THE PROPAGATION AND EVOLUTION OF DESIGN CONSTRAINTS: AN INDUSTRIAL CASE STUDY

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The research in this paper reports a case study of a design project which had two scopes for a variant and an adaptive design type. This is quite common practice where designers commonly propose short and long term solutions to design problems. In this particular case, preference was not voiced for an adaptive solution until the 3rd stage-gate of the project. The researcher acted as project manager of the design project using a participatory action research methodology. During the design work the researcher recorded and classified the various design constraints introduced and propagated throughout the design project. Where it was hypothesised that the variant design type will contain all constraints of the adaptive design with additional ones, the study should this not to be the case. The study also revealed that contrary to popular belief, changes at higher systems levels may exhibit less creativity despite having a greater impact.

Keywords: Constraints, Requirements, Specification, Design types.

1. INTRODUCTION

Understanding the design process is of vital importance to the design research community. It is important to understand the design process in general terms in order to effectively implement design support tools and research findings broadly across the design community.

In this paper the authors would like to consider the design process from the perspective of design constraints. This is not an uncommon approach as many previous authors have explicitly considered design to be "a constraint-satisfaction process", "a constraint-driven process" [1], "a constraint-sensitive process" or "a constraint-orientated activity"; all of these example were taken from the engineering design research community. This constraint based viewpoint of design was chosen as the initial part of an investigation into creativity at different stages of the design process. It is the authors' longer term hypothesis that creativity has different modes and support needs depending on the nature of the task and the design type. Understanding the introduction, modification and propagation of constraints may be the best way to understand the nature of different design tasks.

This study follows a short design project through a formal stage-gate process by mapping out the constraints throughout the self reflected and observed design process. The project provides an interesting case as it contains two design tasks, one relating to adaptive design, the other relating to variant design. A classification scheme was developed and applied and the findings from which were compared against current theoretical descriptions described in the following section.

2. LITERATURE REVIEW

The following review relates to theoretical work that help to first describe the design process in terms of the constraints and requirements being introduced (Sec. 2.1.) and how the constraints propagate during the design process (Sec. 2.2.).

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2.1. Feasible Design Spaces

Several models have been proposed in literature describing design in terms of changing design spaces. The authors' perspective on this work is that the design space is the space for possible solutions bounded by the constraints and requirements of the project. This is based on work by Gero [2] who suggests there is a space for feasible designs which can be expanded by creativity. This could be considered as a constraint-breaking process.

With reference to Figure 1, Gero states that there is a space for routine solutions which involves simple parametric design. Innovative designs on the other hand involve an extreme for of parametric design where one or more variables are extended beyond what was though possible. Creative design accounts for all of the other changes made to allow design outside the original space for possible solutions.

These types of distinctions are described in more detail by McMahon [3] who suggests there are 5 modes of change in engineering design. The first of which is 'Parametric Design', similar to Gero's routine design. The second is 'Understanding Attribute Relationships', this would help to gain a more optimised 'routine' solution or may stray into what Gero terms innovative for more complex problems. The mode relating to 'Modifying the Feasible Design Space' through improved technologies would enable a larger range for variables using the same solution principle. The other 2 modes: 'Change of Design Specification' and 'Change of Solution Principle' are related to creative designs changing the design space.

From the constraints modelling community there is a tendency to describe spaces in terms of 'sets'. This is an approach also used in C-K theory [4]. The basic premise is that there are a set of solutions bounded by a (or set of) particular requirement or constraint, termed collectively as a 'proposition' in C-K theory. As each constraint is added, the set of possible solutions diminishes as the design space shrinks. Thus if a design specification comprised of requirements a, b and c, the overall design space would be created as the intersection of design spaces A, B and C.

2.2. Propagation of Constraints

It is possible to describe technical systems in terms of systems, sub-systems and parts. At each level a 'horizontal' process of design activities takes place which involves:

- Function design: Understanding the requirements and constraints of the task
- Behaviour design: Producing a solution principle for the system
- Structure design: Setting out the requirements for the modules of the systems level below and the constraints between them (Embodiment design).

When decisions are made during each of the above design activities the design space for feasible solutions will shrink, often occurring at design review meetings or stage gates. We can also view this using a more concrete representation describing systems levels and design modules [5]. Requirements are passed 'vertically' through the systems levels usually starting from the market or environment by means of functional decomposition [6]. Constraints are shared between each of the design modules

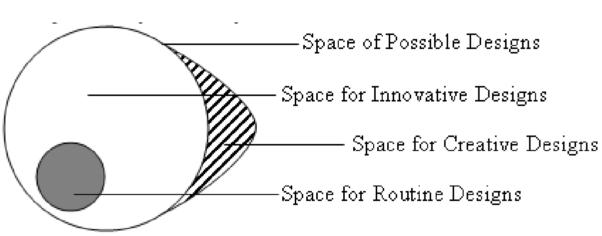

Figure 1. Feasible Design Space [2].

on a particular level. For example, a hole-punch has a requirement to punch a hole(s) in x number of sheets of paper and is constrained by size, hole positions for ring binder folders, weight, physical laws etc. If a basic office desktop hole punch arrangement is chosen, a module such as the lever arm of the punch, needs to deliver some specific requirements, such as to act as a lever to transmit force to the top of the bladed pin. It is constrained by the pin positions and the fulcrum position determined by the force required by the operator, the distance the pin must travel.

3. ESTABLISHING CRITERIA

The criteria described in this section are an attempt at a classification of constraints within design, with the aim to highlight some of the potentially interesting and useful attributes by which to distinguish between different types of constraints. These attributes will help to profile and understand the differences between an adaptive design project and a variant design project (see Sec. 3.4).

3.1. Constraints and requirements

Perhaps the first insight gained from this research was that certain terms such as requirements, constraints, preferences and concepts were conceptually overlapping terms. All of these are essentially propositions that narrow the design space or space for possible solutions (as described in section 2) and may be viewpoint dependent. This leads to the first level of decomposition where a constraint (a proposition that narrows the design space) was separated into two categories:

1. A Requirement: One of a set of agreed statements which characterise a design project by the potential impacts of a satisficing solution or the function it fulfils.
2. A Design Constraint: A relationships between design variables that restricts the range of possible values or a physical limit of one variable.

3.2. Requirements

A requirement is defined above as a specific type of constraint describing the function or purpose of the design. It has the characteristic of describing a problem or design task whilst remaining solution neutral (a requirement should not hint at a particular solution). Requirement is standard term used in industry commonly found in official documents at the early stages of the design process such as a requirements specification. A requirement is commonly separated into two further categories regarding mandatory nature of the requirement; namely, 'musts' and 'desirables'.

Musts by definition are requirements that have to be met for a design to be valid and are often termed as 'needs', 'expectations' or typically donated by a 'shall', if the requirement specification is also a contract. In reality, musts are characterised by extremely high preference values, so much so that it becomes inconceivable that a design could exist without satisfying it. However, in many cases these high preferences can be relaxed to accommodate promising concepts.

Desirables often relate to auxiliary functions (what else the design could do) and allude to the capabilities that could be taken advantage of in order to provide more commercial leverage. Desirables have a lower preference value as they are not seen as necessary to fulfil the principle functions of the design. These are also commonly referred to as 'wants', 'wishes' or typically donated by a 'should', if the requirement specification is also contract.

3.3. Design Constraints

Design constraints are the constraints that arise as a result of a design decision and are inherently not solution neutral. Every decision made along the design process will result in the introduction of one or more design constraints. For the purpose of this research two decomposition schemes were been proposed for Design Constraints, one relating to the type of variable, the other relating to the rigidity of the constraint.

The following list describes the Design Constraints in terms of the variables they affect:

1. Time constraints (T): Imposed by deadlines
2. Financial constraints (F): Various constraints imposed by company finance
3. Process constraints (P): Constraints of the existing manufacturing process
4. Standardisation constraints (S): Constraints imposed by company & product standardisation
5. Dimensional Constraints (D): Constraints imposed by dimensions.

Each of the above types of Design Constraint may have different levels of rigidity, positioning them in one of two categories, either:

1. An Absolute Design Constraint: where the constraint is constant, fixed or non-negotiable and cannot feasibly be altered.
2. A Flexible Design Constraint: where the constraints has a tolerable range which can be affected by changing other variables.

3.4. Types of design project

In order to further understand the implications of constraints within the design process, it was decided that the classification scheme proposed in this section will be assessed in terms of the types of design task being undertaken. Pahl and Bietz [7] proposed the most well know scheme defining the different 'design types' in design, original, adaptive or variant design. In a comprehensive review [8] is was shown that although many authors propose alternative schemes of design types, they are all in much agreement and most of the alternatively named design types map onto Pahl and Bietz's scheme:

Original Design: an original solution principle is determined for a desired system and used to create the design of a product.

Adaptive Design: an existing design is adapted to different conditions or tasks; thus, the solution principle remains the same but the product will be sufficiently different so that it can meet the changed tasks that have been specified.

Variant Design: the size and/or arrangement of parts or subsystems of the chosen system are varied. The desired tasks and solution principle are not changed.

This paper will report on the observed differences between the constraints in the *adaptive* design and *variant* design tasks within the same design project.

4. METHODOLOGY

This study took on a form action research known as participatory action research. In this type of study the researcher is embedded in the situation being studied. The role is not as a passive observer but instead the researcher actively contributes to the task and activities being studied. In this study, the researcher assumed a role as a design consultant, working with the collaborating company, Apex Pumps (www.apexpumps.com). However, this was not a traditional role as an action researcher where reflections and interventions are made with the collaborators to achieve a common goal. In this instance, the researcher made contributions and interventions toward the collaborators goal but made reflections towards a separate goal: that of understanding design constraints. Although the process is very difficult to undertake and has inherent issues of validity due the self interest of the researcher, the act of action and self reflection can bring deep understanding and insights. This method is exemplified by the seminal work of Hales [9].

As described above, the research methodology relies on both action and self reflection requiring the designer to simultaneously conduct a design project and a research project. Here the design project essentially forms the 'data' for the research project.

The research methodology selected come from Design Research Methodology (DRM) [10] and focuses on the first two stages of establishing criteria and a descriptive study. The findings from the

Table 1. The design process.

Phase	Summary of Activity
Task	The design problem was presented at the design brief meeting following which provided relevant background on the project, and also a general statement of objectives.
Specification	A formal statement of Requirements was prepared based on the design brief meeting, which is to be approved at Stage Gate – I
Concept	Concepts were generated both for the variant and adaptive designs
Preliminary Layout	Concepts were developed further in line with evaluation obtained from Stage Gate – II
Definitive Layout	The final designs shortlisted from Stage Gate – III were developed to completion, and subsequently cost analysed.
Documentation	A design report detailing the entire design project is prepared
Solution	The final solution is presented to the company

descriptive study aim to provide greater understanding when put in the context of the theory in the previous section.

4.1. Feasible Design Spaces

The design project was conducted with the collaborating company Apex pumps. Apex pumps is based in the UK and manufactures a range of centrifugal pumps for a variety of applications such as, petrochemical plant, building services and sea water pumps. The majority of the pumps are made of Cast Iron. A project was proposed to improve the performance and manufacturing processes for a range of pumps. An area for improvement was identified regarding the application and quality of the current protective coatings. An engineering design graduate was selected and acted as the designer and researcher throughout, following the design process described in Table 1.

The requirements specified by the company were as follows:

Musts:

1. Corrosion protection provided for the full life of 7 years ensuring rejection of no components in 2 years, 5 in 100 5 years, and 10 in 100 in 7 years.
2. A waiting period of less than 24 hours between coats (B-Coat Exclusive)
3. Immediate use with a maximum allowable waiting period of 2 days post application
4. Reduction of design related time delays by at least 50%
5. Coating thickness not greater than 300 microns – this would remove the current need for post application machining which take a lot of time and resources.

Desirables:

1. Easily verifiable process
2. Self healing coating
3. Coating that doubles up as exterior finish

Concepts were generated and selected by the designer and several were evaluated and rejected at one of the three formal stage gates (SG) which are represented in Figure 2.

4.2. Capture and Coding of Data

One of the main goals of this project was to capture as much information along the project timeline as possible. This meant utilising a range of capture technologies which included video recording, transcriptions, pictures, artefacts, field notes, emails and design logbook entries. For the data analysis NVivo was used in the initial stages and was then replace with a light weight version using Excel.

4.2.1. Meeting and Design Sessions

Meetings and design sessions were video recorded and stored in wmv format. The audio from the meeting was transcribed and coded using classification scheme proposed by Huet [11] along with

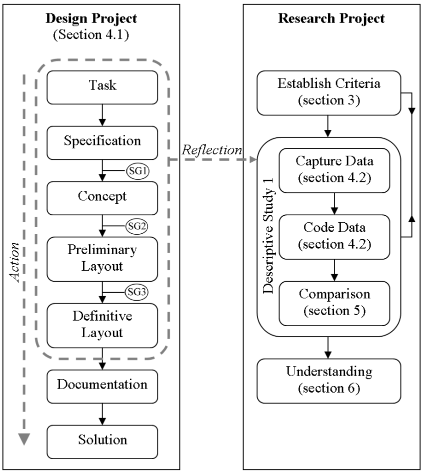

Figure 2. Relationship between the design activities and the research.

those established in Sec. 2. All artefacts referenced were either kept and stored at the university or photographed/videoed to aid the analysis and design. All documents referenced during meetings were kept in the form of Pdf's to aid the analysis.

4.2.2. Emails and correspondence

The researcher-designer had several correspondents involved in the design project, including several personnel from Apex pumps (the parent company), several 'child companies', usually coating suppliers, who could be considered as potential stakeholders in the task and other researchers to bounce ideas off. All emails exchanged during the project were stored and then analysed using the coding schemes in Sec. 2. All phone conversations and informal meeting were summarised in a logbook and then coded.

4.2.3. Design record

The design record for this project was constructed in a researcher's logbook. Left pages of the book were solely for the design work, where all design developments decisions and notes were recorded. On the right page were the analysis, coding and notes on the content of the left page (the design work) for the research project.

5. FINDINGS

The following section gives the outcomes from the design project when analysed in terms of constraints identifying how and when constraints were made explicit (Sec. 5.1.), the types of constraints identified (Sec. 5.2.), a comparison between the adaptive and variant design sub-projects (Sec. 5.3.) and the analysis of the proposed designs at the final stage gate (Sec. 5.4).

5.1. Making constraints explicit

There were 8 formalised requirements made explicit throughout the design project. All requirements were considered to have been declared during the initial briefing meeting by the 'parent' company (Apex pumps) except for one which was declared by the one of the suppliers at a later stage. Three of the 8 requirements were formally modified throughout the project.

There were also 8 design constraints identified during the variant design project. All bar one design constraint was identified at very early stages of the process and one design constraint was identified at a later stage by one of the suppliers. For the adaptive design project, 10 design constraints were

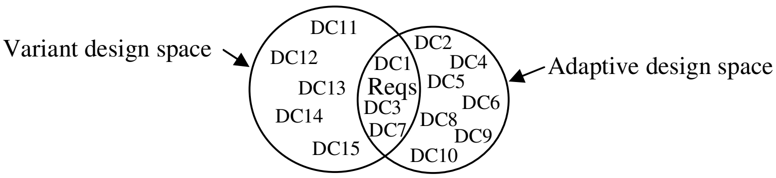

Figure 3. The overlap of constraints and requirements for and adaptive and variant design.

identified, 8 by the parent company; one by the designer which was later modified by one of the suppliers into two further design constraints.

5.2. Types of Constraints

The requirements consisted of four musts and three desirables. An extra 'must' requirement was declared by the child company at the later stages of the project. Three of the original 'musts' were modified throughout the design process by the designer, leading to greater specificity.

For the variant design activity the majority of the formalised design constraints were considered to be 'absolute' including the design constraint introduced by the child company. Only one design constraint was classed as 'flexible'. In contrast the adaptive design activity contained more flexible design constraints than absolute, of which the introduced and modified design constraints were both flexible.

5.3. Adaptive Design and Variant Design Constraints

On deeper scrutiny of the design constraints, it was revealed that the types of constraints were quite different between the adaptive and variant versions of the design project. The adaptive design project was overwhelmingly influenced by 'financial' design constraints, whereas the variant design was more influence by 'process' considerations.

It was also noticed that although the adaptive and variant design projects had the same requirements (Reqs) the design constraints (DCs) were quite different as can be seen by the Venn diagram of the two projects in Figure 3. The overlapping constraint set is the intersection.

5.4. Final Designs

Four designs from the adaptive design project and two from the variant design project were presented at the final stage gate.

The two designs proposed at the final stage gate were: an alternative material (adaptive design solution) and a customised applicator (variant design solution).

6. CONCLUSIONS

As expected, there appeared to be an increase in the number of constraints or design commitments throughout the design process, in line with previous studies [12] also described by the set and design space theories in Sec. 2.

It was also expected from theoretical work described in Sec. 2, that variant design would consist of the constraints of the adaptive design project but with a few extra constraints added due to the vertical propagation of constraints (described sin Sec. 2.2). Thus, the variant design space (VD) would be completely within the adaptive design space (AD) such that $VD \cap AD = VD$. Using our definitions and coding scheme this was not the case. Instead, one 'absolute' design constraint for the adaptive design exists that is not explicitly mentioned in the variant design (though it may be considered considered implicit to the variant design space. Further, the adaptive design project had several explicit 'flexible' design constraints that did not exist in the variant design set.

Identifying the overlapping constraint sets between variant and adaptive design briefs of a single project is an interesting concept. If done at an early stage this may help to prioritise design effort. This is a kind of platform concept thinking for resolving constraints and satisfying requirements. This platform concept could then be developed into either adaptive or variant variations of the design, though another study would have to be conducted to see if this could be done in reality.

Perhaps the most interesting insight into the design process was the relationship between the systems levels and the adaptive design and variant design projects. It was previously thought that the interventions made at higher systems levels will have greater impact and exhibit more creativity. In this case the adaptive design project was intervening at a higher systems level than the variant, however it required less creative work on behalf of the designer. For several adaptive solutions, the designer was merely undertaking a selection activity. In the variant design project, more of the design was fixed due to the additional constraints, however, the applicator concept required a great deal more creative design work. This has two implications, firstly, creativity is not completely dependent on the position of the design task in the systems hierarchy and creativity can be required at the levels of the sub-systems, usually considered to be detailed design. Secondly, that the impact of design may be higher at higher systems levels despite the lower levels of creativity required to produce a feasible solution.

It was not until the 3rd stage gate that the case company set a prioritisation or preference for the adaptive design project. It is believed by the authors' that this prioritisation could have been made at an earlier stage of the process had the company been involved from the beginning to make early modifications to the constraints.

The coding scheme was far from faultless and was applied inconsistently due to a lack of clarity and understanding. The theoretical descriptions describing the systems levels with propagating constraints did not match as expected onto the design types. Thus we conclude that using the definitions provided little insight into the difference in classification of the two types being design. There remains a lack of understanding in this area.

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