Design Research: Current Status and Future Challenges

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Abstract

This paper presents a broad review of progress in design research in recent years, before making suggestions for some key research challenges that must be resolved if the grand societal challenges of the early 21st century are to be overcome. The review builds from the foundations in systematic and methodological approaches to design developed in the later decades of the 20th century through to recent research presented especially in the International Conference in Engineering Design (ICED) series of conferences. The consolidated research themes of the ICED conferences are presented together with an exploration of topics of particular focus in recent research before describing developments in research methodology and in design theory which form a foundation for current research in the subject. It is proposed that the present status is that a consolidated view of design can be formed based on accumulated recent research results. A suggested curriculum for design based on these is presented. The paper concludes with a discussion of key current research challenges, including the need for better sharing of design knowledge and exploitation of design data, the need for better computer-aided design tools and the need for a theoretical foundation for design of complex systems.

Keywords: design research, design theory, research methodology, grand challenges

1 Introduction

At the beginning of the 21st century, human societies face a number of unprecedented challenges. The technologies on which they have come to rely and which have been the basis for the enormous growth and prosperity of the 20th century threaten the stability of our planet's climate. There are enormous pressures on energy, water, food and other resources to serve a global population rapidly fast approaching 10 billion. That population lives in crowded communities, with increasing numbers of aged and infirm people. Economic crisis has brought hardship to many and has threatened political stability. These societal challenges [1] are all design problems: we need to redesign our material world to be more sustainable; we need to redesign our products and living spaces to be more inclusive of the aged and infirm; we need to identify new products and services that will revitalise our economies. And we need to redesign all these things faster and more efficiently than we have ever managed before. Can what we have learned from design research guide us in what needs to be done?

The answer to the question at the end of the previous paragraph is 'partly'. Design research has made great progress in understanding the nature of design and design processes, of design thinking and design skills. This understanding needs to be consolidated, articulated and disseminated. But there are gaps in this understanding and a new agenda is needed for future design research to fill the gaps. This paper seeks to summarise the present status of design research and to make suggestions about the 'grand challenges' in design that will require further research. It will do this by first reviewing the progress that has been made in design research, highlighting especially the methodological and theoretical developments that have allowed a rigorous understanding of many facets of design to be developed. It will then present a suggested structure for a consolidated view on design before making suggestions for a future agenda to address design research grand challenges.

2 Progress in Design Research

This section will first give a broad overview of the progress in design research in recent years, of the areas in which important results have been reported and especially on the developments in research methodology and in design theory which form a foundation for further research in the subject.

2.1 Background

Research in design goes back many decades but it is in the last 30-40 years that it has really flourished. The early development in Germany of systematic approaches to engineering design is noted by Wallace and Blessing [2], and there were very important developments in neighbouring countries in Europe, including of course what is now the Czech Republic, in the second half of the last century. Coming from rather different perspectives, a number of books on design methodology were published in the English language in the 1960s: the industrial designers Asimow and Archer published on design methods at this time, as has been well described by Cross [3], and Herb Simon wrote in 1969 his "Sciences of the Artificial" from the perspective of a wide research base in economics, psychology, political science and sociology [4]. From these promising foundations the 1980s and 1990s were very active decades in design research: Hubka published 'Principles of Engineering Design' in English in 1982

[5] and the English version of Pahl and Beitz' 'Engineering Design – a Systematic Approach' was published in 1984 [6]. Crispin Hales' seminal PhD thesis on the engineering design process in an industrial context was defended in 1987 [7] and by that time the National Science Foundation (NSF) in the USA and the UK's Science and Engineering Research Council (SERC) had established programmes of research in design, and new journals were emerging (e.g. Research in Engineering Design and the Journal of Engineering Design). The years 1988 to 1991 saw a real peak in activity with the establishment of the CIRP design seminar, the early days of the ASME Design Theory and Methodology (DTM) conference, and the ICED conference (see below) being held out of Europe for the first time.

There has been continuing progress in design research in the ensuing 25 years. From small beginnings in Rome in 1981 the International Conference on Engineering Design (ICED) has grown to attract regularly in the order of 500 participants, and to alternate between Europe and the rest of the world. Thirteen conferences were run under the auspices of the Workshop Design Konstruction (WDK) organisation before responsibility for the conferences was passed to the Design Society in 2003. The Society has built up a portfolio of activities including the Engineering and Product Design Education (EPDE) and Design Creativity conferences, and endorsement of the Dubrovnik 'Design' conferences, the International Conference on Research in Design (ICoRD) and many other events [8].

The growth in design research has accompanied a revolution in design practice, in particular through the pervasive use of information technology (IT) but also as companies around the world have learned new techniques. As well as systematic approaches to engineering design, a number of approaches have been developed to assist the designer, including techniques such as Quality Function Deployment (QFD)[9] and Design for Manufacture and Assembly (DFMA)[10]. Equally revolutionary has been the ability to model products in a computer in three dimensions and then to physically realise these models through rapid manufacturing and prototyping techniques. Through the application of these and other methods there has been enormous progress in the quality, cost and performance of engineered artefacts.

Much of what has been described above is the result of work in the engineering design research communities, especially by mechanical and manufacturing engineers. They have not been alone in their work. The early work in design methods by industrial designers has been pursued by a vigorous community with an 'art and design' and industrial and product design perspective, and architects, interior and furniture designers are also very active. Technology and innovation management is a particular focus of management researchers, and design is of course of interest to urban planners [11], students of the history of technology [12], software engineers [13] and information systems engineers [14] to name but a few. Each of these communities has brought new knowledge and insight to the challenge or design and designing.

2.2 A consolidated research agenda

An indication of the scope and focus of the research in design at the end of the 20th century was given by the paper published by Mogens Andreasen at the International Conference on Engineering Design (ICED) in 2001 in which he reflected on the papers that had been published during the first 20 years of the ICED conferences [15]. He observed that papers could be grouped into four broad areas. The first was a large group of papers seeking to articulate what constituted design science: what was the scientific basis for the subject and what were the appropriate research methodologies to be used in its study? The second reflected a development from a concentration on engineering design, especially machine design, to a wider emphasis on product development. There was in particular a developing interest in 'design for X' (DfX), where 'X' describes life cycle properties of the designed artefact that included especially manufacturability and assemblability but also issues related to environmental performance, and to design for the whole life cycle. In this group as well were papers on team work, on the human aspects of design – collaboration, creativity and so on. The third large group of papers reflected the strong interest at the time in computer-aided design, but also showed developing emphasis on wider application of information technologies in many aspects of design from synthesis to information and knowledge management and many aspects of modelling. A fourth and final group of papers Andreasen entitled "delimitations of ICED", describing the papers in this group as broadening out from the engineering focus to a wider interest in innovation more generally.

The developing emphasis on the different life cycle properties of the artefact that Andreasen observed has also been reported by De Weck and his co-authors in their 2011 book on Engineering Systems [16]. Based on a survey of the titles of papers published between 1884 and 2010, and of the frequency with which terms were included in Google searches, they trace the developing interest in 20 or so life cycle properties of artefacts which they term the 'ilities', noting the growing emphasis in the middle part of the last century on usability and maintainability, and then more recently on interoperability (especially with the growth of the Internet), and sustainability.

The ICED conferences have since 2003 been organised under the auspices of the Design Society, and two aspects of the Society's work give a good indication of the current emphases in design research. The first is the Special Interest Groups (SIGs) that have been established in the Society. SIGs are transient groupings of the Society set up to explore issues of particular relevance and significance. **Table 1** shows the list of SIGs existing at the time of writing and their areas of research focus [8].

Exploring the research focus and outputs of the SIGs gives an indication of how the design research community continues to develop in the 21st century. In the past 10 years the Design Theory and the Decision Making SIGs have done fundamental work in the scientific underpinning of design, and more recently the

Design Creativity SIG has also contributed strongly in this area, especially through its focused International Conference on Design Creativity [17]. The DfX theme of product development is continued in the Eco Design SIG, while the Modelling and Management of Engineering Processes and Risk Management SIGs reflect a growing interest in the management of product development processes. A strong emphasis on the human in design is shown by the Collaborative Design, Human Behaviour and Creativity SIGs. But, by contrast, computers and IT in engineering have, perhaps surprisingly, not spawned Special Interest Groups except in the application area of mechatronics and the rather specialist research area of design synthesis – the Formal Design Synthesis SIG was originally the called the Computational Design Synthesis SIG.

When we get into the realm of delimiting ICED we see two areas where work that is new to the ICED community has been introduced. Firstly, the Managing Structural Complexity SIG involves study of management of the structure of a system by means of complexity management approaches which tackle complex systems by looking into how a system is set-up internally, i.e. the constellations and typical patterns (= "structures") of the elements and their relations [8]. Secondly, the recently formed Emotional Engineering SIG reflects the continuing broadening of the focus of the research community, and is an example of a topic that runs across engineering, cognition, art, neuroscience and beyond.

The Design Society has also been working hard both to characterise the design research space and to identify opportunities for collaboration. In 2009 a number of key themes were proposed as a basis for the organisation of the ICED conferences and the publishing of its proceedings and were also adopted (with extensions) by the Design Conferences held in Croatia in alternate years. These key themes, together with the proportion of papers in each of the last three conferences published in each theme, are shown in **Table 2**.

ICED conferences traditionally had a very significant emphasis on 'design methods and tools', and it can be seen that this was still the largest theme at the 2009 conference, ICED09, making up nearly ¼ of the papers, although the emphasis has reduced recently as the research focus of the design community has broadened. The number of design education papers has declined also (perhaps reflecting the success of the specialist EPDE conferences [18]). The areas that are growing are 'Human Behaviour in Design' (including topics such as design cognition and experience, design teams, collaborative product development, design

Table 1 Design Society Special Interest Groups

SIG	Concerned with:
Collaborative Design	The study of design as a collaborative endeavour
Decision Making	Processes and tools of decision-making in design.
Design Creativity	The nature of creativity and creative behaviour in design
Design Education	Design education and training at all academic levels
Design Theory	Development of a theoretical understanding of design and of design processes
Mechatronic Products and Systems	Development of products and systems requiring multi-disciplinary inputs, especially mechanical and electronic
Eco Design	The design of products and systems to minimise their environmental impacts
Emotional Engineering	Designing to appeal to human emotion and sensibility
Formal Design Synthesis	Formal methods and computational tools for design synthesis
Human Behaviour in Design	Human behaviour in design, including behaviour of designer(s) and user(s)
Industrial SIG	Industrial applications of design and of design research
Managing Structural Complexity	Managing complex structures such as product architectures, process networks or organisational structure
Modelling and Management of Engineering Processes	Strategies, methods, and tools for modelling and managing engineering processes
Risk Management	Management of uncertainty and risk in product and systems development and design
Robust Design	Approaches to the design of products and systems that are insensitive to variation in their internal parts or their environment

Table 2 Papers published in ICED consolidated topics, 2009-2013

ICED Theme	2009 papers (%)	2011 papers (%)	2013 papers (%)
Design Processes	14	12	14
Design Theory/ Research Methodology	11	9	7
Design Organisation and Management	9	9	10
Product, Service and System Design	8	11	14
Design Methods and Tools	23	20	13
Design for X, design to X	8	8	9
Design Information and Knowledge	9	12	12
Human Behaviour in Design	9	12	17
Design Education and Lifelong Learning	8	7	4

communication, idea and concept generation, user experience and design for emotions), and 'Product, Service and Systems Design', in 2013 including service for the first time, and covering product structure, product architecture and so on. 'Design Information and Knowledge' includes computational aspects of knowledge and information management as well as the human and organisational sides of knowledge management and sharing and has also been a topic of strong interest in the 21st century.

2.3 Research methodology

Underpinning the development of design research has been a deepening understanding of the importance of research methodology and of the need for correct identification and application of research methods. This is necessarily a very broad topic and so for brevity two aspects of research methodology will be introduced here, based on Henri Christiaans' summary of two key focuses of design research: "Design knowledge resides firstly in people: in designers especially. Therefore, we study human ability - how people design. This suggests, for example, empirical studies of design behaviour, but it also includes theoretical deliberation and reflection on the nature of design ability. It also relates strongly to considerations of how people learn to design. Design knowledge resides secondly in processes: in the tactics and strategies of designing. A major area of design research is methodology: the study of the processes of design, and the development and application of techniques which aid the designer." [19].

Christiaans' first emphasis on the study of how people design has led to the design research community adopting a number of research methods from the social sciences. If we ask, 'how can we study design', a whole armoury of techniques is now available to us, to study actors in the design process (designers, customers, users and so on) including:

- **Asking the actors for their views**. This involves the widely used methods of interview, questionnaire and focus group, and is of particular value when trying to understand the experiences and opinions of participants in the design process. Questionnaires are typically used to measure responses or gather statistical information using closed or open questions, and generally on larger research cohorts. Interviews by contrast may gather lived experience and understanding using open questions on smaller cohorts [20]. An example is the research into social aspects of learning and knowledge transfer in product-service context carried out by Easterby-Smith using approx. 100 interviews, plus observations and review of documents [21].
- **Observing the actors in design activities**. Observation is widely used in design research, including participant observation, ethnography, video and audio recording and the like. Recently a number of research groups have developed instrumented 'design observation laboratories' to support the study of design and design teams [22].
- **Asking the actors to describe what they are doing and why**. A variant on observation is the use think-aloud techniques or protocol analysis, in which the subject of study makes verbal reports of their actions (protocols) which are then studied and interpreted by the researcher – for example a designer talking through the generation of sketches or design concepts.
- **Asking the actors to make records from their activities**. Observation and protocol analysis are generally used to study specific closed episodes, often on a timescale in the order of hours. When the study aims to understand something that takes place intermittently or over longer periods the subject(s) of study might be asked to make records in the course of their work, for example through diary study, in which the participant makes (typically) semi-structured observations at key times in their work (for example Wild's study of designers' information requests [23]). A variation is the use of computing devices to prompt the participant to make entries at specific times, for example Robinson's use of PDAs carried over 20 working days to collect information, again about the information-seeking behaviour of designers, by asking engineers to categorise their current work activity at random alarm-points within each hour by entering data on 12-16 screens [24].
- **Studying what the actors produce**. An alternative to asking research participant to produce records specifically for the purposes of the research is to use the documents and other objects produced in the course of their work as the basis for the study. Such document analysis has involved for example the study of concept sketches [25], engineers' log-books [26] and project email corpuses [27].
- **The researcher can also be an actor.** In Action Research the researcher studies the design activity through participation, often in an iterative cycle of planning acting, observing and reflecting [28].
- **Studying historical records**. Insights can be obtained by studying historical records of design and of designers. Particular examples of this include the study of expert designers, for example by Cross [29] or Vincenti's "What Engineers Know" [30].

Each of these techniques is most appropriate in different circumstances, and often the techniques are used in combination. For example the DTRS7 workshop (one of a series of Design Thinking Research Symposia) invited different researchers to interpret observations and artefacts from meetings from two projects including multi-angle video recordings, plans, drawings, sketches, flip-charts, and transcripts from the meetings [31].

It is important for researchers to choose the most appropriate research method for their study. As an example of the variation that exists in design research, **Figure 1** shows research methods reported in ICED09 papers for four of the research themes at the conference. The methods include action research, observation, survey and interview (shown in the figure just as 'survey' for brevity), modelling and simulation (shown as 'modelling'), literature study, case study, workshop, experimental application of method (shown as 'Expt'l method') and experimental construction of a tool (shown as ‘Expt’l tool’). The figure shows that the research papers studying Human Behaviour made extensive use of observation and questionnaire/survey, that studying the Organisation and Management of Design was by contrast largely based on a combination of literature study with questionnaire/survey, case study or modelling. Research into Design Processes made extensive use of modelling (typically through process models, often supported by computational modelling tools). For research into Design Methods and Tools the predominant research approach was experimental application of the method. The design researcher needs a clear understanding of which method is most

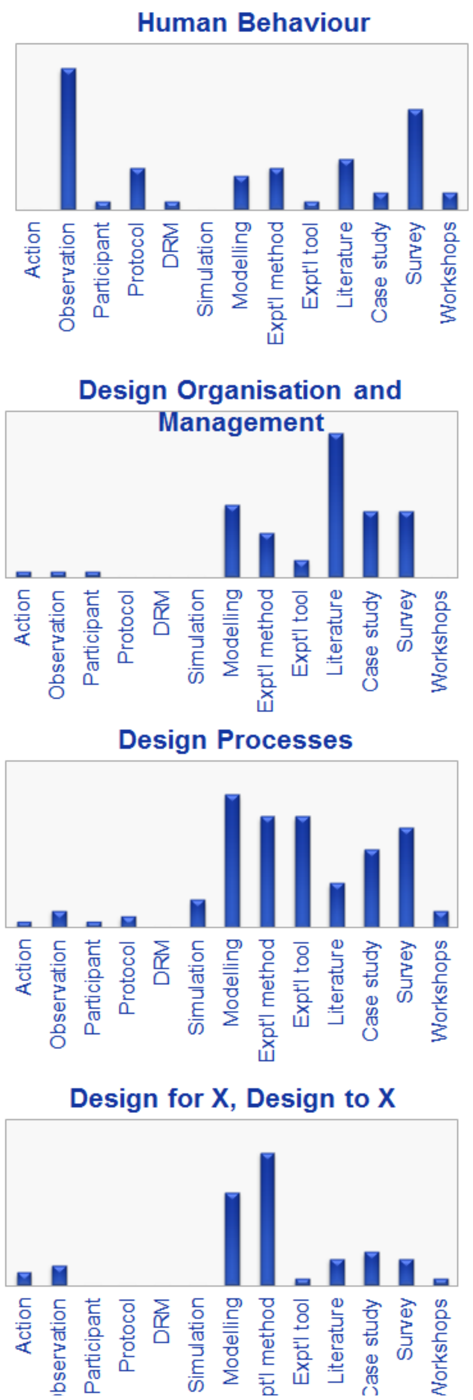

Fig. 1 Methods used in design research [32]

appropriate to the research question of interest.

Christiaans’ second emphasis - on the study of the processes of design and the development and application of techniques which aid the designer - leads us to the significant emphasis in design research in recent years on the methodological framework in which research is done, especially influenced by the publication in 2009 of Blessing and Chakrabarti’s book ‘DRM, a Design Research Methodology’ [33]. DRM describes a multi-stage methodology for design research, with four key stages comprising:

- A **Criteria Definition** stage to identify the aim that the research is expected to fulfil and the focus of the research project;
- A **Descriptive Study I** stage to identify the factors that influence the formulated measurable criteria and how they influence these, to provide a basis for the development of support to improve design and to provide more details that can be used to evaluate developed design support.
- A **Prescriptive Study** stage to develop an impact model or theory, based on the reference model or theory from the Descriptive Study stage, describing the expected improved situation.
- A **Descriptive Study II** stage to identify whether the support can be used in the situation for which it is intended and that is does address the factors it is supposed to address

An example of the application of DRM is Salehi’s development of new approaches for the construction of parametric/associative CAD models for the automotive industry which involved after an initial stage to establish research criteria [34]:

- An Descriptive Study through questionnaire, interview and study of existing CAD models to establish the ‘as-is’ situation
- A Prescriptive Study to develop a new method for model construction based on an adaptation of the Design Structure Matrix (DSM) technique.
- Second Descriptive Study using controlled experimental use of the new method by groups of engineers, supported by interviews.

The progress in design research methodology overall has been strong, but there is still much to do, especially in the study of the lengthy, distributed processes used for the design of many of today’s complex artefacts such as transportation systems.

3.4 Theoretical Underpinning

The development of a solid methodological foundation for design research has been accompanied by the development of a strong theoretical thread running through the research activities of the last half century. Prominent early contributions were Suh’s Axiomatic Design [35], Yoshikawa’s General Design Theory [36] both of which viewed design as involving the mapping process between functions and design parameters or structures [37] and Hubka’s Theory of Technical Systems [38]. Hubka’s work laid the foundation for a systematic approach to design and also recognised that the need for both a theory of the design process and of the artefact (machine/technical systems) is particularly important. In recent years there has been a resurgence of research into design theory, with a number of new theoretical ideas. Shai and Reich's 'infused design' theory uses abstract graph representations to enable injection of knowledge, methods and solutions from one domain to another and has been applied in a number of engineering fields [39]. Hatchuel and Weil's C-K theory proposes that design is characterised by the proposal of concepts, defined as propositions without a logical status (i.e. not true or false) represented in a concept-space (C-Space) [37]. In C-K theory, design reasoning involves expansion of such concepts and then reasoning about them in a knowledge or K-space. The creative aspect of design results from two distinct expansions: C-expansions which may be seen as 'new ideas', and K-expansions which are necessary to validate these ideas or to expand them towards successful designs.

Infused design and C-K theory inform the act of designing but perhaps have less to say about the nature of artefacts, in particular of technology, in which regard W Brian Arthur's The Nature of Technology [40] provides an elegant theoretical explanation of the origin and evolution of technologies. At the interface between the theory of the artefact and that of the process of designing, Thomson and Paredis' Rational Design Theory explicitly includes uncertainty considerations and enables quantitative trade-offs between the utility of the artefact and of the process by which the artefact design is created [41]. The development and unification of these theories and their integration with the extensive corpus of design methods and tools will be a clear indication that design research has come of age.

4 Are we in a position to consolidate?

So has design research matured to the point that a body of work that is "intellectually tough, analytic, formalizable, and teachable" may be identified (in Herb Simon's terms [42])? To answer the question, one could imagine that the following 'curriculum for design' could be taught across the engineering disciplines, and even beyond:

- **The nature of design and of technology**: we have a good understanding of the nature of design and of design thinking, of the nature of the design process, and of the relationship between products, services and systems. We have a developing understanding of the nature of technology.
- **Product and systems architecture**: the identification and development of novel arrangements of design elements is fundamental to innovative design, as is emphasis on the architecture or arrangement of such elements and the rules and constraints governing interfaces between the elements. These aspects have been the subject of extensive research across multiple engineering domains and can be comprehensively described, although some harmonisation of the understanding of product and systems architecture and of product platforms is needed.
- **Modelling in design**. We can consider design as concerning the characteristics of the artefact which describe its structure and shape, and the properties which describe its behavior [43]. Analysis, whether mathematical, computational or physical, consists of determining and/or predicting a product's properties from the existing or established design characteristics. Synthesis and product development consists of establishing and assigning the product's characteristics to achieve the desired properties. Modelling to support analysis and synthesis has been the basis of the engineering sciences and of computer-aided engineering for many years and can be comprehensively described, although the comment in the section 4.3 below about the limitations of current computer-aided design (CAD) techniques should be noted.
- **Design for the life cycle**. Design for the life cycle, for 'X' or for the 'ilities' has been introduced above. The ideas and frameworks are mature, especially in discrete-part manufacturing, but the range of 'ilities' that is comprehensively covered is very small and needs expanding. There is rapidly developing emphasis on sustainability.
- **Design methods and tools**. A very extensive range of teachable methods and tools is in place, including among others (a) methods for generating new design concepts: creativity methods, methods for generating new combinations of design elements, analogical methods; (b) methods for defining and then searching a design space (optimisation tools, constrain-modelling tools); (c) methods for problem solving (d) methods for accumulating understanding of a design such as quality function deployment (QFD) failure mode and effects analysis (FMEA), design rationale capture and so on (e) methods for dealing with variation such as robust design, 6-sigma.
- **Organising and managing design**. As noted above, design processes, risk and uncertainty management in design and design decision-making have all been extensively researched in recent years and robust teachable material is available in all of these areas, and also (although perhaps to a lesser extent) in the area of the management of innovation.
- **Human issues in design**. The behaviour of designers and design teams, individuals and groups of users have also been extensively researched such that that consolidated material can be presented on subjects such as risk perception, creativity, cultural issues in design, team behaviour and design for emotion.

Furthermore, not only is it possible to identify a coherent and consolidated set of design principles, methods and tools that apply across engineering, design approaches can also be very usefully applied in other domains. For example, in his recent book, Howarth attempts to describe what lawyers do in terms of their design activities – designing contracts, trusts, companies, wills, conveyances and so on for their clients and regulations, statutes, constitutions and treaties for the state [44]. He suggests that many of the approaches used by designers may also be applied by lawyers in their work. We see similar moves in a number of fields, suggesting that design thinking can impact on social innovation, healthcare design and so on [45]

5 Challenges for Future Design Research

While great progress has been made in advancing our understanding of design, there is still enormous progress to be made, and it is important that the design community articulate its 'grand challenges' for the future, as has been done for example by the systems engineering community [46]. In this section a number of proposals are made for very pressing issues that the design research community should address, especially those that need to be resolved if we are to be able to achieve the rates of change required to tackle the societal challenges of the 21st century.

5.1 Most design knowledge is proprietary.

If one tries to find out from the World-Wide Web how to design any engineering artefact (e.g. a diesel engine, the undercarriage of an aircraft, the compressor of a refrigerator) the result is often the discovery that the available information is extremely limited, or at very least poorly consolidated. There are usually some descriptions of the basic principles of operation of devices, but try to find out about the embodiment and detail design of real devices and very little is there. The same applied to consolidated data: for example, there is a great deal of information about cost estimation and modelling tools, but the availability of real cost data is limited. Most design knowledge is held by companies, in particular as tacit knowledge held by the engineering staff of the companies or explicit knowledge embedded in the documentation of the companies. Commercial considerations mean that this information is not in the public domain. This lack of publicly available engineering design data means that (1) it is very difficult to teach or learn many aspects of design except in the context of practice in companies that do design (2) anyone seeking to develop a novel artefact outside of an experienced commercial organisation often has an enormous learning curve to climb in order to develop the required knowledge and understanding for themselves (and a corollary of this is that firms do not put much emphasis on radical change as they concentrate their efforts on what Clayton Christiansen calls 'sustaining innovations' [47] that build on their existing expertise) (3) the need for engineers to develop domain-specific knowledge means that they can very quickly get tied in their careers to particular industries and (4) inexperienced designers are forever repeating mistakes that have already been made. We need new ways to capture, document and disseminate design knowledge: for firms to share information not directly related to their artefacts (e.g. cost data, manufacturing capability and methods, embodiment and detail design principles), for design issues in different industry contexts to be described in a common language such that designer mobility and diffusion of ideas is encouraged. There is an important job for the design research community to do here.

5.2 The classification of design challenges.

An enormous number of design methods and tools have been developed over the years, but the 'space' or the total problem domain of possible design problems is only incompletely covered, and approaches that we might use to categorise that space are even more incompletely understood. To take the coverage issue first, in many situations (e.g. many automotive, aerospace or marine design cases) a key design challenge is 'packaging' - getting a known set of elements to fit in the engine compartment of a car, the engine room of a ship, or the circuit boards of a computer. Does the designer have robust tools, other than experience, for such tasks? In other situations a key challenge is identifying an appropriate architecture and then in matching elements within that architecture (e.g. in gas turbines – matching compressor and turbine; in electric vehicles matching all the drive train elements). In others a key challenge may be learning from scale tests (e.g. in aircraft, wind turbine or in wave energy converter design) and so on. When and where in design research are such challenges categorised? Are the required approaches to them generic? Similarly, in addressing technological design challenges similar issues must be met repeatedly – e.g. many structural or heat transfer problems. How well are such challenges and their solutions categorised? TRIZ gives some ideas of how one may identify generic challenges (and then match onto generic solution principles [48]) but it is a very high-level approach and difficult to apply successfully. There is an urgent need for the design research community to produce a comprehensive approach to identifying and classifying design issues and the methods for approaching them, such that methods and tools can be more confidently applied and exploited.

5.3 CAD provides little assistance with design.

The development of CAD has substantially stalled in the past two decades. The main mechanical CAD paradigm (parametric-associative boundary representation modelling) was established in the late 1980s and is still in use today. The models that we produce in design often have practically no semantic content. Many of the elements we use in design are standard, catalogue items for which we could imagine CAD tools that know all about their characteristics and properties (using Weber's terminology [43]). Still more elements are designed according to codes and we could again imagine standard reusable intelligent design modules for such elements that we can incorporate in any CAD system. In other cases we could imagine a demand for tools in which companies can embed their design knowledge; in others CAD tools that allow us to mix electrical, electronic, software and mechanical models that are currently incommensurate. In all these respects the capabilities of our current tools are woefully inadequate. As a research community we should be prepared to be very critical of what the commercial CAD vendors offer and to specify what we think are the capabilities really needed in future CAD tools and how they may be achieved.

5.4 Validating our design analysis tools

The failure load of an aircraft wing or the fatigue life of an automobile suspension part can be predicted fairly accurately because we have a lot of experience reconciling results of design analysis with observations from experiment, test and use. However, when we stray very far from cases that we know and understand, our analysis tools are often too uncertain to be trusted. The consequence is that novel designs need very extensive and expensive testing. The issue is again one of proprietary data (see section 4.1) and of accumulating and sharing engineering knowledge, but is also a 'Big Data' challenge [49] - how can we learn from the very extensive data that we have, firstly in the public domain, and secondly in engineering companies, about the performance of our analytical tools? We need to identify computational approaches that allow data to be interrogated and aggregated (publishing engineering data in PDF or other document formats is not appropriate for this task) and we also need to identify ways that confidentiality constraints can be overcome to allow data to be shared while allowing commercial confidentiality to be maintained.

5.5 Extending beyond design research

A number of other academic communities have very interesting and important things to say about design. The 'innovation and technology management' community has compelling explanations about the role of 'dominant designs' [50], of modes of technical innovation [51] and of topics such as 'open innovation'. The 'history of technology' community documents historical design episodes and technical developments [52]. Other communities philosophise about the nature of engineering and technology. Architects, town planners, industrial designers, user interface specialists and other engineering disciplines all research design from their different perspectives. In many cases the research from these communities has led to very insightful results. Can we reconcile the knowledge and understanding achieved by our community with what these other communities have learned? What can we in turn say to them that would be of value to them?

5.6 Understanding cost/time implications of design.

For a politician or a decision-maker in a company, the time required to make a radical change, and how much it might cost, are critical questions. What advice can the design research community give in this regard? Can we offer any insights into how long it will take (and how much it would cost) for a firm to develop a new product or a country a new industry? What can we say about the potential cost of developing new more sustainable technologies? Can we shed light on the escalating cost of systems projects, or the potential costs for emerging economies to develop a design capability? As well as having the tools and methods to propose novel concepts we also need to be able to advise on the time and resource implications of realising these.

5.7 Design of engineered systems.

For the final 'grand challenge' let us turn to a view expressed in a recent report in the USA from a NSF workshop into the design of engineered systems [53]: "We believe the sustained failure of systems engineering methods, processes and tools is due to the lack of a fundamental rigorous understanding of nature of large product development, in which a large team of people is organized to design a complex artifact. There is a profound need for a normative theory of engineering design that encompasses the aspects of organization and complexity that are essential parts of these development programs. With such a theory, we ought to be able to assess methods, processes, and tools, and determine which can lead to a successful systems engineering process and which cannot. In fact, a normative theory of the engineering design of large systems should point the way to correct methods, processes, and tools for systems engineering". Notwithstanding recent developments by the Theory SIG, we still substantially lack credible theoretical foundations to our discipline when we deal with artefacts and processes of any substantial complexity.

5.8 Breaking away from 'locked-in' solutions

One of the consequences of the limitations that are described above is that novelty in design is very expensive to bring to practical fruition and very economically risky. So at a time at which we desperately need novel solutions to be explored to address the global challenges that we have identified, we concentrate our engineering efforts on existing dominant designs to which we are locked-in [54], making incremental improvements (admittedly to generally very successful effect in the short term) but not overcoming the real challenges that are faced. As a consequence of our concentration on dominant designs we adopt a number of practices that reinforce that dominance: 'right-first-time'; no-prototypes; virtual prototyping; stage-gate processes; concurrent engineering and lean engineering all work best when incrementally building on what has gone before. The increasing current emphasis on short-term impact from research encourages a similar concentration on incremental technological advances. We need instead to shift to an emphasis on what Hatchuel calls "intensive innovation" [55].

6 Conclusions

This paper has reviewed the recent progress in design research, especially in the underpinning theoretical and methodological foundations. It is suggested that sufficient progress has been made for it to be possible to identify the key topics of a curriculum for a new 'sciences of the artificial', building on pioneering work in the 1970s and 80s. But it is also suggested that a great deal of work is to be done addressing a number of research challenges that must be resolved if the grand societal challenges of the early 21st century are to be overcome.

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