaningful trade-offs between requirements and design parameters
- Understand the design space and find answers to the questions:
    - o What are the important parameters?
    - o How the requirements compete?
    - o Where are the most promising solutions?
- Manage risk

For further work there are several directions of interest. One is to further strengthen the interaction with different scientific communities, such as the engineering disciplines, computer science, visual analytics communities, mathematics and cognitive decision making specialists.

Secondly, already in its current state of maturity, there is an exploitation track to explore. The needs and contexts prevailing in decision making situations during product development can already now benefit from the ability to bring in complex data sets, link them to high level objectives and increase interaction with specialists. There is a route to more clearly understand, demonstrate and implement support for decision making in complex product and production development situations. The ability to represent and characterise architectures via internal and external dependencies is a promising area, where research is needed to enhance representation, definition and evaluation methods and tools. It is likely that the actual decision making process throughout a development project will continue to develop new practices. One of which is the facilitation of more interactive, visual and analytical tools.

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