Constraints and conditions: drivers for design processes

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Abstract A theory of design that is useful for understanding and improving design processes in industry should account for both the similarities and the differences between processes, across products, companies and industries, and indicate how they can be influenced. Design processes are shaped by the constraints the product and the process need to meet and the context in which development process takes place. This chapter advocates the incremental development of design theory by identifying the major causal drivers that influence how designing is done, and constructing and revising causal stories for how they affect design. A number of important drivers are identified and related to different types of constraints on products and processes; one important factor is whether or not conformity to requirements can be assessed objectively.

Introduction: Factors shaping design

Existing theories of design have aimed at understanding design as a unified phenomenon, describing the key steps that all design processes go through or the fundamental elements that all designed products need to have. However to date there is no theoretical understanding to explain or predict the differences and similarities that we observe when studying design processes across a range of products and domains. This chapter describes the first steps towards developing a theory of design in terms of the constraints and drivers on the design problem and process, to interpret how a process behaves, and to predict important aspects of the behaviour of new or modified design processes. The view put forward here is neither a theory of design nor a model of design in the sense of a representation of a selected part of the world or a representation of a theory (see Giere, 1988, 2004; Frigg, 2003). It is an approach to generating partial theories of aspects of design: theory fragments that help to make sense of given situations and can help to predict how design processes might unfold.

The key theoretical concept in this approach is the causal driver: a phenomenon that influences the form or behaviour of a causal system – in our case a design process. The drivers that we are concerned with are characteristics of classes of products or processes or the conditions in which they are created, that enable us to look for and locate important similarities and differences between processes. Thinking about a process in terms of drivers providing causal pushes for design processes can help to make sense of observed behaviour as rational responses to a given situation; and therefore enable an analysis of where the process can be influenced. Particular patterns of constraints shared by similar design problems are among the most important drivers shaping design processes.

In this paper we argue that incremental theory development is needed, and introduce our our perspective of causal drivers of design processes, and the methodology behind our comparative approach to understanding design. We go on to argue that the influence of different types of constraints can be observed across different industries; we discuss some of these, illustrating our argument with two examples.

Local incremental theory development

Most previous theoretical accounts of design have taken a very broad slice along the dimension of the range of possible types of designing, aiming to cover all design, or the whole of a broad field like mechanical engineering; and have taken a very narrow slice along the dimension of aspects of designing behaviour that they encompass. They tend of come from a discipline perspective, addressing design for example from a social or a cognitive perspective. Theories about the nature of design or how designing is done are typically presented with insufficient consideration of how much of designing they actually cover.

Our research makes a conscious attempt to integrate cognitive, social and cultural perspectives (see Eckert and Stacey, 2001). We are primarily interested in why design processes are as they are, and how they could be made to work better, to produce better products, to increase the profitability of companies or produce products faster and with less effort, or involve happier, less stressed, more fulfilled participants. Therefore we are interested in a theory that explains and predicts the behaviour of real design processes at a level that is not trivially true for all processes. The scope of the predictions the theory can make about different processes must therefore be clear from within the theory.

We develop fragments of a theory of design processes by looking at design processes in a range of different domains. This involves looking at the ways in which design processes are similar to those for different products or for similar products in different companies; and at the ways in which they are different. We look at design from a variety of theoretical standpoints, using the methods and conceptual frameworks of a number of different disciplines to make sense of different aspects of design, and trying to integrate the findings and insights they produce into a coherent picture. ‘Design’ as a human activity – or broad cluster of human activities – is far too complex and too diverse for understanding the whole of design in one step to be feasible, so we need an incremental approach to accumulating understanding. It follows from this that developing design theory involves constructing pieces of theory, assessing their validity, assessing their limits of applicability, and progressively stitching them together to make a larger coherent whole.

Applying this approach involves recognising that the theory elements we currently have are at best fragments of a fuller theory of designing, and adding to them, looking at much narrower and more explicitly circumscribed slices of the dimension of the range of possible types of designing, and broader slices of the dimension of aspects of designing behaviour. The theory is provisional not just in that the relationships between drivers and design processes are open to revision, but also the definition of both the drivers and the phenomena they influence are open to revision, to provide better abstractions over concrete cases that yield stronger predictions or more conceptual clarity or better understanding of the differences between processes. Incrementally developing the theory fragments into a more coherent theory of design involves two kinds of operation. The first is to compare pieces of theory with the reality of particular design processes, and explain failures to observe the phenomena the theory fragments predict either in terms of the falsification of the theory, or by elaborating the theory fragments to cover a wider range of causal factors and distinct situations. The second is to connect theory fragments into larger more complete partial theories covering more of the interlocking causal processes shaping how designing is done, by matching and merging the elements of different theory fragments.

Our theoretical perspective: Causal models of systems

The conceptual foundations of the approach we are advocating come from systems theory. We view design processes as causal systems comprising a range of human, physical, conceptual and social entities connected by a web of interlocking causal processes operating at different scales. We start with the basic premise that similar influencing factors will tend to cause design processes to be similar in significant ways, and that differences in these influencing factors will tend to cause design processes to be different in significant ways. We want, first, to identify the important causal effects that make design processes operate the way they operate and, second, to describe these influences in a philosophically defensible way that enables us to make predictions about the behaviour of unfamiliar design processes when we observe them, or existing design processes when we try to change them.

This gives us our core theoretical concept: a driver of design behaviour. A driver is a phenomenon that causally influences some other phenomenon or causal system. Descriptions of causal drivers are abstractions of the concrete causal influences that operate in each individual situation – what Weber (1904) termed *ideal types*. The scope of applicability of a theory fragment depends on the abstractness and generality of the description of the drivers and other elements and processes it includes.

Causal drivers are closely related to constraints: many, typically most, are direct consequences of the constraints on the product and the process. However, driver is a broader notion than constraint; drivers are theoretical explanatory concepts referring to bigger, more general, more coarse-grained phenomena, whereas constraints are specific, depend on the individual problem, and come in swarms. Some types of constraints, or characteristic patterns of constraints, constitute drivers. Conversely, needs acting as drivers lead to the formulation of particular types of constraints, which then act as external influences on other parts of the design process.

Design processes are influenced not just by the external constraints on product or process, but also by the characteristics of the system itself: the product being designed, the people doing the designing, their organization and how they conceptualize and structure their work. What is an external causal influence on a system and what is an internal characteristic is a matter of perspective. We can draw a system boundary around the parts of a causal network that constitute (parts of) a system, such as a design process, and think of drivers as factors external to the system boundary. However, we may draw system boundaries in different places according to different conceptions of what the system is, so we don't want to draw any sharp distinction between an external driver of system behaviour and a component of a causal system. The appropriate system boundary for one part of the design process may be very different from the appropriate boundary for another part. Features of the emerging product often strongly restrict the form that other aspects of the design can take: they act as important external constraints on the design processes for those other aspects of the product. The relationship between design processes and their constraints is also bidirectional: identifying constraints, and turning broadly and vaguely formulated needs into exactly formulated requirements, is an important part of many design processes.

Theories and Models

The theory fragments comprise partial *models* of design processes, but with a very different scope and purpose from the process models that are constructed by design practitioners for practical purposes and the prescriptive models proposed by methodologists, which are themselves epistemologically slippery (see Eckert and Stacey, 2010). The claim of these theory fragments is that the models *represent* the structure of real, if abstractly described, causal processes (what it means for models to represent reality is a controversial issue in philosophy; see Frigg, 2003, for a discussion). Thus the claims of the theory fragments depend on the relationship between model and reality. Morgan and Morrison (1999) summarize van Fraassen (1980) as "We assess a theory as being empirically adequate if the empirical structures in the world (those that are actual and observable) can be embedded in some model of the theory, where the relationship between the model and a real system is one of isomorphism". However, Giere (1988, 2004) also emphasises the non-linguistic and abstract character of models, but argues that scientific theories make claims about *similarity* relationships between model and reality, which do not necessarily require isomorphism. The nature of this similarity relationship is subtle and needs further elucidation, and may differ for different cases; the relationship between scientific models and reality is the subject of extensive debate among philosophers (e.g. Teller, 2001;

Suárez, 2003; Mäki, 2011). The drivers presented in this paper are not necessary and sufficient conditions for processes to behave in such a way. Design processes are determined and affected by far too many factors to ever make such a claim. Nor can the drivers be interpreted in a counterfactual way, meaning that a process would not necessarily have unfolded in a different way, if the driver had not been present. We interpret the drivers as causal pushes, that make a particular situation more likely than another.

Modelling social systems

As many design researchers have acknowledged, designing is almost always a collaborative enterprise involving social processes. Understanding design processes as systems involves viewing social processes as causal mechanisms and social facts as elements of causal systems. Whether, when, and how far social structures should be treated as though they have real, objective existence has been fiercely contested in sociology for many decades (see Burrell and Morgan, 1979). These arguments are directly relevant to the question of how to understand designing at the level of social and organizational processes, not just for academic purposes but for the application of practical methods for improving work processes and specifying computer tools to support work activities, including designing. On the one hand, how social structures and social processes work at a level broader than individual human thoughts and actions is not only the subject matter of sociology but something we need to think about to live our lives; we all treat them as objectively real and (unless we are hardline interpretivists) believe they are real. Functionalist approaches to social science depend on seeing social structures as systems of interlocking causal entities that are broader and less concrete than individual people (for instance, Parsons, 1951). On the other hand, it is difficult to see how anything beyond physical objects and individual human thoughts and actions are genuinely objectively real, deserving the ontological status of things; and people can legitimately disagree about what the social structures are and how they work. In the case of the division in sociology between the Durkheimian positivist camp and the Weberian interpretivist camp, we are inclined to be pragmatic: we are in sympathy with the interpretivist view that individuals' differing conceptions of social structures and phenomena are real and primary, and that social structures cannot be said to have objective existence even when there is a great deal of consensus about them, but we take the view that it is frequently both unavoidable and useful to treat social structures as though they were objectively real, and regard doing so as a legitimate pragmatic compromise. Our ideas have been influenced by Soft Systems Methodology (Checkland, 1981), which is an approach to understanding and suggesting improvements to work systems that combines a systems theory view of what is going on as comprising interlocking causally active components with the central premise that different views of how the system works are equally valid and there is no objectively correct view. However Checkland (1981) is emphatic that treating any particular view as being objectively correct is not only illegitimate but harmful, and that it is essential to avoid this in applying Soft Systems Methodology.

At a finer-grained level, what can exert a causal influence so that it should be regarded as a participant in a causal structure is also debated. One important theoretical approach is Actor-network theory (Latour, 1987, 2005), which insists firmly that inanimate objects have properties and behaviour that influence what humans do, and play essential roles in human systems of activity, so should be treated as actors in their own right. Others do not wish to ascribe agency to inanimate objects. As design researchers who are acutely aware of the importance to design communication of the properties of the representations used to convey design information, we favour the view that objects should be treated as participants in causal systems.

Methodology

This chapter draws on two types of studies carried out by the authors: case studies of design behaviour, developing a detailed understanding of how particular aspects of designing are handled in individual companies, and a research project specifically on comparisons between different design domains. The Across Design project invited twenty designers to present witness accounts of the practices in their fields focusing on one of their own projects (see Blackwell et al., 2009, for a discussion of the methodology; Eckert et al., 2010, for a summary of the results). The witnesses were design experts with 5 to 50 years of professional experience from a wide range design fields including engineering design, software design, product design, graphic design, fashion design and food design.

Table 1. Summary of empirical studies

Domain	***Interviews***	***Companies***	***Year***	***Focus***
Knitwear	80	25	1992-1998	Communication in teams, inspirations (Eckert, 2001; Eckert and Stacey, 2001, 2003)
Engineering	42	2	1999-2003	Engineering change (Eckert et al, 2004)
Engineering	25	2	2000, 2005	Planning (Eckert and Clarkson, 2009)
Engineering	15	1	2008	System architecture (Eckert et al, 2012)
Architecture	13	1	2007	Decision making in design
Construction	8	4	2009-2012	Decision making in hospital refurbishment projects (Garthwaite and Eckert, 2012)
Engineering	11	1	2011-2013	Testing in design processes (Tahera et al, 2012)

Table 1 summarizes the empirical case studies, which all followed a similar format of semiformal interviews lasting between 30 and 120 minutes. As far as was possible, these interviews were recorded and transcribed. Otherwise field notes were taken or summaries generated immediately after the interview (in the early knitwear studies). The interviews were conducted to investigate a particular question in each study, such as communication and later inspiration in the case of the knitting studies. However the issues considered in previous studies were revisited with additional questions in later interviews. For example the issue of communication, the subject of the first study, was picked up again in the context of studying planning practice (Flanagan et al. 2007). For the original analyses the transcripts were analysed using a combination of grounded theory (Goulding, 2002) and deliberate falsification of current assumptions (Stacey and Eckert, 1999).

This chapter takes a slightly different approach in that it reflects over the insights of the other papers to come up with a higher level perspective on the drivers of the design processes.

We have looked before at the relationship between constraints and how designing is done, focusing on creativity in design. We have argued (in Stacey and Eckert, 2010) that the main difference in the modes of creativity between engineering and artistic design domains lies in how constrained the design problems are that the designers have to engage with. Engineering designers are usually confronted with difficult, complicated, tightly-constrained problems and have to be creative in the way they reconcile and frame often contradictory constraints to have a well-defined problem; while artistic designers engage in a deliberate constraint-seeking process to narrow the potential design space to again end up with a reasonably well-constrained problem. Design spaces are rarely equally strongly or loosely constrained across all aspects, so that designers can trade off freedom in one area against constraints in another. Following on from this, we argued (in Eckert et al, 2012) that in engineering, designers are often looking for solutions that meet new requirements and constraints but require the fewest changes to existing designs. Creativity therefore often lies in the clever tweak rather than in the radically different solution.

Constraints

A constraint is a restriction that an action or the solution of a problem must comply with. Designers use constraints on the designs they develop not just to check the viability of design proposals but also to guide the generation of new design ideas. Constraints on designing take a variety of forms: constraints of different types exert different influences on designing (see Stacey and Eckert, 2010). They vary in whether the constraint is explicitly stated or tacitly assumed; in whether conformity is binary or a matter of degree; in whether they refer to measurable physical properties or are experiential; in whether conformity can be measured objectively or is a matter of subjective judgement; and in whether they are hard or soft – that is, whether the constraint must be met, or can be relaxed if necessary to reach some solution rather than none.

Explicitly stated constraints play an essential role in more formal approaches to designing. Constraint programming is an important technique in artificial intelligence (for a survey see Rossi et al, 2006). It plays an important role in design optimization (Talbi, 2009); and has been applied successfully to design problems, such as circuit board design, which are well defined and where any solution can be employed as long as it meets all the constraints (Van Hentenryck, 1989). Constraint-based planning is often combined with hierarchical task planning (for instance Ambite et al, 2005). The success of constraint programming for some specific design problems notwithstanding, this paper is not suggesting all design problems are fundamentally search problems that can be resolved if the constraints are known; rather that constraints in the sense of conditions on a solution or its process of creation fundamentally shape the human design process.

Although human reasoning about design problems is radically different, as it employs subtle and powerful pattern recognition and synthesis operations, and cannot employ the extensive combinatoric searches that are easy for computers, humans also depend on understanding or making constraints to contribute elements of solutions and restrict the scope of imagination to possibilities that are likely to be fruitful. Research on creative idea generation, such as Finke's (1990) work on pre-inventive forms, where he encouraged people to imagine particular shapes, and then use them in creative tasks, indicates that tasks requiring imagination (but soluble in a wide variety of ways) are made easier by tight constraints that supply elements of solutions to be combined and adapted, and reduce the spaces of possible solutions (see Finke, Ward and Smith, 1992). The nature of the constraints determine what people think the design problem *is*, as well as what appears to be a plausible part of a solution. The central role of the most salient constraints in guiding the conceptualization of the design problem and the generation of the key elements of the design has been well recognized by design researchers for a long time (see Darke, 1979).

Constraints on design have three main sources:

- The *problem* that the design must solve or the need that the design must meet; this includes product requirements, manufacturing requirements, and constraints stemming from the strategic goals of the company.
- The *process* by which this is achieved.
- The *emerging solution* - since making certain decisions will rule out or restrict options for other later decisions.

The constraints are different for each design problem. Many constraints are specific to the particular design, but many arise from the individuals that design the product, the product context, the organizations involved in it and the wider market context. Figure 3 shows a set of sources of constraints for our case study examples.

In software development, requirements that a system should meet to do its intended job successfully are usually distinguished from constraints, which are restrictions on what the system must be or do separate from user needs. In engineering design where many constraints are expressed explicitly, constraints and requirements are very similar. However, constraints arising from the emerging solution are usually not expressed as requirements. For the purposes of this paper we can treat requirements as being constraints.

Problem constraints

Constraints in design are closely linked to requirements but go beyond what is expressed as requirements. Requirements for the product arise from the user needs and desires that are addressed with the product as well as organizational needs for the products, such as cost targets. Many requirements can be immediately expressed as constraints, e.g. the vehicle must carry of a load up to 1000kg, while others are far more vague. For example, the aesthetic effect of the sound of a car engine is a vague experiential requirement, but car companies have techniques and procedures for defining the desired acoustic properties and turning them into objective performance requirements. In the early stages of a design processes these requirements are translated into a technical specification. The technical specification defines the characteristic that the product must have in ways that can be assessed. A product is both tested against the technical specification in verification processes and against the requirements in a validation process. In generating a technical specification many of the potential contradictions in the list of requirements are resolved. However design work often starts with a contradictory set of requirements.

Most engineering products are designed by modification from existing products. The products are assessed where they don't meet existing requirements and are changed accordingly. At the same time engineering companies aim to minimize novelty in a product, and therefore set percentage targets for the degree of reuse or explicitly ring-fence particular components. However changes have knock-on effects on other parts of the product, which were not intended to be changed (Eckert et al, 2004). They can also bounce back when a component cannot be changed and a new solution needs to be found. The new design is severely constrained by what can and cannot be changed.

For many products, regulatory frameworks are a major source of constraints. For example the automotive industry is very severely constrained by emission legislation. Unless they have an engine that meets a particular requirement, they won't have a product to sell. The aerospace industry has to comply with stringent regulations to meet certification requirements. While safety-critical products are most highly regulated, other products are also constrained by legislation, for example around the use of materials.

Process constraints

All design projects are constrained by time, cost and resources even though the degree of severity of these constraints might vary. The skills of the designers in house and across the supply chain affect the solution itself as well as the process by which it is generated. For example an engineering company with a large in-house control engineering department might develop or adapt their own control software and therefore can make changes to control software throughout the design process. Without this resource the company might subcontract the development of software and be reluctant to ask suppliers for a late change, and deal with an emerging problem in a different way. Time and cost constraints affect the amount of design effort the company can afford. This limits the range of ambition or the degree of innovation. This has to be traded off against other factors such as testing time or cost, or cost and lead time. Organizations typically have standard processes, which govern when and by whom decisions about the product need to be taken. They also have established ways of interacting with their suppliers and dividing the work across the supply chain. Characteristics of the organization are directly reflected in the process constraints.

Solution constraints

The way the process is managed and organized constrains the tasks the designers undertake, and the order in which they are undertaken. This is one way in which the emerging solution constrains the further development of the new product. The order in which decisions are taken fundamentally affect the freedom designers have (Eger et al., 2005). Some components are given from a previous design and others have to be frozen early because of long lead times. This in turn sets parameters for other components in the product, even though they are not affected directly by external requirements. Typically companies keep components with shorter lead times open to the end to be able to absorb changes. For this reason many changes in later stages of a project are dealt with by software changes. Lead times are, however, not the only reason to freeze components or parameters. Decisions also need to be taken if multiple teams need to work with set values to reduce iteration. Sometime these products are designed by different designers using preliminary values for each other's decisions to develop a first attempted solution which is then refined during several round of iteration until convergence is reached (Wynn et al., 2007). To avoid this, engineering companies use performance models to derive key parameters from the requirements and cascade them down across the product, making decisions in a planned sequence (see Wyatt et al., 2009). In the diesel engine case study company, reuse of components is managed by feeding them as constraints into a requirement cascade process.

Meeting constraints

Engineering designers are often confronted with contradictory constraints; for example weight and performance requirements might be in direct contradiction. The TRIZ methodology for engineering creativity (e.g. Altshuller, 1988) is based on resolving such pair-wise contradictions between requirements by identifying a new solution principle for what might be a well-known class of problem.

Meeting conflicting requirements as well as possible involves two distinct but integrated operations, relaxing constraints and finding solutions. Weak constraints can be relaxed to allow less ideal but feasible designs; conflicting strong constraints, that must be met, make a design solution impossible unless some constraints are relaxed. Design problems are constrained both by explicitly formulated requirements and constraints, and by implicit assumptions about the form of the solution. (Designing is often influenced by *fixation* on the features of previous similar products, see for instance Purcell and Gero, 1996; Altshuller, e.g. 1988, discusses various sources of psychological inertia and how they can be overcome within TRIZ.) However, designers often have a choice in how to approach a given design problem. For example the development of a new vehicle might include targets for the percentage of components to be reused, but designers have a choice which components they will try to keep and which they change.

The tightness of the constraints varies enormously between problems, and individual products can be very tightly constrained in some ways and loosely in others. Technical problems can be underconstrained where the requirements are weak or are not yet understood. Sometimes engineering solutions must meet tacit sociocultural expectations, for instance concerning the aesthetic appearance of an engineering product. Similarly artistic designers are often faced with seemingly impossible constraints from the business context or the technical realisation of the product. In knitwear design it is often novices and outsiders who produce innovations pushing the boundaries of what is possible; Stacey et al. (2002) argued that this is precisely because they don't know the tacit and implicit constraints and therefore dare to push for what seems impossible or not worth the fight to the experts.

Drivers affecting product classes

The constraints discussed in the previous section are individual for each product. However many of the drivers that shape design processes are shared with other products, not necessarily ones in the same domain. This section discusses drivers that shape the design processes of entire product classes. These correspond to broad needs and product characteristics that translate into particular types of constraints for individual products. They also go a long way to explaining differences between processes, for example in explaining why design processes in the aerospace industry are different to those in the automotive industry.

Different drivers

There are many drivers that affect classes of products. The following ones were particularly pertinent in our case studies. This is by no means a complete list, but illustrates some high level drivers, which are properties of the product or the context in which they are deployed.

Product complexity affects not only the effort that is involved in a design process, but also much of its execution. Very complex products, such as aircraft, have to be designed by big teams of designers, who have little overview over all of the activities going on the development of the product and therefore need additional layers of management to coordinate. This is for example a marked difference between the development of jet engines and the development of diesel engines. Most of the diesel engine engineers understand how all of the components work at least at a higher level and therefore know the key dependencies. This also enables them to communicate proactively across the design process (see Flanagan et al., 2007). Product complexity is a strong driver for incremental design and the reuse of product models, to reduce the overall effort and thus the product cost.

Safety criticality is of course a matter of degree, but certain products like aircraft or power plants are subject to the most rigorous safety criteria. These products are very rigorously tested, which adds to the cost of the development. In software safety critical software not only needs to be tested, but needs to be mathematically proven to be correct. Because of the effort involved in testing, designers are also very reluctant to change the product, because every change would require retesting and potentially recertification.

Product lifespan, both in terms of time in production and lifetime of the product, determines many of the design tasks that need to be undertaken. Long lifetime requires very careful user analysis and a system architecture that potentially enables the company to upgrade parts of the product without affecting other parts. This requires a certain degree of redundancy in the product and an awareness of the margins for change of components. Long lifetime products also require spare parts over a long period of time; either these need to be stockpiled or manufacturers need to assure that they can deliver parts. An interesting illustration is how companies handle issues around rare earths. Jet engine manufacturers are aware of long term resourcing issues and are making sure they have the spare parts and look actively for alternative designs. Mobile phones are also affected by shortage of rare earths, but for them it is a cost and an issue of recycling the materials at the end of the product’s lifespan.

Volumes of production have a huge effect on how cost-critical all design decisions are. In the automotive industry, volumes for platform components, like car lights, can be in the hundreds of thousands, where every cent saved adds up to a huge amount of money, compared to thousands in the aerospace industry. By contrast building are typically one-off designs. In a one-off design it is possible to negotiate compromises or problem fixes with one client, without needing to be concerned about other users or other contexts. Whereas high volume products have to operate under all the circumstances in which all the potential users might operate them. High volumes also provide companies with enormous power over their suppliers, who will adjust their ways of working to attract volume customers. For one-off products the power often lies with the suppliers who are supplying multiple customers. For products produced in smaller volumes the pattern of supplier relations is more varied. Companies in the aerospace industry usually have a dedicated range of suppliers who make money out of long standing collaborations and the long term spare part contract; however on components where they are competing with the automotive industry, aerospace part are much more expensive and potentially difficult to source.

Connectivity within product ranges refers to the relation between different products designed in the same company. Some companies offer a range of products or product families which are themselves not very well connected; for example a manufacturing tool maker might make different types of tools and for each type offer a product family without much connection between the product families in terms of functionality or components. Other companies work very hard to develop a product platform, where parts are shared across a wide range of products. Changes to any platform part are expensive, because they not only affect the cost of that particular product but have knock-on effects on the profitability of other products built on the platform, either because the standard part becomes more expensive or because it is produced in smaller volumes.". This makes these organisation both reluctant to make changes and bureaucratic in carrying out the changes. Large platforms also almost inevitably mean that the components are better suited to be used in one product than in others. There is an inherent conflict between an optimal platform and an optimal part. In those respects the designers of one-off products have much greater freedom.

Interactions with users varies enormously between different products. Products that are sold directly to the end user require direct engagement with the users' requirements and issues of usability. Components for other products designed without direct contact with the end user still have to comply with requirements from the user, but concerns about human interactions focus on manufacturing and maintenance where the personnel can be trained and the interaction can to some extent be controlled. Products for end users have to engage with issues like ergonomics and inclusive design. For products with direct user interaction aesthetic criteria are a major concern. These products must appeal to the users and not just meet requirements. Products that are sold to professional customers, like production machinery, still benefit from an aesthetic appeal, but are mainly sold on functionality. Aesthetics is not an issue for components inside other products, like hydraulic pumps.

Fashion plays a huge part in the design of many products that are sold to end consumers. For products like garments or many consumer products the functionality remains relatively stable, but the form depends on a context set by other products. Consumers select cars to some extent on their visual appearance, and a wrong call on the car styling can jeopardize the commercial success of a technically very good product. Fashion has a certain built in obsolescence; this affects the lifetime of products and thus sets many technical constraints on a product, e.g. targets for durability.

Profile of drivers

The factors are not independent, but act as causal drivers for each other. High product volumes for example encourage companies to consider the development of product platforms, because it increases their opportunity to make savings. Many of the highly complex products also have long lifespans, because users and clients cannot afford to replace them all that often.

Figure 1 shows indicative profiles of drivers for different industry sectors on a simple high, medium and low scale for each driver. The product classes reflect products that are often studied in the design literature. While there is of course an enormous variability within each of these classes, as the graph illustrates the spectrum is completely covered and most combinations of these drivers do exist in some product or other.

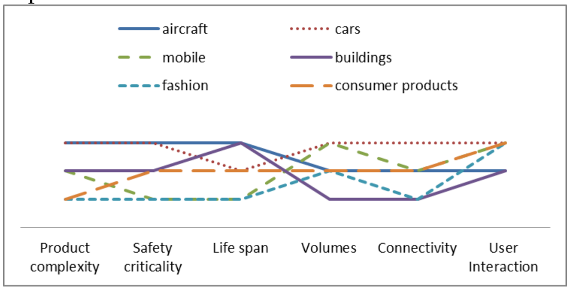

Fig. 1. Profiles of drivers

Objective or subjective constraints

Products are assessed against the product requirements, but projects are also assessed against whether they have met the other constraints placed on the product. For example an excellent product that has run over time in the development process can cost its company a lot of money and mean that it will lose market share. Companies are assessed against the profit that they make, but also against the reputation they have built up through their products.

Many of the constraints are explicitly expressed in product specifications as ranges, absolute values or clear descriptions of the target behaviour or function. Others are expressed explicitly elsewhere in the organisation, but might not be spelled out clearly for a particular product. For example a company might aim at a certain level of innovation across its range of products. It does not necessarily parcel out an innovation target for each project, but designers are aware that innovation is an issue. However constraints may be unstated for a number of reasons. Some are almost too obvious to state. For example an item of clothing needs to be safe to use: this is not included in any specification for a specific product, yet designers are conscious of it and consider it for example in the context of flammability of materials. Experiential constraints work rather differently: some factors that are evaluated perceptually are recognised to be important and govern conscious choices. Tacit constraints influence the procedures designers follow and the choices they make without the designers necessarily being fully aware of them. Brand image in general is very difficult to express explicitly, yet designers are aware of what constitutes a product in the brand style. Jonathan Cagan and his colleagues have explored the use of shape grammars as a means for making perceptually understood brand styling explicit, which is not a trivial task (see for instance McCormack et al, 2004). Knitwear designer often comment that they can't describe what their brand's products look like, but they recognise them when they see them. Aesthetic characteristics are also often tacit. They are not defined in product specifications or even on a higher level for an organisation, but it is understood that products need to fit into current fashions and styles. Even if a style or theme is given, what this entails can rarely be expressed explicitly. However, as we have argued elsewhere (Eckert and Stacey, 2000) it can be expressed indirectly by providing indications of a legitimate solution space in terms of other objects that already express this space.

This points to another important distinction, that between constraints that can be objectively assessed and those that cannot. Many engineering constraints can be assessed objectively when they are measured during tests. For example a testing regime reveals fuel consumption of engines under many different circumstances. However many of the perceptual requirements and constraints are very hard to assess objectively. While it is possible to express some aesthetic considerations in explicit rules like the golden ratio and assess them objectively, many are completely tacit. Assessments that require an awareness of a rich context are often very subjective. For example the assessment of styling of textiles or cars require a deep understanding of other products, and whether the product would appeal to the target customers given the other products that the customers are likely to be familiar with. While other designers or users might concur with these judgements, consensus does not make the assessment objective.

This changes the role that designers play in the design process. With objective product criteria the success of the product and the success of the individual designer can be separated. The product might be late or not sell, but as long as it can be demonstrated that, say, the stress analysis has been correct, individual designers won't be negatively affected by product failure beyond being affected by the fate of the organisation. By contrast, for products which are partially or wholly assessed subjectively, the designer is also the person who makes judgements on how well the design works. The designer becomes the guarantor of success. This is particularly pertinent in fashion products.

Without objective evaluation criteria, companies, designers and customers have to fall back on their own instincts or use reference points to assess a product against. One way of selecting reference points is by looking at the work of established designers or prominent companies. This is extremely important both in the fashion industry and in product design, where famous star designers set trends that are followed by others. In architecture well-known buildings serve as precedents that serve to validate design choices as well as sources of ideas (Oxman, 1994; Goldschmidt, 1998; Defazio, 2008; cf Clark and Pause, 1996). The cult of the star designers is a direct result of the inability to assess the quality of designs objectively. There are few famous engineers.

Examples of different behaviour: diesel engines and knitwear

Two processes that we have studied over a long period of time are diesel engine design, in our studies on engineering change, product planning, system architecture and testing; and knitwear design in studies on communication and mechanisms of inspiration. The products and processes are very different in terms of both constraints and drivers. Figure 2 shows the profile of drivers for both domains.

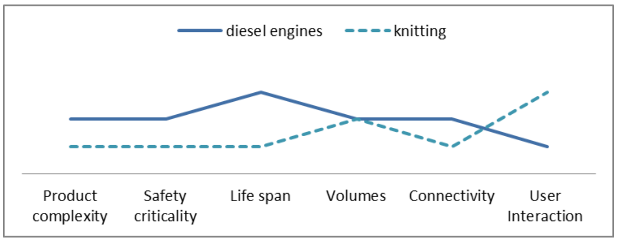

Fig. 2. Profiles for diesel engines and knitwear

Knitwear designs can involve technically tricky detail design but are simple products compared to large-scale engineering (see Eckert 2001; Eckert and Stacey, 2003). The key driver for knitwear design is fashion. For clothing, fashion is still seasonal. While a strict schedule of two season launches every year has been softened to several releases every year in most companies, clothes are still dictated by the weather and seasonal events and designs need to be ready to be launched on time. This makes time one of the greatest constraints on the design process. The designers work on the clothes by season or as groups of garments that are launched together; and start as soon as possible when the previous collection has been passed on to production. Much time is required to get the details of garments right. There are simple characteristics that a garment much have (e.g. fit the body measurements, display the key motifs, etc.), but much is a matter of aesthetics and therefore very subjective. The designers and their technicians work on the designs until they run out of time, and release products even though they know that they could be improved. The textile industry typically produces runs of 100 to 1000 garments and the profit margins on individual garments are very small. Therefore the designs have to be costed very carefully, and development effort even by two or three individuals is a major cost factor. In some cases it is possible to pass the costs on to customers, but usually knitwear designs are sold in price brackets so that they have clear target costs. These costs are balanced across an entire collection. Within a collection there is a balance between successful design features picked up from the previous season and new features that are introduced. Designers need to aim for an appropriate degree of novelty in relation both to their own past designs and to fashion trends that are emerging. Knitwear designers do not interact directly with their customers, but they have a sense of the taste of their target market and how it will evolve over time, therefore they know how much novelty they are aiming for in a collection to attract their customers, while not alienating them.

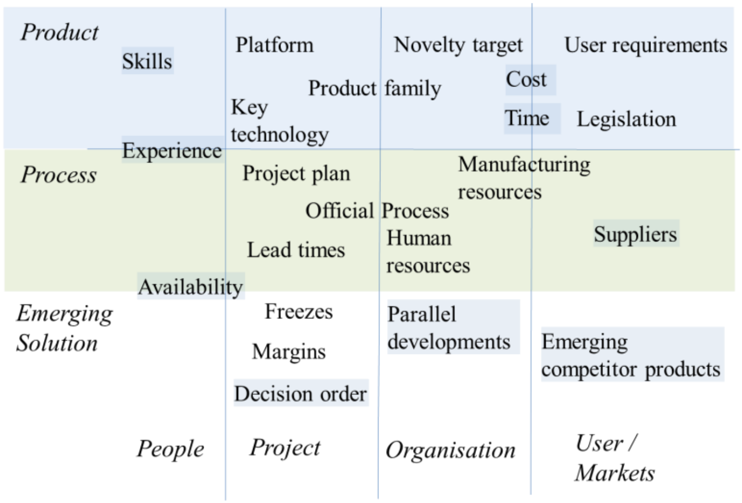

Fig. 3. Constraints for knitwear design and diesel engine design

Diesel engines are an established technology that has been refined over the last hundred years. Diesel engines have become increasingly more complex, but have not reached the level of a jet engine or an aircraft. Individual designers have a clear understanding of the core technologies. Diesel engines are very compact, because they typically need to fit into tight spaces. This adds to the challenges posed by their highly interconnected architecture, and keeping track of the product connectivity can be very difficult. Diesel engines are highly regulated in terms of emissions for particular markets. The progress of emissions legislation sets a tight schedule for the development of new products as well as product constraints that need to be met. Off-highway engines are used at nearly peak capacity for most of their lives and have very strenuous requirements in terms of robustness and durability. Reuse of tried and tested components and solution principles is a way to manage that, and the company has stringent novelty targets that must not be exceeded. To meet the strict launch times the company needs to manage its supply chains very carefully and freeze components in time. The frozen components therefore very strongly constrain the rest of the design as it emerges. To enable timely freezes and planning of the design process, decisions are being taken about the design early to enable different teams to work in parallel and follow the targets set by both the official design process and the suppliers. Diesel engines are usually provided to the OEMs for vehicles, so that the diesel engine company has relatively little contact with the end users, but they receive strict requirements from their customers. At the same time they have to be mindful of the use conditions of the product. Key technologies are employed across a range of product families, and innovations on other product families are usually lifted across to a new development. Standardizing as much as possible across different product families is a major driver that generates constraints on product development.

Figure 3 shows the key constraints in both knitwear and diesel engines. The constraints with the dark background apply to both domains equally, while the remaining constraints mainly applied to the diesel engines.

Conclusion

This paper argues that design processes are influenced by the constraints placed on the product and the process as well as those that arise through the way that the design process unfolds. Many of the constraints are concrete manifestations of factors that apply to classes of products and act to shape their design processes in similar ways. The paper has discussed a number of these causal drivers and patterns of constraints that were apparent in the authors' case studies, and which explained aspects of how the design processes were organized and the types of problems designers were confronted with.

The view put forward here – modelling design processes as networks of interlocking causal processes influenced by causal drivers – is an approach to building partial theories of aspects of designing that explain why particular design processes are similar or different in particular ways, and help to predict how new or modified design processes will behave. We see the main benefit of the analysis of causal drivers influencing design processes in proving questions that lead to a deeper understanding of an individual design process: Does this causal influence happen here? If so, what form does it take? If not, why not?

This paper stands at the beginning of a long term research agenda to understand design processes in terms of drivers, constraints and characteristics, which will need to go through several steps. An ontology of the key concepts, such as driver, constraint and requirement, will need to be defined to enable a clear distinction of concepts, as well as a clearer account of how drivers, constraints, requirements and so on can vary. By looking at the constraints governing specific processes and causal drivers influencing different design domains, typologies of constraints and drivers can be built, and a set of causal maps constructed, which together draw a broad picture of design. This can then be consolidated into larger and fuller causal maps, providing a toolkit for characterizing and predicting the behaviour of new design processes.

Future research is required to develop clearer distinctions between different classes of causal drivers, such as requirements, constraints, drivers and conditions or the definition of one clear concept encompassing all – constraints – that is seen in terms of relevance and malleability. To both validate and apply this way of thinking it is necessary to develop a set of categories of drivers and constraints that are applicable to a wide range of processes."

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