Past Designs as Repositories of Tacit Collective Knowledge

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Abstract: As most engineering design proceeds by modifying past designs and reusing and adapting existing components and solution principles, a significant part of the knowledge engineers employ in design is encapsulated in the past designs they are familiar with. References to past designs, as well as encounters with them, serve to invoke the knowledge associated with them and constructed from them. This paper argues that much of this knowledge is tacit consisting in and/or made available by the perceptual recognition of features and situations, using a discussion of design margins to illustrate how engineers use tacit knowledge in reasoning about the properties of new designs.

Key Words: Philosophy of design, tacit knowledge, know how, object reference, engineering epistemology, design knowledge, engineering design practice.

1 Introduction

The design of complex products like trucks, cars or helicopters usually builds on past designs (see Eckert et al., 2010). As sources of elements for new design at different levels of abstraction, past designs are important repositories of knowledge for engineering organisations. Many larger engineering organisations use knowledge management methods to capture knowledge about how to develop products in terms of procedures, general precepts and indicators of best practice, however as Addis (2016) argues for construction knowledge, the limitations of the codification of knowledge are grounded in the nature of the types of knowledge engineers employ in product development. Understanding how past designs function as repositories of knowledge requires both theoretical insight into the nature of engineering knowledge and the way engineering processes work. Product behaviour is heavily dependent on the context in which it is used and holistic product properties which are difficult to describe explicitly often depend on multiple interacting factors (see de Weck et al, 2011). During testing organisations use various methods (with simulation techniques in particular gaining in importance) to assess holistic product properties, but the assessment of such properties is still heavily reliant upon expert judgement (Tahera et al. 2019). Experts assessing these holistic properties often have years of experience working with one kind of product and talk about having a feeling for a product. Due to their developed sense about how a product behaves they can predict how new designs will behave based on their understanding of existing and similar products. For example, the handling of a car is difficult to describe explicitly as this depends not only on the components of the car like the suspension and seating but also upon road and weather conditions with experienced test drivers having a sense for this. This paper is interested in how this form of tacit knowledge is related to past design and how past designs serve as a trigger for this form of knowledge.

The fPET community has traditionally looked at technology either from a philosophical perspective or a practitioner's perspective. This paper comes from a slightly different perspective: Engineering design research, which has the aim to improving practice through the development of guidelines, methods and tools based on a solid understanding of designing (see Blessing and Chakrabarti, 2009). (Whether design research constitutes science, or how much of it does, is a controversial issue, but the term *design science* is often used for the field.) Horvath (2004) argues that in design science the "knowledge obtained by empirical exploration and/or rational comprehension should be transformed for practical/pragmatic deployment". To achieve this it studies engineering design processes, for example through interviews or observations, but also through lab experiments, drawing on the methodology of many academic fields (see Eckert et al, 2003). It uses the insights of other fields to elucidate phenomena in design and feeds rich practical examples back to the contributory research disciplines. Archer (1981) has argued that design epistemology is one of the key disciplines of design science. Our contribution is to design epistemology in this tradition.

The argument put forward in this paper is grounded in the second author's own empirical studies of design processes over a period of nearly 30 years, exemplified by our studies of design margins, which involved the active participation of industry experts, introduced in section 4. We seek to connect our empirical observations to a Rylean perspective on the nature of know how (see Ryle, 1946, 1949; Löwenstein, 2017), to understand the role that past designs play as repository of design knowledge and to a Wittgensteinean view of how language is used to communicate concepts (see Wittgenstein 1953).

2 Object References in Engineering Design

Engineering designers frequently refer to both their own and others' past designs (Eckert et al., 2005). For example, engineers for a military helicopter used phases like "a radar like the one for the Italians" to refer to a exceptionally heavy radar, which required significant reworking of the helicopter tail (Eckert et al., 2004). For the purpose of this paper, we use the term "object reference" loosely for verbal or ostensive references to existing products or elements of products. Existing designs contain combinations of components or solution principles which would be difficult or time consuming to describe in other ways than by object references. Such references can be specific or refer to classes of objects. Object references are a powerful and parsimonious way to express engineering designs and think about them. The objects referred to are shorthand ways of expressing relational concepts, solution chunks and experiences during the product development or life cycle process. Object references recall positive and negative experiences in the design process such as those with team working and suppliers. These experiences can be deeply personal, as engineers experienced them in their own way and interpreted these experiences in their own way. This gives object references a degree of subjectivity. As future product behaviour can be partially understood through calculations and simulation, engineers draw on experience of similar products to a certain extent deduce design rationales, recall past product behaviour to predict future behaviour, and often have tacit understanding of how product features and changes to them affect product behaviour.

It should be observed at this point that the ways that object references work depend on the other knowledge designers have, their intentions, and the interpretations they put on the object references. Object references differ not just in the intended scope of what they include but also in their specificity; sometimes referring to individual objects, sometimes to individual designs, sometimes to broader categories of types of artefact, which can lead to miscommunication. Because of this, the notion of 'object reference' we use is a natural concept emerging from the family resemblance of many different uses (see Wittgenstein 1953). It follows that a requirement of understanding object references is that there must be intersubjective knowledge of the objects they refer to; however, the hearers' knowledge and experience will not be identical, so the interpretations hearers put on object references may not be quite the same. This view aligns with a view of language as a practice within a community of users (Wittgenstein 1953). For object references to be comprehensible engineers must have the technical knowledge to understand what they are seeing and recognise the significance of particular details. Such background can be acquired through gaining general engineering knowledge but much expertise is slowly developed through working with a product and in a particular organisation.

3 Design Margins in Object References

To illustrate the importance of tacit knowledge in object references, we draw on out cases studies on design margins (see Eckert et al., 2019 and Eckert et al., 2020 for a discussion of case study methodology and the resulting theory). While the concept of a margin intuitively indicates some manner of buffer, the word is mainly used in the aerospace industry. In case studies engineers also used terms such as room for growth, intentionally designed in and protected margins, design margins for allocated buffers against changes in the requirements during the design process, safety margins against misuse of the product and so on; other industries use terms like excess, bias or overdesign for margin-like concepts. For present purposes a design margin is defined as "the extent to which a parameter value exceeds what it needs to be to meet its functional requirements regardless of the motivation for which the margin was included" (Eckert et al. 2012). Margins are critical for determining whether a system part requires significant redesign or can be adapted for the new design. They can be divided into buffers against the variability of uncertain requirements and excesses which can be taken away or repurposed with different groups of engineers adding margins throughout the design process (Eckert et al., 2019). As illustrated in Figure 1 engineers add margin requirements as safety margins, to enable growth in future planned product iterations, and to permit product definition to accommodate requirement changes during the design process.

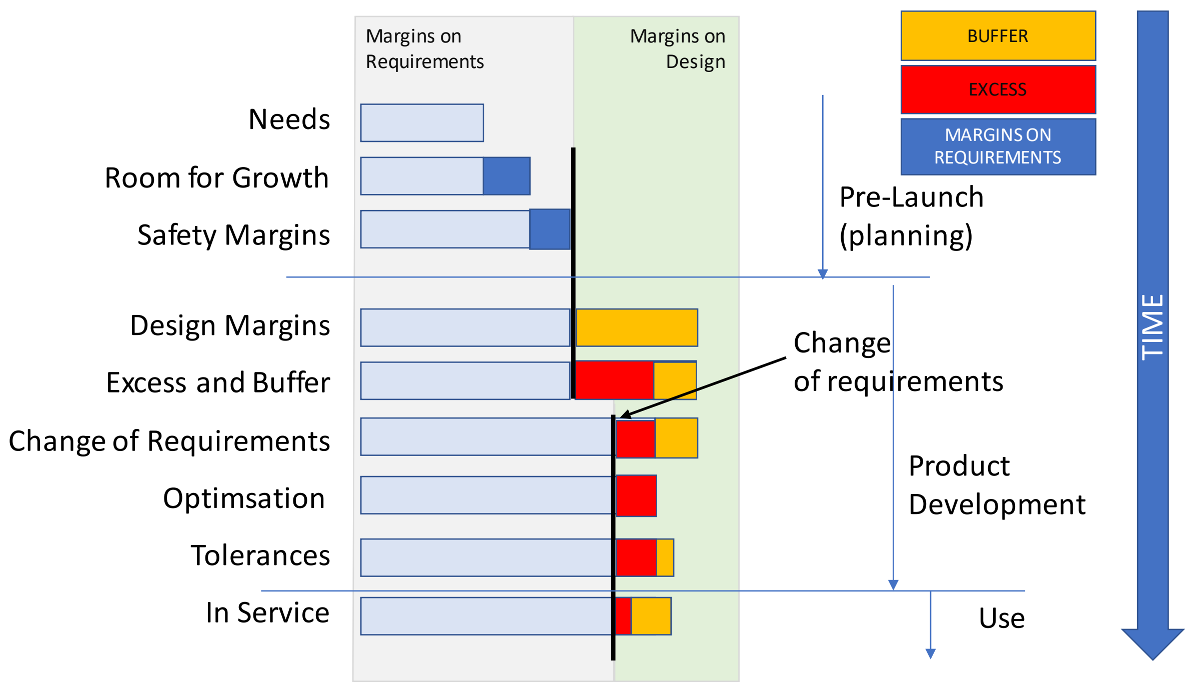

Figure 1: Margin concepts through the product development process [Eckert et al. 2020]

Engineers add design margins from the start, which are slowly eroded during the design process as requirements increase, or the product requirements change; and removed in the product optimisation phase. Exceeding margins can lead to possible large scale change propagation (Eckert et al., 2004). Yet engineering companies don't track margins systematically, but experienced engineers working on particular product aspects are aware of these margins through understanding design intentions or interpreting test data.

Although it is theoretically possible to establish product margins by testing a product to destruction or running simulations to establish margin values under certain circumstances, in most cases the understanding engineers have of these margins is tacit (Eckert et al. 2004). As margins are not captured explicitly, only engineers with experience of past design processes know at the beginning of the design of the next product generation how easy or hard it is to adapt systems and which margins require protection. Systematically searching for margins can be very time-consuming so engineers either remember or use their intuition to identify where there might be usable margins. Such intuitions are grounded in tacit knowledge bringing together multiple aspects of engineering knowledge. For example, engineers try to recollect failure or warranty cases in similar design or check whether a component or an aspect appears out of proportion with judgements of similarity, exception or relevance being tacit. Such judgements require deep contextual knowledge of how the product has been used or what challenges have been faced during the development process. In this sense the past designs serve as indices for knowledge.

Margins cannot easily be deduced from conventional design representations (such as CAD models) because margins depend on both on intended product use and interrelationships between different product components. For example, whether a component can carry additional payload depends on the load from other components but also on how the product is used (such as in a hot climate with heat expansion producing vibration requiring extra dampening). Past designs serve as a shorthand for bundled collections of knowledge.

4 Object references as parsimonious descriptions of engineering designs

Products can be and are frequently described completely unambiguously in different models, such as CAD models or manufacturing models. However, such models are partial as they only focus on their intended purpose (see Pirtle, 2009, and Eckert and Hillerbrand, 2018, for a discussion of models and their epistemic functions in engineering). For example, a CAD model typically describes the structure of a product, that is the shape of the elements and their relations. As the example of the margins illustrates, not all important information is typically not captured in CAD models, which also do not capture the rationale or the intended function. However, in conversation or when thinking about new designs are in the early stages of development these do not exist yet. Designs can also be sketched, but sketches are partial and ambiguous (see Purcell and Gero 1998 for a review of research on sketching). A verbal description of an emerging design, like any other kind of complex phenomenon, is generated from a particular perspective and expressed through a narrative. This may introduce a bias in the description of the design which is not immediately apparent.

Object references are parsimonious descriptions which allow the expression of complex concepts through simple pointers. They are valuable because in engineering design the complexity of the product and the consequent amount of information associated with it can be enormous. Object references allow shifting between levels of details and bringing out explicitly what has come into focus, while leaving the wider context implicit. Conceptualising object references in an epistemological way, as keys into elements of engineering knowledge, enables us to see how the import of object references can be variable and contextualised, with the content and level of detail of the knowledge invoked being dependent on the intended use of the object reference. While information exists on different levels of abstraction, there is a limit to what an individual engineer can know and what they can describe in finite time. Recognising these limits on the scope of individual knowledge and thus the implications of this for intersubjective knowledge and agreement is crucial for the effective use of object references in engineering design practice. Tacit knowledge in practice encompasses both product and background knowledge as both are combined in understanding object references.

5 Object references and engineering knowledge

Engineering knowledge can be sliced up in many different ways (for example see Houkes 2009). Vincenti (1990) in *What Engineers Know and How They Know It* influentially outlined a map of engineering knowledge, grouping what engineers know into six categories, namely:

- fundamental design concepts
- criteria and specifications
- theoretical tools
- quantitative data
- practical considerations
- design instrumentalities

Design know how comes under the category of design instrumentalities but also involves knowing how to make use of his other categories of knowledge (such as quantitative data). Although Vincenti does not disregard the action skills involved in design practice and the other knowledge generation activities he is primarily concerned to characterise the explicit articulated knowledge engineers use, with declarative knowledge of how to conduct procedures forming part of this. Using these distinctions four broad categories of engineering knowledge can be identified:

- information about materials, artefacts, and systems that can be articulated and shared in a symbol system
- explicit shareable information about how to perform processes (Houkes 2006)
- awareness of properties and behaviour of objects, and relationships between their elements triggered by perceptual recognition of objects and situations
- skills for performing physical and mental actions in context (Ryle 1946 and 1949)

Individuals develop tacit knowledge from experience and the application of explicit knowledge. Explicit knowledge can be shared with this process depending on awareness and understanding of past designs. Tacit knowledge can be shared by individuals with common experiences and this enables engineers in an organisation to develop a community of practice that involves understanding specific object references. Experienced engineers have the expertise to recognise a situation or problem from perceiving a small part of it (see Gobet 2019 on the role of chunking in expertise). They can recall and adapt solutions based on recognition of problems from partial information and often have tacit knowledge of the associated issues. Engineers also use object references to recall and informally classify process experiences, for example they remember the additional work that occurred on past projects when they had exceeded margins and therefore that this should be avoided. Experienced designers have learned where the safe boundaries for changes are.

Much knowledge used by experienced engineers is tacit understanding of relationships and effects which depends upon the situation as well as pattern recognition combined with reasoning and imagining skills. Such tacit understanding is used to predict behaviour in existing and new systems, including human interactions with these systems, to anticipate problems, guide testing and apply computational methods. An important part of what experienced engineering designers do is behaviour prediction of new designs in extreme situations based on previous product behaviour. Much of the knowledge required for this, especially that invoked by object references, is situated procedural skill. This includes the envisionment of the interaction of specific design aspects with the context of use of the product. It is important to observe that this claim is grounded upon there being acquired skills for the recognition of features of engineering artefacts and predicting their behaviour which are learned from experience with these artefacts and sometimes from models and simulations of them, and are triggered by looking at the artefacts themselves or representations of them. Young (2018) posits that tacit knowledge rests on a "cultivated receptivity to relevant features of a particular environment", rather than on something inexpressible but known in advance.

Object references are often used to provide evidence by pointing out where something has or has not worked in the past. As Kerr (2017) points out "Evidence and evidence-gathering in engineering is then neither wholly personal nor wholly impersonal; neither wholly interpretive nor wholly practical, although it contains aspects of each type". Object references function as keys to two distinct repositories of engineering knowledge, first the physically existing artefacts, graphic representations of them and documentation about them, and second the individual's memories of them. How engineers' memories work in conjunction with physically present artefacts to produce usable knowledge, and how much is perceived, remembered, and inferred, is not obvious. However, remembering is as much construction as recall (see for instance Koriat et al. 2000). The extent to which feature recognition is possible from mental representations, or how far one can only think with what is explicitly included in representations constructed purely from memories remains controversial in psychology; however the ability to manipulate mental representations differs among individuals. We will not discuss this further except to note that the evocation of knowledge through object references involves a process of active construction.

Using Vincenti's (1990) framework for present purposes significant distinctions are those between:

- explicit knowledge and tacit knowledge which cannot be fully articulated as explicit knowledge
- factual knowledge of concepts, structures, properties, relationships, behaviour and the like, and procedural knowledge of how to design, solve problems, and generate knowledge in various ways
- individual and collective knowledge

Objects, and memories of them, can only function as repositories of knowledge (about the form of the objects, properties, function and behaviour) in conjunction with other kinds of engineering knowledge. Vincenti (1990) does not explicitly cover objects as sources of knowledge, or the physical and social organisation of repositories of knowledge. We argue that objects, and, secondarily, memories of them, function as repositories for knowledge in several of his categories. We take the view that the way in which objects function as repositories of knowledge is best understood in epistemological terms by looking at the knowledge that they enable engineers to use rather than trying to unpick the ontological status of the object references and their referents.

Whilst formal specification documents make their content explicit, many of the informal criteria that guide designing are in practice expressed through references to past designs. In practice engineering companies derive much of the quantitative data they use either from in-use data of past designs or tests carried out on modified versions of past designs. Currently data is often derived from simulations which are calibrated against past designs. Vincenti's category of design instrumentalities, that is, engineers' knowledge of how to carry out design, would also cover experience of past design processes, which they associate and retrieve through references to past designs. However, object references that invoke knowledge of how to design only work in conjunction with Vincenti's other categories of knowledge.

Poser (2013) argues that engineering processes are fundamentally driven by ignorance, i.e. what engineers don't know, and the goals that they pursue. Object references are means of resolving this ignorance in a way tailored to the goal. The same object references invoke knowledge of fundamental design concepts embodied in the design of the objects they refer to (Stacey and Eckert 2021). Engineers need an understanding of engineering to understand and interpret other products. Experienced engineers recognise why something is done in a particular way in a competitor's design. They can often construct the rationale for design decisions from seeing and interacting with a product. The fundamental design concepts and the theoretical tools provide a vocabulary to talk about existing designs and understand observed behaviour. Object references also show the limitation of engineering descriptions and the vocabulary engineers have to construct them. There are many elements or features of machines that do not have specific names or can only be identified with a highly technical reference number.

6 Practical Challenges of Handling Object References

Much of the knowledge associated with object references is in fact tacit. For example, engineers have a sense of margins on components, without knowing them explicitly. Experienced engineers often have a sense of margins just by looking at a component. For example, if they see a thin strut in a standard material, they know whether this is a likely to be an optimised component, that is, one without margins, just by looking at it, but also by knowing whether the design process of the component would have gone through an optimisation loop. In referring to an object they make a multitude of these judgements simultaneously. Tacit knowledge is implicit and contextual with the consequence that any particular piece of tacit knowledge can be further interpreted and more finely classified (see Young, 2018, for a discussion of tacit knowledge in engineering). The purpose relativity of the use of much tacit knowledge is a further reason why ontological classification is highly problematic (Addis 2013). As a consequence of this, this paper does not attempt to draw up a classification of tacit knowledge but wishes to identify some important distinctions.

Some tacit knowledge can be made explicit if suitable effort is put into it. For example, many margins can be explicitly described if a suitable test or simulation are run. One engineer might have a tacit sense that there is a not a lot of margin on a component and avoids touching it and another might be able to explicitly see that there is only a 1% margin on a key parameter and therefore make an explicit case that this component should not be changed. For example Eger et al., (2005) report on an engine company, which froze the design of one their key components, i.e. barred anybody from changing it, but only very few engineers knew that this was due to the component having almost no margin.

Here it is important to distinguish between aspects which it is not practical (such as for reasons of cost effectiveness) to make explicit and those which are for various reasons impossible (or at least very hard) to make explicit. Due to the complexity of engineering products and the importance of small details, expressing an element of a product (such as its entire surface) can be very difficult and time consuming. A tacit sense for what the margins are plays an important role when considering the multitude of different use cases. Experienced engineers often know whether a particular component is strong enough for a particular application, because they understand the margins with regards to multiple use cases (see Isaksson et al., 2014). However anticipating the properties of other design features, such as the exact details of a curve that make it aerodynamic or resistant to accumulating dirt, is something that engineers learn at least partially by looking at examples that work and examples that do not work. While such design features can sometimes be sketched, they are often extremely difficult to describe succinctly, except in terms of how they differ from previous designs. Over the years expert engineers develop finely tuned perceptual skills. This plays a hugely important role in directing designing and targeting testing.

A development of Ryle's well known regress argument (Ryle 1949) shows that not all tacit knowledge can be converted into explicit knowledge (Addis 2016). A corollary to this is that recollected or imaginatively generated knowledge is situated in a way that knowledge which is explicitly encoded in a general form is not. The examples of engineering design previous discussed can be seen in various way to illustrate the difference between tacit knowledge which can be converted into explicit knowledge regardless of how difficult or impractical this is and that which cannot. Categorisation of tacit knowledge in object references by the extent to which such knowledge can be converted into explicit knowledge is useful:

- product knowledge which is not explicitly captured (notably margins)
- procedural knowledge such as how to run a design process, do a calculation or manage an organisation. The experiences that engineers have with needing to deal with margins that are exceeded falls under this category.
- contextual knowledge about problems or solutions such as vibration on a particular pavement and suspension type
- experiential knowledge especially non-theoretically grounded

A challenge with the use of object references in the design process is that engineers may not be aware of the limits of their individual and tacit knowledge. For example, they might not know whether a system still has margins or about the effects of certain changes during the design process. Not realising such limitations to knowledge has the consequence that engineers might conclude that they understand past designs better than they actually do. They might assume that other people interpret object references in a similar way with divergences becoming evident in implementation problems. The fact that not all tacit knowledge (whether situated in and triggered by design activities, or another kind) is convertible to explicit knowledge provides further theoretical grounding for the earlier discussion about the importance of expert tacit knowledge in design margins. These problems with significant practical implications demonstrate the importance of continued theoretical and practical research into the nature of know how in vocational and professional environments.

7 Conclusions

This paper is aimed at advancing understanding of what engineering knowledge is and how it is used in engineering design in industrial practice. It argues that in engineering design the past designs that engineers are familiar with constitute an important repository of knowledge. References to objects, that evoke this knowledge, are extremely effective and powerful representations of complex design ideas. In particular they play a crucial role in the generation, communication and application of tacit knowledge whether that knowledge is not explicated for practical reasons or is knowledge about elements of design which is extremely difficult to express. Object references enable the construction of details from general engineering knowledge when required without necessarily invoking long complex narratives or excessive detail. However, interpretations of object references by others and periodically by oneself after a significant time lapse are strongly influenced by personal experience and knowledge, thus are subject to interpretation in different ways. Object references are taken for granted by practitioners and have been overlooked in the philosophical discussion of engineering knowledge, which rarely engages with the messy practice of engineering design in industrial practice.

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