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Open Issues in Design Informatics

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Abstract

Design informatics—the use of computers as a means of generating, communicating and sharing data, information and knowledge in design—has been a central theme in design research and practice for many years. This paper reviews the recent progress of research in design informatics, and makes suggestions for future research directions. The review encompasses various technologies of computer-aided engineering and computer-supported collaborative work with an emphasis on applications in mechanical engineering and related disciplines and on support from conceptual design to life-cycle support. Topics include viewpoint modelling and artefact semantics, model-based engineering, support for creativity and for distributed design, machine learning and the potential for deep learning in design.

Keywords: design informatics, computer-aided engineering, engineering design

1 Introduction

In the past 50 years, digital technologies have transformed many aspects of our lives, especially our engineered products and systems. They continue to be an area of enormous interest as we consider the potential of cyber-physical systems, 'Big Data' and the Internet of Things (Sun et al. 2016). Digital technologies have also become deeply embedded in the processes by which we design and develop products and systems. Information is the lifeblood of design, and thus design informatics - the application of information technologies in design – has been a central focus in design research for many years. This paper considers the evolution of design informatics over the past 40 or so years and makes suggestions for the challenges that should be addressed as we move into the next phase of digitalisation.

A central message of the paper is that we have always had very high ambitions for our computational tools, but these ambitious have not always been realised, at least not in the way we imagined they might be. What can we learn from the successes and failures of the past that might inform the choices we make in the future? As an example of the ambitions for our tools in the past, in 1982 Requicha and Voelcker

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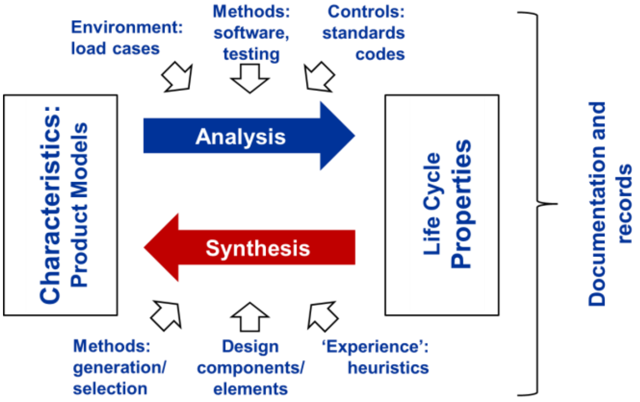
wrote that “an informationally complete [geometric] representation would permit (at least in principle) any well-defined geometric property of any represented solid to be calculated automatically” (Requicha and Voelcker, 1982), envisioning integration and automation of design tools around a geometric model. Today, in Industry 4.0 we envisage computer-based Product Lifecycle Management (PLM) as “a central source for all data regarding a product, from the initial idea and production to sales and marketing” (Hannover Messe, 2016) and that we are close to achieving “digital twins” that are, for example, “ultrarealistic in geometric detail, including manufacturing anomalies, and in material detail, including the statistical microstructure level” (Tuegel et al, 2011). How well were Requicha and Voelcker’s ambitions realised and how close are we to achieving today’s goals?

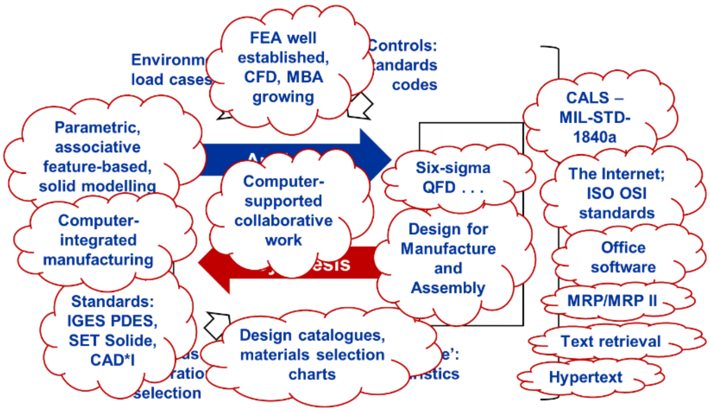
2 Design Informatics and the Engineering Design Process

The scope of design informatics can be defined by considering it as a development of engineering informatics, which Subrahmanian and Rachuri define as “the discipline that supports codification, organisation, exchange, sharing, storage and retrieval of digital objects that characterise the multi-disciplinary domain of engineering” (Subrahmanian and Rachuri, 2008). Combining this with Shah’s view (Shah et al., 2004) of the need to support knowledge-intensive design, and Horvath’s emphasis on informatics covering people, products and tools (Horvath, 2001) then we propose a definition of design informatics as “the codification, organisation, exchange, sharing, storage and retrieval of digital objects related to humans, products and tools to support knowledge-intensive design” (McMahon, 2016).

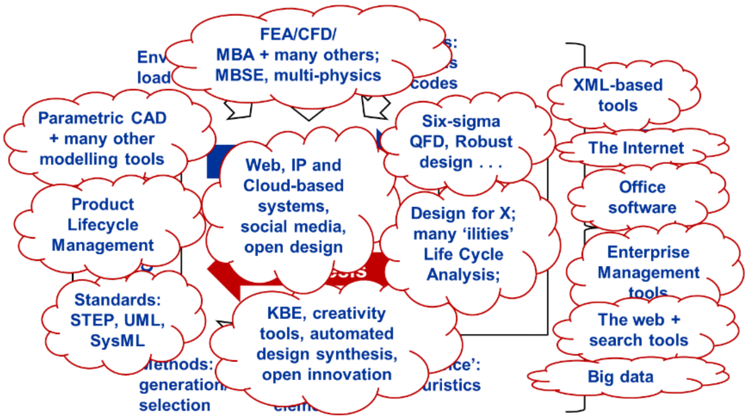
To understand how the various elements of design informatics fit into design activities, consider Weber’s Characteristics-Properties Modelling/Property-Driven Development (CPM/PDD) model of design (Weber and Deubel, 2003). In this model, the designer is responsible for defining the characteristics of the artefact, conventionally represented by drawings, diagrams and bills of materials (more recently by computer-aided design (CAD) models), in order to achieve the desired properties of the artefact – strength, performance, longevity, quality, reliability, maintainability, sustainability and so on (often called the ‘ilities’). The process of going from characteristics to properties is analysis, supported by all sorts of analytical tools and methods, and the process of identifying the required characteristics for an artefact to achieve particular properties is synthesis, again supported by many tools and methods (and both are supported by a great deal of accumulated knowledge). Design informatics needs to be based on model representation of characteristics and properties, to support tools and methods for analysis and synthesis, and to support and document the human activities in the process. Figure 1(a) shows the relationship between design characteristics and properties, based on Weber and Deubel, together with some of the elements that feed into the analysis and synthesis processes that allow design characteristics to be developed and the properties of the resulting design to be evaluated.



(a) Design characteristics and properties



(b) Key design informatics technologies in 1989



(c) Key design informatics technologies in 2017

Figure 1. The development of design informatics technologies

By the late 1980s, just before the first developments in the World Wide Web, many of the models and methods of design informatics that we use today were well established. Product characteristics could be modelled using parametric, associative boundary-representation geometric models, and wider management of product data could be done using product data management (PDM) software (McMahon and Browne, 1992). Standards existed for the main geometric modelling approaches. In analysis, the finite element method was well established, and computational fluid dynamics was developing rapidly. Many tools for computer-aided process planning, design for manufacture, quality management and so on were in place. Extensive 'office' tools and tools for computer-supported collaborative working (CSCW) supported design collaboration (Marmolin et al., 1991). The constituents of the World Wide Web (WWW) – hypertext, file transfer and mark-up languages – were well-established (Berners-Lee et al. 1995). Figure 1(b) shows the relationship of these and other technologies to the characteristics/properties diagram shown in Figure 1(a). The acronyms used are: FEA – finite element analysis, CFD – computational fluid dynamics, MBA – multi-body analysis, QFD – quality function deployment, IGES – initial graphics exchange specification, MRP/MPR II - material requirements planning/manufacturing resource planning, ISO OSI – International Organisation for Standardization, Open Systems Interconnection model

In the intervening years there have been many developments built on this foundation - computer performance has broadly followed Mohr's law, mechatronics has strongly influenced product development, and networked and cloud computing dominates the computational world. In design informatics, the underlying tools are still broadly the same, but they have been developed in many directions. PDM has become Product Lifecycle Modelling (PLM) (Terzi et al. 2010). The range of characteristics and properties that we model has been extended, and we combine these in multi-physics analysis. We are able to manage the repeated execution of tools, for design optimisation and exploration, using tool management systems such as Isight/Simulia[1] . We have developed many tools for specific properties (typically called 'design for X', where X is some property such as life cycle impacts). The coverage of standards is very-much extended, through the ISO10303 Standard for Exchange of Product data (STEP) and other developments (Pratt, 2001). Meanwhile the WWW and ever faster digital communication has permitted us to move to 'design anywhere, make anywhere, sell anywhere". This pattern of tools and technologies is shown, again mapped onto the characteristics/properties diagram of Figure 1(a), in Figure 1(c). acronyms are as follows: MBSE – model-based systems engineering, UML – unified modelling language, SysML – systems modelling language, KBE – knowledge-based engineering, XML – extensible markup language.

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[1] https://www.3ds.com/products-services/simulia/products/isight-simulia-execution-engine/

3 Representation of Characteristics

Although the capability of design informatics tools has increased enormously, and there have been useful developments in their integration, general interoperabiity of the tools has been challenging. The problem is that the model representations know nothing of the design intent – they have no semantic content (i.e. the representation does not include such issues as the functions of the represented elements, how they operate and so on) and are largely just model geometry. Reasoning with the geometric models has been explored, to recognise for example where particular manufacturing operations were appropriate – i.e. to recognise manufacturing features - or to build models for analysis, with some partial success (Babic et al., 2008). However, the feature recognition tools needed to be laboriously constructed and many geometries were difficult to deal with. As an alternative to feature recognition, we also tried building models by assembling from standard features, again with some success, but each discipline needs its own feature set (the features of value to a structural analyst are different from those needed by a manufacturing engineer), and they are not compatible nor were they ever sufficiently complete for widespread use (Sanfilippo and Borgo, 2016). The use of annotation may be a promising alternative to design by features (in that the CAD model may be annotated from multiple perspectives), and by using lightweight representations of the original boundary-representation model it may be possible to share annotations throughout the product life cycle (Li et al. 2013)(Ding et al. 2009)

We have had some success in the automatic generation of analysis models from CAD, but this has been challenging, as noted by Nolan et al. “The process of progressing from a manufacture-orientated CAD model to a simulation model remains time-consuming and is not robust” (Nolan et al. 2014). When we need to explore the design space in optimisation or for stochastic and trade-off studies, especially with multi-physics models, we are often restricted to using script-driven tools passing parametric descriptions between the different tools, and getting robust reusable parametric descriptions has often been challenging (Johansson, 2014)(Salehi and McMahon, 2009).

The modelling of characteristics today is made much more complicated by our use of multiple discipline-specific models – for example geometric models, models of electronic circuits and systems, software models, control systems models and so on (Törngren et al. 2014). Integration of these is made difficult by the different scientific bases and by different levels of fidelity used in models at different stages of the product life cycle. Again, much of the semantics of the artefact is not captured in the models, and even representation of geometry is made more difficult today by the possibilities offered by new manufacturing processes such as metal additive layer manufacturing and structural composites. These do not match well onto the prevailing geometric modelling paradigms and have led to alternative approaches such as voxel-based modelling being proposed (Chandru et al., 1995)

4 Modelling and Evaluation of Properties

In the development of design informatics tools for the modelling and evaluation of artefact properties, similar patterns may be seen. The number of properties for which tools are available has expanded as has the number of issues that need to be considered (De Weck et al., 2011). The linking of these tools is made challenging by the different underlying analytical bases (e.g. time-based differential equations for control vs state-transitions for software) by the multiple model bases (e.g. boundary representation for representation of geometry in CAD, spatial enumeration for its representation in FEA), by the extensive use of empirical data, for example in design for manufacture or for disability, and by the need to combine artefact models with process models, for example for life cycle analysis. In the development of standards, much less progress has been made, and it is more fragmented, than is the case for standards for the modelling of characteristics. These various constraints mean that it is in general only possible to link different tools together in relatively limited ‘tool chains’, a term used in software development, but also applicable in computer-aided engineering, to describe environments in which sets of tools are used where the output from one tool becomes the input or model for another (Imran et al. 2015).

5 Synthesis, Collaboration and Documenting the Process

In the area of tools and methods to support synthesis – identifying what artefact characteristics might enable a desired set of properties and often proposing a conceptual solution - there has been a lot of activity, with a spectrum of approaches. There have been attempts at automated design synthesis, which have given some useful results within narrow bounds – e.g. shape design through generative grammars and through topology synthesis (Chakrabarti et al. 2012)(Yildiz & Saitou, 2011). In support for the designer, we understand much better the nature of design creativity (Nagai & Taura, 2016), and how it may be stimulated for example using tools to prompt the designer (including, for example, tools that use biomimetics, and based on patent analysis) (Srinivasan et al., 2017). In well-defined domains (e.g. product configuration, design in product families), the rules for synthesis have been built into knowledge-based engineering (KBE) tools, and we have had many tools and methods developed in areas such as robust design or design for sustainability (Maier et al., 2017). Nevertheless, many methods essentially embody well-organised heuristics and accumulated advice on good practice, with very little based on any significant theoretical foundation. There is thus still a lot of opportunity for improved tools for synthesis. Model-based systems engineering (MBSE) may suggest a way forward through building reusable unified models of elements that incorporate both characteristics and properties and their relationships, and it is especially valuable in ensuring completeness and consistency among models from different viewpoints, but again it is difficult to see any very extensive theoretical foundation for the approach.

The early tools for CSCW have become the basis for international collaboration. Distributed design is supported by globally accessible product databases, voice and video calls over the Internet, social media and other computer-supported sharing. We have also had some success in better documentation of the design process, though development of tools for recording meetings and design rationale capture (Giess et al., 2008)(Bracewell et al., 2009), but we need to better embed the tools for collaboration and documentation into the designer's work practices.

6 What is the Current Status?

A summary of the current position is as follows. We are 'locked-in' by historical choices to many of the ways that we use informatics in design. Our models have little or no semantic content and as such have only limited value as a basis for automated actions. The new challenges that have been added in recent years – such as the need to support the design of cyber-physical systems – have led to the need for new and modified modelling approaches to deal with their special characteristics, and the expanded range of properties that the designer considers has also led to the need for new tools and modelling approaches. This escalation has further compounded the issue of the limited interoperability of tools and methods. The consequence is that we have 'islands' of good performance in our systems (and in particular we have cases where we can form limited tool chains of connected tools), but for the most part we need to spend a lot of time on data manipulation, conversion and re-entry. However, and in contrast, we also have much better computational performance, and storage and communication bandwidth are less constraining than before. But to move forward we need to (1) better understand the way we use models through the life cycle, especially the way we manipulate models when we form tool chains, and the way changes propagate among models (2) continue to work on a compatible framework to associate the domain-specific models, manage the dependencies and develop interoperability.

7 Big Data and Deep Learning in Design

The prize that may be gained from progress in interoperability and from understanding the way models are used is the possibility of exploiting in design the current developments in machine learning. As LeCun notes, "Ultimately, major progress in artificial intelligence will come about through systems that combine representation learning with complex reasoning" (LeCun et al., 2015). Can we envisage such developments in engineering design? Could we develop systems that could genuinely learn - for example how to build a good model for finite element analysis from a CAD model, or what the best-practice costs were for different manufacturing processes? It is suggested here that the pre-requisites are to have access to sufficient examples of computer-readable models for patterns and features to be identified and then to be able to map in a computer-interpretable way the dependency relationships between the information objects generated in the design process. To have sufficient number of examples seems to be crucial. Until recently a lot of machine learning involved carefully developed 'supervised learning', that builds on the sort of labour-intensive coded feature-recognition approaches that we have taken in computer-aided design. Today, the most stunning recent developments are taking place using unsupervised learning using enormous data sets (LeCun et al., 2015). The barrier to this taking place in engineering is that most engineering data is proprietary in ownership and often also in data format. To be able to exploit such data, beyond what can be learned in a single organisation, we need mechanisms to allow data to be shared for learning purposes while maintaining confidentiality. As Siemens ATOS notes in a recent position paper, insurance, automotive and transport companies, for example, have much to gain from working together in cross-industry collaboration, but in any data-sharing venture, the management of compliance and confidentiality become central to success (Anon, 2016).

8 The Need for Improved Synthesis

The final point to be made is that we are at a point in history when we need to redouble our emphasis on synthesis. We need products and systems that are less resource intensive and of lower environmental impact. In a circular economy, we need products that are easier to maintain and to recycle and reuse. However, the need to serve global markets and the demand for product quality has led many manufacturers to be very cautious about deviating far from what they know. We are 'locked-in' to artefact arrangements by the choices we have made in the past (Arthur, 2009). We need to concentrate our efforts on the synthesis of future artefacts: what are the characteristics of products and systems that will have the required properties of performance, resilience and sustainability, and how can we design them efficiently and effectively? Our research in design informatics should reflect this need.

9 Conclusions

During the last 30 years, design informatics has become firmly entrenched as an enabler of design practice, built on solid foundations established in the previous three decades. Increases in the performance of computers and computer networks have made computing ubiquitous in design. However, although enormous progress has been made, a number of challenges remain. The multiplicity of tools and methods in engineering design has meant that interoperability is still an issue, and moving beyond representations of geometry in CAD has not been easy. These issues are further compounded by the technological developments in mechatronics and cyber-physical systems. To exploit the opportunities that these developments offer, and the possibilities of data analytics and artificial intelligence, it is necessary to redouble our efforts to achieve interoperable systems capable of representing the diversity of viewpoints found in design.

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