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ORIGINAL PAPER

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A treatise on order in engineering design research

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Abstract Engineering design research shows a rather fragmented, if not a chaotic, picture. But does it have a hidden order? Can we explore it, or should we impose a reasoning model? This paper looks for the answer in the purpose of engineering design. It is destined to sustain human existence and well being by virtual creation of artifacts and services for the society. To this end, the engineering design discipline should provide a proper body of knowledge. The design knowledge obtained by empirical exploration and/or rational comprehension should be transformed for practical/pragmatic deployment. It was assumed that this purposely streaming of design knowledge gives a unique rationale for engineering design research. Based on this, a framework of reasoning was constructed, including source, channel, and sink categories of knowledge and research of engineering design, respectively. Within each category, research domains, trajectories, and approaches were identified. The semantic relationships of domains, trajectories, and approaches form a hierarchical structure. The proposed framework enables a grounded argumentation about the order of engineering design research, as well as about the articulation of the engineering design knowledge.

Keywords Engineering design research · Purpose of engineering design · Intentional stream of knowledge · Research categories · Research domains · Research trajectories

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1 Introducing the problem

Engineering design research is the instrument of exploration, description, arrangement, rationalization, and utilization of design knowledge (Pugh 1990). Design research aims at increasing our understanding of the phenomena of design in all its complexity, and at the development and validation of knowledge, methods, and tools to improve the current situation in design (Blessing 2002). Due to the progress achieved so far, design could be identified as a discipline in its own right, independent of the various areas in which it is applied (Andreasen 2001). Design research intends to build new knowledge structures rather than only to systematically describe empirical rules. Design knowledge is inherently multi-faceted, having both formal scientific knowledge and tacit human knowledge as sources. Engineering design research was developing fast in the last few decades, and as a result, it shows a rather fragmented, if not a chaotic, picture (Arciszewski 1990; Hundal 1990; Tomiyama 1990). The reason is that the order of knowledge does not spontaneously develop with the increase of knowledge. Nevertheless, science involves a search for order that appears not only in the arrangement of knowledge, but also in the methods of inquiry (Davies 1968). In the realm of natural and formal sciences, research is, typically, structured, as it is implied by the governing theoretical/methodological paradigms of reasoning. In the discipline of engineering design, these kind paradigms have not yet been identified.

The boundaries of engineering design are somewhat fuzzy (Fig. 1). For instance, mechanical engineering design overlaps product design, but also, to a smaller extent, technology development (Levy 1985). Design philosophers investigated the epistemic, taxonomic, logical, chronological, phenomenological, and other principles of the engineering design discipline. The knowledge of engineering design has also been considered from several aspects, such as governmental, industrial, historical, technological, educational, scientific, sociological, and

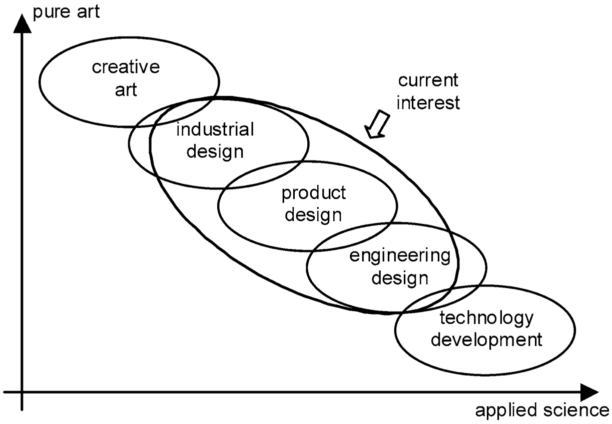


Fig. 1 The fuzzy area of investigation

practical. Engineering design has been understood to be a partially scientific discipline. Yet, design science is supposed to categorize and arrange all pieces of the explored knowledge (Ridley 2001), as well as to acquire design-related knowledge on a continuing basis, to search for all forms of truth, to look for an understanding of design, and ultimately, to explain the act of designing (Chalmers 1999). It comes from the so-called analytical rationality, which is especially dominant in natural and abstract sciences. Structuring the elements of knowledge is a feature of scientific methods and it supports proper actions, judgments, and evaluations (Eekels and Roozenburg 1991).

Does engineering design research have a hidden order? Can we explore it, or should we impose a reasoning model if we want to talk about the order of engineering design research? But how can we impose order on engineering design knowledge if the research that produces this knowledge does not, apparently, obey order or rule (Blessing 2002)? Or, can we understand engineering design research without a proper comprehension of the knowledge of engineering design? These were the observations and the main questions for my research whose recent results are reported in this paper.

2 Previous work

One of the pioneers in this field, Archer (1981), presented a reasonable classification of the fields of design science. He identified the following scientific areas:

1. Design history
2. Design taxonomy
3. Design technology
4. Design praxiology
5. Design modeling
6. Design metrology
7. Design axiology
8. Design philosophy
9. Design epistemology
10. Design pedagogy

Surprisingly, fields such as the study of: (1) design knowledge, (2) designed artifacts, (3) designed processes, (4) design-related humans, and (5) design applications have not been considered. Archer's work was undoubtedly an important step to establishing knowledge categories of engineering design, even though the identified areas do not cover all existing branches, do not represent fundamental categories, and the order has not been addressed explicitly. For these reasons, this classification motivated further thinking and other approaches have been proposed based on different reasoning, views, and levels, respectively.

Driven by their intent to survey the research in engineering design, Finger and Dixon (1989) arrived at a structural arrangement of the various approaches. Based on the view they obtained from their extensive literature studies, they split research in mechanical engineering design into six attention areas: (1) descriptive models of design processes, (2) prescriptive models for design, (3) computer-based models of design processes, (4) languages, representations, and environments for design, (5) analysis support of design decisions, and (6) life cycle issues of design. From a philosophical point of view, this structuring is empirical (also phenomenological) and reflects a given stage of development. Actually, this was the aim of the authors. They made projections based on the state-of-the-art accomplishments to issues, which might qualify as outstanding research issues.

In the work of Hubka and Eder (1996), design knowledge appears in the context of technical systems, i.e., in the objects and processes involved in them. The role of technological sciences (to which design science belongs) is to organize the knowledge as expediently as possible, and to strive for a complete and suitable form. They differentiated object, process, material, and engineering sciences as parts of technological sciences (Fig. 2). Design science is understood as a system of logically related knowledge which should contain and organize the complete knowledge about and for designing. They decomposed design science into: (1) theory of technical systems, (2) design object knowledge, (3) theory of design processes, and (4) design processes knowledge. In this model of reasoning, the human role

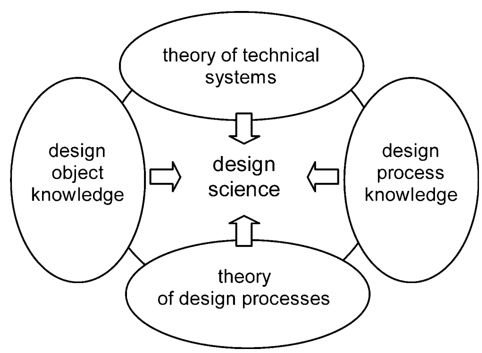


Fig. 2 Knowledge categories of engineering design on the basis of technical system theory

and the human-related aspects in engineering design remain somewhat hidden and mechanical engineering design is the main scope.

With the aim of covering the existing branches of engineering design research, Beheshti and van der Veer (1999) presented a research-domain-oriented classification. It is actually an expansion of Archer's classification by further clusters. They observed that other areas, such as design management, design policy, design aesthetics, design semantics, design decision making, design evaluation, design logic, design ontology, design logistics, design syntax, design ethics, and design informatics, could extend the above-mentioned group of knowledge areas. They concluded that a general framework of classification including all relevant areas is to be defined or explored. They recognized that the areas of attention belong to three main categories: (1) areas that define the agents of design (design cognition, ~ philosophy, ~ logic, ~ modeling, ~ epistemology, ~ psychology, ~ syntax, ~ grammar) and can describe the study of creative and cognitive activities of design (~ aesthetics, ~ semantics, ~ ontology), (2) areas that define the influences of design in terms of studying both internal (~ history, ~ pedagogy, ~ evaluation) and external experiences of designing (~ axiology, ~ policy, ~ decision making, ~ ethics), and (3) areas that define the operations of design in terms of studying the organization (~ taxonomy, ~ praxiology, ~ management, ~ logistics) and the product of designing (~ technology, ~ metrology, ~ informatics). The authors populated the design application domain with areas of attention such as: (1) design decision support systems (design support environments, intelligent design and planning tools, interactive virtual reality environment), and (2) design and planning informatics disciplines (design informatics, planning -, geo -, hydro -, building -, building and construction robotics). They introduced and articulated the basic design tool domains as containing: (1) processing tools (image processing, computer vision, computer graphics) and (2) artificial intelligence tools (knowledge representation, human and machine intelligence, machine training and learning systems, and case-based reasoning systems). This approach reflects a flow of knowledge towards practical application, in which the focus has been placed onto civil engineering. The significance of their work is in raising the awareness of three issues related to any expanded taxonomy. First, completely different sorting can be generated based on a different reasoning, having a different view, or viewing from different levels. Second, if the real rationale behind the structure of knowledge cannot be seen, then the classification may seem to be somewhat arbitrary. Third, a taxonomy cannot show all inherent and contextual relationships between the fields of knowledge and activities.

Fulcher and Hills (1998) applied the principles of numerical classification and multi-variate statistics to develop a descriptive taxonomy of design research topics by agglomerative clustering. Their goal was to increase objectivity in the strategic understanding of the rapidly expanding field of engineering design research. The approach is bottom-up, i.e., a large number of publications on engineering design research were studied, marked-up and modeled textually by keywords, and sorted into larger and larger sets with the assistance of numerical cluster analysis. The low-level descriptive attributes were converted to numerical data based on percentage agreement, and grouped into hierarchical classes based on similarity measures. Applying dendrogram cutting, the authors obtained three primary clusters and eight secondary clusters. The first primary cluster is *systems, tools, and techniques,* with three secondary clusters of *product synthesis and optimization*, *working means application*, and *working means theory and technical basis*. The second primary cluster is *processes and principles* with two secondary clusters, *process comprehension and modeling* and *decision making*. The third primary cluster is *management, research and education*, which comprises *research and education*, *design management*, and *case histories*. Their taxonomy seems to be weak on the lowest level, since certain elements could appear in other clusters.

Eekels and Roozenburg (1999) also made efforts to contribute to the clarification of engineering design science. A higher level of abstraction plays a key role in their approach. This can be referred to as vertical compared to the above-mentioned, horizontal ordering, approaches. They dealt with the context and the boundaries of the realm of engineering design science following a stratification principle. It says that we can talk about engineering design on different levels of abstractions, which can be transitively arranged (Fig. 3). They stratified engineering design knowledge on five levels, sub-sequentially containing: (1) general philosophy of science, (2) philosophy of engineering design science (including design epistemology and ontology), (3) engineering design science (including design phenomenology and methodology), (4) engineering design methodics, and (5) engineering design practice. This stratification reflects a flow of design knowledge from general to specific, as well as from abstract to concrete.

Love (2000) recognized the need for "some means of structuring existing concepts and theories to bound the unnecessary growth in abstractions and terminology so that it is clearer to design researchers which concepts,

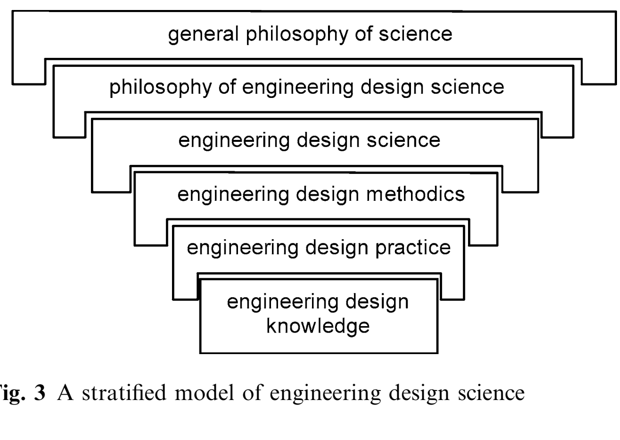


Fig. 3 A stratified model of engineering design science

theories, and theoretical strands are pragmatically more useful or better justified, and what their relationships are to each other." He proposes a meta-theoretical approach as a means by which epistemological and ontological clarity could be brought to design science. He interprets design philosophy as a meta-theoretical structure for design theory and his main finding is that concepts and theories are abstractions whose relationship needs to be analyzed at a higher level of abstraction. For classifying abstractions of design theory, he proposes the following levels: (1) direct perception of realities, (2) descriptions of objects, (3) behavior of elements, (4) mechanisms of choice, (5) design methods, (6) design process structure, (7) theories about the internal processes of designers and collaboration, (8) general design theories, (9) epistemology of design theory and the theories of objects, and (10) ontology of design. Levels (2) and (3) relate to objects, levels from (4) to (7) to design processes, and levels from (8) to (10) to philosophical matters. He found that different sub-disciplines of design research have a different balance of activity at each level in this meta-theoretical structure.

Friedman (2000) assumed that a designer is a thinker whose job is to move from thought to action. He proposed a taxonomy of integrative design knowledge domains that describes the frames within which designers act. Three domains are from the domains of theory: (1) the natural sciences, (2) the humanities and liberal arts, and (3) the social and behavioral sciences, and three are from the domains of practice and applications: (4) human professions and services, (5) creative and applied arts, and (6) technology and engineering.

The study of literature shows that the desire of understanding or introducing order in the knowledge and research of engineering design has existed for a long time (Wallace 1981). Supposing that it does exist, there have been several ideas about how to find and interpret the rationale of engineering design research. The three main approaches have been: (1) phenomenological sorting, (2) ontological taxonomization, and (3) contextual reasoning. The various approaches are difficult to compare since they represent strongly different philosophies and have different objectives. Even if they are striving after objectivity, empiricism and subjectivism are, to some extent, always incorporated.

It is presumed in this paper that the order becomes apparent if we have the proper view to see it. It proposes a framework of reasoning to place the fields of engineering design research into a systematized picture.

3 Assumptions and thoughts on a framework of reasoning

I assumed that engineering design research does obey some sort of order. The issue is how to get closer to it. After Bohm (1980), two alternative views can be formed; explicate and implicate. The explicate view is related to observations and allows creating order by phenomenology. In our case, the strategy of inductive reasoning to reach from the facts observed in real life and literature to a hypothesis or to a model of reasoning does not work. The implicate view relates to comprehension and allows the creating of order by cogitation. Unfortunately, nomothetic relationships have not yet been identified; as a matter of fact, it is a work for future research to show whether such relationships exist and, if so, in which form they exist. Nevertheless, my conjecture has been that applying the implicate view can yield a deeper understanding of the relationships of design knowledge. The question is what specific principle can be adopted to describe the relationships of design knowledge in a rational way? I tried to look for the answer in the purpose of engineering design.

Design research as well as engineering design is driven by human intentions and purpose (Dilnot 1982). It is destined to sustain human existence and well being by the virtual creation of artifacts and services for the society (Rzevski 1991). The whole of engineering design is determined by this purpose rather than by mechanical causes (Rosenberg 2000). Actually, the contribution of engineering design to fulfillment of societal needs for products and services explains its occurrence and the way of occurrence (Ferguson 1992). That is the reason why we can talk about the teleology of engineering design. This teleological view also means that the primary function of design knowledge is to contribute to the attainment of human purposes and objectives. To this end, the engineering design discipline should provide a proper body of knowledge.

The purpose interpreted above imposes order and governs the relationships of engineering design knowledge. The design knowledge obtained by empirical exploration and/or rational comprehension should be transformed for practical/pragmatic deployment. In other words, engineering design knowledge moves from the bedrock of scientific knowledge to the practical exploration and development of concrete technical solutions—a fact supported by many fundamental observations. My perception is that this *purposely streaming* introduces unique categories of design knowledge and gives a rationale for engineering design research. Hence, I used the context of purpose as the basis of demarcation of the fields of knowledge and the areas of attention in research. Based on these arguments, I constructed a framework of reasoning, including source, channel, and sink categories of engineering design knowledge and research, respectively (Fig. 4).

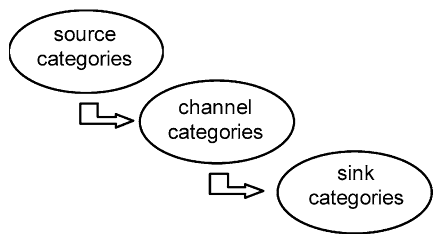
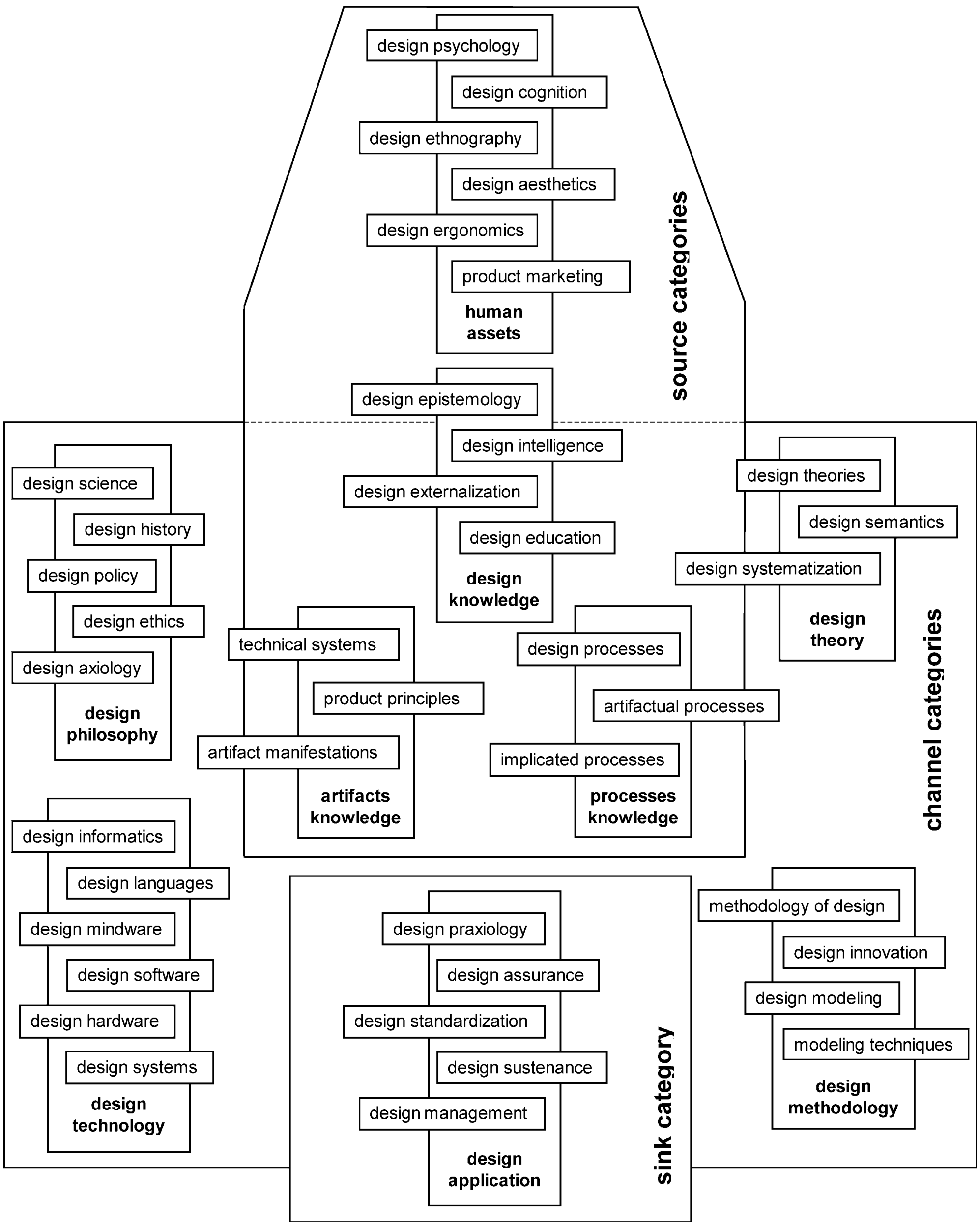


Fig. 4 The purposely streaming of engineering design knowledge

A *research category* is a philosophical concept that is based on our thoughts and organizes our experiences accordingly. As specific to engineering design knowledge, I found nine research categories important to being inaugurated in the framework. Within each category, research domains, trajectories, and approaches have been identified. A *research domain* is a disciplinary branch of engineering design knowledge and research representing a particular field of competence or expertise, such as history, ergonomics, or management. A *research trajectory* indicates a flow of operations sharing the same objectives and concepts of modeling a typical example. Finally, a *research approach* concerns the concrete treatment of a specific research issue in engineering design research. Figure 5 shows the proposed structuring on the level of research domains. The semantic relationships of domains, trajectories, and approaches form a hierarchical structure. The proposed framework enables a grounded argumentation about the order of engineering design research as well as about the articulation of the engineering design knowledge.

The *source categories* of engineering design knowledge and research are the categories that endow us with the fundamental mental capacity for engineering design. From an epistemic point of view, knowledge pertaining design may belong to one of the four contextual categories: (1) knowledge on human assets that is an all-preceding source category, (2) generic knowledge of design that represents a part of the universal knowledge, likewise, (3) artifact knowledge and (4) process knowledge that complement each other. The *channel categories* provide knowledge for establishing couplings between

Fig. 5 The framework of reasoning about categories, domains, and trajectories of engineering design research



categories of scientific/theoretical knowledge and categories of pragmatic/technical knowledge. The purpose of design philosophy is to improve understanding; of design theory, it is the proper reasoning with knowledge as well as crystallizing theories for designing; of design methodology, it is the proper utilization of knowledge; and of design technology, it is the effective application of knowledge. The *sink category* is concerned with the (generation of) knowledge that is necessary for the ultimate deployment of the whole engineering design knowledge. Design application represents this category alone. Due to the space limitation in this paper, the discussion of the proposed framework of reasoning has to be restricted to design trajectories. The identified research trajectories will be presented in the figures and the related explanations will disclose the various research approaches. The boxes in these figures will have two meanings: (1) the topic of a research trajectory and (2) the results of research in a trajectory.

4 Research in human assets

We regard human assets as the whole of the mental and physical capabilities and potentials that is owned by a community of human beings and that a business needs to enable its processes to generate new values. Humans can have a relationship to engineering design in three forms. They can be: (1) scholarly originators of general and specific design knowledge (design philosophers, design scientist, design theoreticians), (2) design problem solvers (design methodologists, engineering designers, products designers, design system developers) (Frankenberger et al. 1998), and (3) profiteers of the design deliverables (manufacturers, undertakers, users, customers, students). Within the research category of human assets, six research domains can be identified that decompose into various research trajectories. They are as shown in Fig. 6.

4.1 Design psychology

Design psychology research studies the mind and behavior of designers, as well as of the people who are affected by design in whichever form applicable (Thomas and Carroll 1979). Individual designers, collaborating designers, and designer–user mixed groups have been considered (Arnabile 1983). Behavioral research studies the human capabilities for design (Nideau 1991), characteristics of human mental and physical performances, the mindset of designers, their attitude towards designing, the behavioral elements in problem solving (Newell and Simon 1972), complexity handling, tool usage, decision making, work coordination, and communication (Chandrasekaran 1990). Ethologic research also forms part of design psychology research, with special interests in character-formation in the behavior of designers and the users.

4.2 Design cognition

Cognition is understood as parallel processes of thoughts, body physiological states, and the perceptions of an individual of those states (Bastick 1982). *Design cognition* research investigates the cognitive mechanisms of knowing, perceiving, and conceiving design knowledge, intuitions, and hypotheses (Frinke et al. 1992). It disregards however feelings, emotion, beliefs, and volition (Madanshetty 1995). Distinction between rational cognition and affective cognition has been made to give a grounding to the non-rational affective aspects of human designing—the set of feelings (Love 1999). Research in rational design cognition explains cognitive design processes in terms of information processing. It also studies the models of designing (Christiaans and Dorst 1992) and the various techniques of eliciting design knowledge from the design activity on decision, product, and project levels (Magee 1987). Research in design thinking investigates the thought processes of the

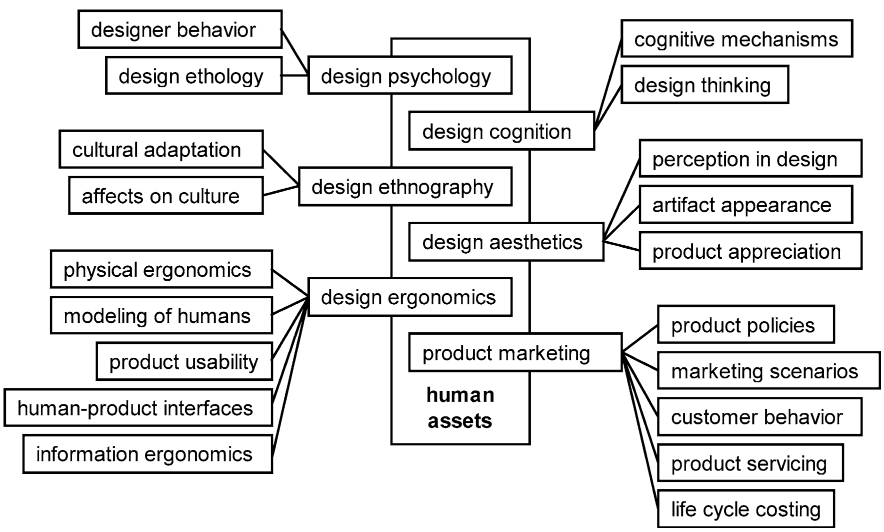


Fig. 6 Research in human assets

designers, with special attention to logical, visual, spatial, and functional thinking (Dewey 1933).

4.3 Design ethnography

Ethnography is the branch of anthropology that provides a scientific description of individual human societies. Being stimulated by the globalization of industrial production and the worldwide need for customized products, *design ethnography* research focuses on the distillation of culturally relevant design knowledge and the culture-sensitive designing of artifacts (Bucciarelli 1988). Design ethnography research investigates the principles and approaches of adapting products to cultural differences and establishes so-called "open to cultural differences" product development processes (Salvador et al. 1999). Another trajectory of research studies the influence of commercialized products on global and local cultures (Button 2000). Recently, various field research methods have been introduced which are able to link ethnography and design (Blomberg et al. 1993).

4.4 Design aesthetics

In the 18th-century writings of Baumgarten, aesthetics is explained as the science of sensuous knowledge. Departing from the traditional conceptions of philosophical aesthetics, *design aesthetics* studies the psychology of creation, appreciation, and imagination of aesthetics, experience along with emotions, evaluation, and preference (MacDonald 2001). Design aesthetics involves the study of appearance and perception of shape, functions, attributes, and behaviors of products (Smets 1995). It investigates the impression and appreciation of beauty in products, the aesthetic attitude and emotional reactions of humans, and the creation of aesthetic values (Berlyne 1974). It prioritizes detailed empirical studies of the nature and creation of aesthetic values in products, and of the actual properties assigned in design and achieved in realization. Design aesthetics research goes beyond empirical studies and stresses a theoretical argumentation about forms, colors, and other sensory properties (Tovey 1997). Research achieved moderate progress with understanding emotional reactions of humans to aesthetic impressions caused by designs. New measures like "pleasurability" have been suggested (Jordan 2000). The rules of creating designs with intended appearance through form giving, materialization, and decoration have not been explored yet sufficiently. Forms and structures of products implied by physical principles are only in the fringe of attention of design aesthetics.

4.5 Design ergonomics

Research in the domain of *design ergonomics* is multifaceted (Andersson 1989). The major research issue is accumulating knowledge for optimization of the interaction between clusters of humans and products/environments (Sanders and McCormick 1992). Physical ergonomics deals with the investigation of physical human–product interactions, as well as of human and work place interactions, with an emphasis on the increase of safety, comfort, and convenience (Eggleton 1983). Central are the measurable aspects such as physical effort, efficiency, and effectiveness at performing tasks. Informational ergonomics pursues very analogous objectives in terms of human–product mental interaction (Wickens and Carswell 1997). It studies the cognitive and perceptual interaction between humans and products—the information flows from product to user and from user to product. Issues such as multimodal interaction, efficiency and ambiguity of communication, comprehensibility of signs, peripheral vision, detectability, visual perception, and information overload are all in the scope of research (McClelland 1995). High-fidelity multi-aspect modeling of humans based on anthropometrical data, material properties and physical functions, and the investigation of human–product interactions in various user environments and workplaces are the other main trajectories of research in this domain (Ayoub 1973). Product usability research investigates usability from both individual context and societal context, defines the boundary conditions of product use, and studies perceptual and cognitive engagement of users in the use environment. Research in human–product interfaces concentrates on various interface concepts for both physical and virtual interfaces. One specialization is being human–computer system interfaces (Dix at al. 2001). Non-quantifiable factors, such as user satisfaction and comfort emotional responses, are getting emphasis in research. A new field of research related to the ergonomics issues of using gestures, hand motions, voice input, and haptic and tactile feedback in human–computer and human–product interfacing is emerging (Dourish 2001).

4.6 Product marketing

Supported by the general theories of marketing, *product marketing* research covers a subset of the fields of interests that specifically belong to the marketing of artifacts and related technical services (van Raaij et al. 1999). The major fields of attention in this research domain are: (1) product policies, (2) marketing scenarios and processes, (3) customer behavior, (4) product servicing, and (5) life cycle costing. Product policies research studies local and global product strategies (Quelch 1990), definition of product families and lines, and the issues of new product introduction. Marketing research has a historical aspect, but it also studies concrete marketing processes such as direct marketing, e-commerce, or e-supply. Customer behavior has received specific attention in marketing research, especially with regards to consumer products (Kassarjian

1971). Customer behavior research is about the buying habits of the customers, the effects of advertisement and product awareness, and the user experiences (Bruseberg and McDonagh-Philp 2001). Product servicing research studies the service functions related to artifactual products and the issues of marketing services as products. Research in life cycle costing investigates product marketing in the financial dimension, and explores principles and techniques for cost pricing and investment optimization.

5 Research in design knowledge

The notion of design knowledge simultaneously means the knowledge about design and the knowledge for (i.e., used in) design. Research in the contextual category called *design knowledge* is predominantly concerned with the knowledge about design. The research domains and trajectories pertinent to this contextual category are shown in Fig. 7.

5.1 Design epistemology

By adopting the doctrine of epistemology of scientific knowledge (Audi 1998), *design epistemology* builds a theory of knowledge with respect to its origins, nature, forms, constituents, and structure, as well as to its validation and methods (Dimarogonas 1993). The epistemological understanding and the basis of engineering design appeared as a central theme in the research and meditations from the early 70s until the late 80s (Campbell 1974). By today, the principal issue has been the auto-organizational interaction between natural science and applied science (technology) (Agassi 1985), or simply, between science and design (Zhiliang 1991). Part of design knowledge is acquired from the natural, social, and technical sciences; part of it has a strong connection to human assets and the human involvement in the design practice. Although it was found fundamentally empirical in nature, engineering design research has made design knowledge more theoretical by structural elaboration, abstraction and generalization, and logical processing (Hubka and Eder 1990). Contemporary research in this domain found that design knowledge could, in the most general sense, be synthetic, as acquired by the cognitive senses, and analytic, as derived by mental reasoning.

5.2 Design intelligence

Intelligence is known to be the ability to think and learn, and the capability of coping with the unexpected. The research in the domain of *design intelligence* investigates humans' design thinking (Koestler 1964), reasoning, and learning, along with the apprehension of specific problem solving capabilities, and the nature and manifestations of design creativity (Delay 1982). Design intelligence extends the intrinsic forms of human intelligence; that is, linguistic, musical, logical, spatial, kinesthetic, and personal thought processes (Gardner 1983). It has three appearance forms, namely: (1) synthetic, (2) analytic, and (3) practical. What distinguishes design intelligence are the non-verbal and non-rational aspects of competence (Cross 1986). Design intelligence research also studies the nature of problems (well defined—inherently algorithmic) and (ill-defined—non-algorithmic), and the handling of holism and complexity of design problems (Chandrasekaran 1989). The general and specific problem solving strategies, intuitiveness, heuristics, awareness, and creativity of designers are all considered (Lansdown 1987). The goal in the trajectories of design intelligence research is to achieve a better understand and to improve the abilities, for instance, to coping with the complexity of design and designing.

Whereas design thinking investigates the cognitive and intuitive mechanisms, design reasoning considers the rational foundations with the aim of deriving principles for procedural inference (Lawson 1980). In particular, it investigates the principles and forms of common, plausible, non-deterministic, and content-dependent design reasoning (Freeman and Newell 1971). Design logic is one of the fundamental forms of understanding intelligence (Popper 1972). Design reasoning based on formal (mathematical) logic has been considered as a means of mechanical realization of design, rather than a means of achieving a creative leap (March 1984). Research has not managed to draw up a general

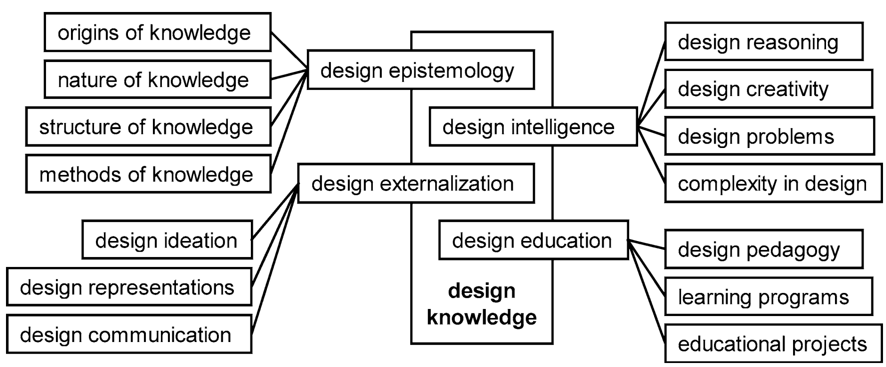


Fig. 7 Research in design knowledge

scheme of formal reasoning, such as inductive, deductive, and abductive, for engineering design as a whole (Zeng and Cheng 1991). The designer is constantly faced with the problem of bounded rationality. The cognitive prototype theory that asserts that designing becomes a process of choosing appropriate prototypes and applying powerful transformations to them came to the attention of many researchers (Gero 1989).

It has been demonstrated that engineering is a distinct discipline relying on deductive problem solving with creative overtones, which is almost an analog of discovery (Lewin 1979). Creativity is the ability to produce new things or new knowledge. Design creativity is a measure of the choices made in reaching the solution to a problem, and expresses both successfulness and unusualness (Martin and Homer 1986). Since it has been found to be a main constituent of the intelligent performance of designers, techniques stimulating creativity have been studied. Defined by Hubka and Eder (1987), the engineering design problem is to achieve the best possible results in the design process, particularly by achieving optimum quality of designed products in the shortest time at minimum design costs, especially with respect to low life cycle costs, societal acceptability, etc. (Braha and Maimon 1996). The issue of complexity appears at least in three distinct forms: problem (e.g., multi-disciplinary, dislocated), product (e.g., functional, structural), and process (coupled, multi-phase) complexity (El-Haik and Yang 1999). Current research in complexity management tries to find dedicated solutions (Warfield 1994).

5.3 Design externalization

In the domain of *design externalization*, research splits to three main trajectories: (1) generation of mental images (concepts) and converting them to abstract or concrete schemata, (2) representations applicable to transfer mental images to external representations, and (3) communication of design ideas, information, and knowledge. Design ideation research tries to understand the mechanisms of emergence, formation, and call-up of design concepts and the relationships between mental images (Galle 1999). It also studies the initial reproduction of the first reflections (Noguchi 1997), i.e., the conversion of mental images to formal schemes such as formulas, patterns, diagrams, forms, structures, and shapes, as well as the potential of the formalized schemes in design (Ulrich and Seering 1989). Typically, verbal starting points are transformed into initial physical representations, which are supported by visuo-spatial thinking (Muller 1989). For instance, schemes, portrayed in function-means trees, are the first reflection of the functional requirements of a multi-disciplinary design (Sharpe 1995). Design representation research deals with sketching as a graphical equivalent of writing and speaking (Scrivener 2000), and it studies the role of line sketches, shaded sketches, symbol schemes, and technical drawings in visual thinking and creativity. For a rather long time, technical drawing was considered to be the major formal representation, but with the advent of digital computers, its primacy is fading away (Tovey 1989). Research also studies the relationship between graphical representations and the strategy of producing a design (van Sommers 1984). Design communication concerns network-based collection, organization, classification, transformation, visualization, retrieval and use of design information, and network-based management of design processes (Safoutin and Thurston 1993).

5.4 Design education

The research in the domain of *design education* decomposes to the study of: (1) design teaching and learning processes, methods, and tools (Atman and Bursic 1996), (2) development and experience with various design learning programs, and (3) exercising product design and realization by co-located or dislocated collaborative groups (Portillo and Dohr 1989). Researchers argued that engineering design education still lacks an adequate base of scientific principles (Dixon 1988) and is guided too much by specialized empiricism, intuition, and experience (Oxman 1999). The main interest of present day design pedagogy research is to get engineering design recognized as an enabling reserve of the society (Dinham 1989). One of the most important findings of research is the observation that design is not separative, like science, but integrative, like art and engineering, which has to be a characteristic for education in the information age (Owen 1990). In terms of the learning programs, finding the best harmony of the arts, the sciences, the technologies, and the humanities in the design curriculum is an issue, along with the integration of information and communication technological means and methods in learning design (Phillips et al. 2000). Starting with the investigations of computer-networks-mediated distance learning, global design programs gradually grew into a characteristic sub-discipline of design pedagogy (Andersen 2001). It is paving the way of future design education (Childs and Brodhurst 2000).

6 Research in artifacts knowledge

Knowledge related to artifacts, also named technical systems or products, represents a specific subset of design knowledge (knowledge used in design). In the context of design, a wealth of complex artifacts appeared during the great industrial revolution and later. Historically, the first artifact theories were about mechanisms rather than about compound machinery or products. Looking back to a long history, the research into artifacts intends to understand the rules, forms, and relations of processing substance, energy, and information in designs (Hubka 1982). I have distinguished three domains of research into the realm of artifacts, specifically: (1) the domain of technical systems, (2) product principles, and (3) artifact manifestations (Fig. 8).

6.1 Technical systems

Research recognizes *technical systems* as goal-implied, synergetic arrangements of organs, and places the emphasis on the laws of transformations, casual changes, and optimization of operations (Hubka and Eder 1988). The notion "general systems" covers all kinds of technical systems for which engineering design is essential. These include mechatronic devices, mechanisms, mechanical engineering machines, thermal engineering equipment, fluid engineering equipment, vehicles, and so forth. Research in these fields belongs to the so-called specialized disciplinary research of engineering design and looks back at a reasonably long history. Following Reuleaux (1876), even at the end of the 19th century, scientific investigations concentrated on studying the movements more willingly than on the energy transformation processes that are typical for general machinery. In the middle of the 20th century, research extended to the studies of physical, functional, morphological, structural, behavioral, realization, and use aspects. The fundamental difference between general engineering systems and the customer product is the frequent and direct interactions of the latter with the users that puts the emphasis on the human aspects and requires unique approaches. The supporting philosophy of industrial product design is often called user-centered design. Research in the user products trajectory investigates both customer durables and consumable products. Research in technical servicing is a new field of attention with a lot of future prospects.

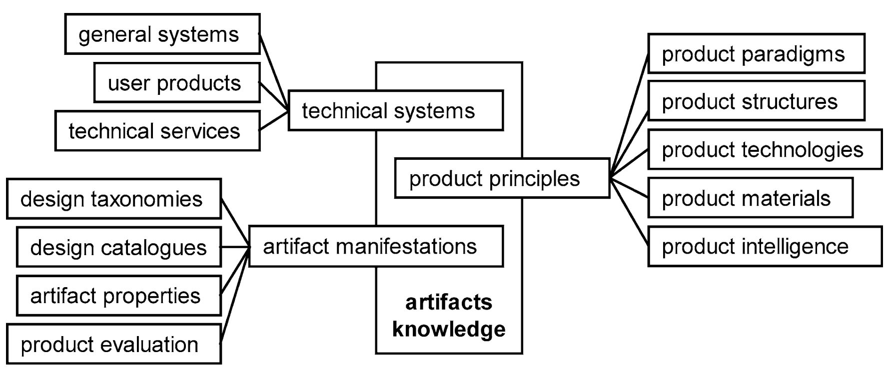
6.2 Product principles

The research domain of *product principles* is populated with the trajectories of product paradigms (Petroski 1994), structures (Thompson 1961), technologies, materials, and product intelligence. Product formation and structuring research has received extra emphasis owing to the recent trends in production technologies and marketing philosophies (Paynter 1961). The current research is strongly influenced by the integration of various product technologies into multi-functional products, a typical indication of the teleological nature of engineering design research. Product materials research investigates how new materials and material compositions (multi-materials) can be considered in the designing of the functionality of products, and what principles and rules designers need to follow in the embodiment (Dieter 1983). Product intelligence research is oriented to the study of the nature of intelligent behavior of products, the implementation of intelligence in products, the human interaction and communication with intelligent products, as well as the philosophical issues of product intelligence. Part of the product intelligence research is combined with artificial intelligence research.

6.3 Artifact manifestations

Research in the domain of *artifact manifestations* is composed of the research in the trajectories of: (1) design taxonomies, (2) design catalogs, (3) artifact properties, and (4) the methods and tools of product evaluations. The aims of research in design taxonomies are to: (1) discover general principles for orderly classifications of designs and their relationships and (2) classify purposeful artifacts in various classes based on extensional or intentional properties (Ullman 1992a). Design catalogs have been studied as: (1) warehouses of artifact related knowledge and (2) means of supporting systematic creativity (VDI 1977b). Important for design automation, the use of design catalogs goes together with following an embedding design methodological framework (Roth 1980). Research in artifact properties identified intrinsic (function, structure, material, dimension, appearance, operation), derivative (behavior, noise, radiation, texture, comfort), and sensible (form, color, sound, scents) property classes (Morris 1971). Design semiotics is the study of how these product properties are delivered through sign vehicles (visual, tangible, aural, olfactory, and gustatory) to the human senses (Lange 2001). Design property research is also interested in controlling or affecting influential properties; for instance, minimizing weight, reduction of complexity, increase of efficiency, improvement of reliability, enhancement of adaptability, and enlargement of

Fig. 8 Research in artifacts knowledge



crashworthiness. Principles and means are offered to the designers by which they can achieve the objectives. The product evaluation research is on the practical side, by working out procedures for physical testing of products, and for user experiments with products (Ishida et al. 1987).

7 Research in processes knowledge

There is a multitude of aspects to talk about design-related processes (Ertas and Jones 1995). I distinguished the main domains of research in this category as: (1) design processes, (2) artifactual processes, and (3) implicate processes (Fig. 9).

7.1 Design processes

Research in the domain of *design processes* decomposes to the study (Ullman 1992b) and modeling (Mostow 1985) of design processes, as well as to the optimization of in-process transformations (Smith and Eppinger 1997) and the use of resources in design processes to improve qualities (Braha and Maimon 1997). In the trajectory of design process modeling, research incorporates the understanding, theoretical explanation, generalization and/or abstraction of observed design processes (Akin 1979), and devising theorems, rules, and procedures as a set of instructions for solving design problems (Kusiak and Wang 1993). Understanding design processes is the topic for the process theory with specialization in design (Sohlenius 1992). Researchers usually talk about phases (sub-processes) of the generic design process, such as definition, conceptualization, embodiment, detailing, and dispatching (Dasgupta 1989). While detail design is the robust part of engineering design, conceptual design represents the lean part (French 1985).

The study of design processes involves empirical means (Ehrlenspiel and Dylla 1989), e.g., protocol study (Atman et al. 1996) and process monitoring (Wallace and Hales 1987). Timed mental, motor, and communication protocols are widely used by researchers as records of the designers' step-by-step information processing and decision making behavior. The variety of the techniques introduced by researches for modeling design processes is enormous (time diagrams (Wiest and Levy 1977), Petri-nets (Horváth et al. 1999), binary matrices (Warfield 1973), etc.). This is because design processes are investigated from the aspect of information flows, design decisions, time requests, and resource utilization, to mention just the most regular ones (Smith and Morrow 1999). Monitoring and protocol study are applied to understand the human ways of designing, processing of design information, application of knowledge, collaboration, use of tools and methods, and design communication (Stauffer et al. 1987). Creative design processes has been found dependent on the sub-conscious ideas that produce something not known beforehand (Hertz 1992).

7.2 Artifactual processes

The research domain of *artifactual processes* spreads over existential, operation, application, and service processes of products. Existential processes are related to the forms of existence of the product in various phases of its life cycle, such as concept product, prototyped product, delivered product, operating product, product in use, and product to be recycled. Involving specific transformations, operation processes are processes performed by artifacts. They are studied from both qualitative (Bobrow 1985) and quantitative aspects. The study of qualitative processes involves qualitative reasoning with natural (physical) objects and processes in artifacts/systems (Forbus 1984). The need for meta-level reasoning about artifactual processes has been stated (Kiriyama et al. 1989). The research in quantitative processes focuses on: (1) building quantifiable models of observable natural and artificial processes and (2) the inclusion of quantitative process knowledge in artifact descriptions, for instance, for behavioral simulation. Research in application and service processes investigates the relationships between the operating products and the environmental conditions of ensuring operation, respectively.

7.3 Implicated processes

By the term *implicated processes*, I am intending to refer to all processes associated with the realization and

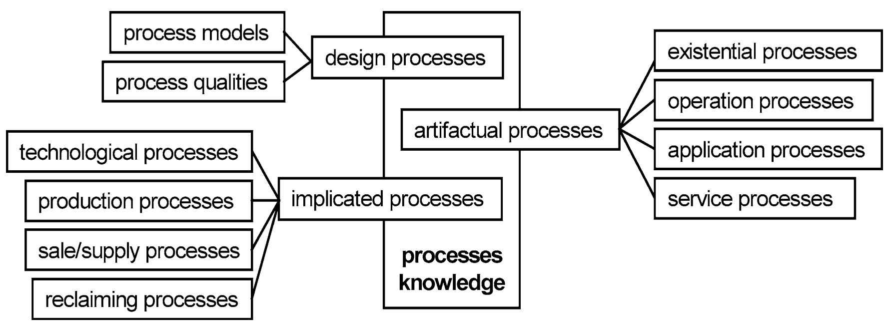


Fig. 9 Research in design processes knowledge

exploitation of products. Research in the domain of implicated processes deals with technological, production, sales, and reclaiming processes. Technological processes are about part manufacturing and assembly (Boothroyd 1992), and are studied to provide information for designers for technology-oriented decisions in the process of designing artifacts (Cay and Chassapis 1997). Production processes are about the realization of products in various production environments, such as conventional, real-time extended, and virtual companies. Research is involved in generating knowledge for the designers on the optimal product development with a view to the way of realization (Clark and Fujimoto 1991). Of current research interest is the concurrent study and integral handling of production processes with sales processes and supply processes (Otto and Wood 2001). Due to the strengthening sustainability and environmental considerations, the end-of-life phase of products is more and more intensively studied with the aim of achieving optimal reclaiming and minimum environmental impact (Graedel and Allenby 1996).

8 Research in design philosophy

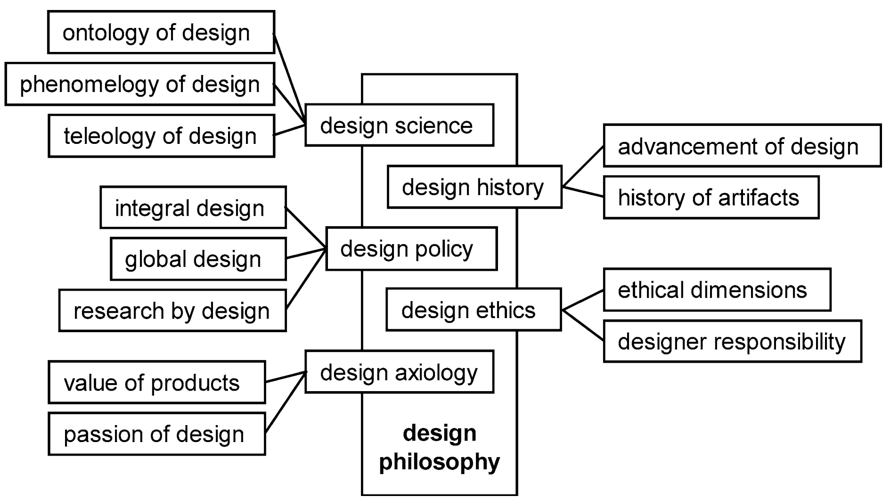
Historically, design philosophy came about when civilians started to think about the usefulness (functionality), beauty (aesthetics), and goodness (ethics) of the artifacts (Churchman 1987). This branch of philosophical inquiry targeted the issues of epistemology, aesthetics, and ethics of engineering (Dimarogonas 1997). Design philosophy is the highest level of speculative thinking about: (1) the existence and manifestation of design, (2) the role and position of design in the society, (3) the historical evolution of the design discipline, and (4) the foundational basis of design thinking (Yoshikawa 1989). Philosophy of design is often equaled to a meta-theoretical framework for design theories by which epistemological and ontological clarity could be brought in (Love 2000), and often to a philosophy of practice (Evboumwan et al. 1996). I have considered: (1) design science, (2) design history, (3) design policy, (4) design ethics, and (5) design axiology as current domains of design philosophy research, as shown in Fig. 10.

8.1 Design science

Design is a historical development. Roughly, around the industrial revolution, it went through a professionalization. Alexander (1964) distinguished the phase before professionalization as *unselfconscious* design, and the phase after professionalization as *selfconscious* design. Professionalization brought in two major things: (1) design has been practiced as a distinct activity and (2) design has been studied as a distinct discipline. Both have triggered open-ended empirical and rational knowledge aggregation processes, which have created a basis for design science. Simon (1969) was pioneering with making the now already classic distinction between natural sciences, which are interested in how things work, and design sciences, which is concerned with how things ought to be. Nowadays, many design scientists and philosophers, followers of him, are talking about design sciences. They are actually referring to various implementations of design in fields such as architecture, engineering, graphics, garment, computer science, medicine, and so on. The most probable reason is that they project the science of artificialness to these domains and perceive the various manifestations of the artifact in various processes. In this philosophical interpretation, design science is a scientific study of the design activity in its context, and it generates a collection of logically arranged knowledge in the realm of design (Orel and Trousse 1995). In contrast, the science of design is the study of a scientific way of designing (Glegg 1973).

My understanding has been that design science studies the phenomena of design above the disciplinary manifestations and achieves an integral view by applying both aggregation and abstraction. Design science decomposes to the study of ontology, phenomenology, and teleology of design. Ontology, a branch of philos-

Fig. 10 Research in design philosophy



ophy, is interested in the essence of things that exist, and in the fundamental principles and categories. Research in the ontology of design speculates about things on the basis of their being thought. In an ultimate philosophical sense, natural science has found a way to exclude the normative, and to concern itself solely with descriptive aspects of nature and its analysis (Batty 1980). Science investigates extant forms and design initiates novel forms (March 1976). The position of design science research is that engineering design, being concerned with the construction of design knowledge and synthesis, needs to be prescriptive.

Phenomenology in science philosophy is a descriptive analysis of subjective processes. Research in the phenomenology of design studies the appearances of, and in, design, largely influenced by the senses, observations, and perceptions. Teleology is the study of the final causes, assuming the existence of some direction-giving reasons. Research in the teleology of design assumes that the essence of design can be formulated by a teleological explanation. It also investigates whether any other doctrine or principle other than teleology would provide better explanation. Willem (1990) observed two knowledge-level interactions between science and design: science contributes to design by creating and delivering a vast amount of natural and applied science knowledge, while it is through design that science exceeds being pure knowledge and participates in creating artifacts for the society. Hubka and Eder (1987) identified two constituents of design science as concepts of technical information and of design methodology.

8.2 Design history

Design history research focuses on the chronological developments of design knowledge and the sub-disciplines, advancement of philosophical and theoretical frameworks (paradigms) (Hill 1984), as well as on political, social, cultural, and economic factors influencing the trends in development of products and designing (Margolin 1992). Design history came to the scene long after the time of the great industrial revolution, and became a distinct sub-discipline with the advent of the product-centered society (Tambini 1996). Two main trajectories of design history research are: (1) the study of advancement of design (Brown and Eisenhardt 1995) and (2) the history of artifacts (Strandh 1989). Advancement of design is about the ontological, methodological, and technological evolution of designs. The strategic role and the societal aspects of engineering design have received balanced attention.

8.3 Design policy

Emerging *design policy* research concerns the executions of complex research projects, knowledge about planning collaborative design processes, and outsourcing strategies for design projects. It usually concerns a high-level overall plan embracing the general design goals and acceptable design procedures. The course of actions and/or applicable methods is selected from alternatives with a view to existing or hypothesized conditions. The research in the integral design trajectory explores the application-independent principles and forms of concurrent implementation of a majority of product development activities. The research trajectory in the global design investigates the realization of products over company, geographical, and cultural boundaries. Research by design is a new concept to explore practice-oriented new knowledge through design processes.

8.4 Design ethics

Research in *design ethics* studies the ethical dimension in engineering design, including: (1) the man-made changes of nature, (2) the principles of a product to be useful for the society, as well as (3) the rules of designing, considering all moral, social, political, cultural, and personal aspects (Lynch and Kline 2000). The main issue of research is what rules reflect the norms of the society and should govern the design activities (Herkert 1998), and what is the ethical sphere of individual responsibility (van de Poel 2001).

8.5 Design axiology

Axiology is a term for the theory of desired, preferred, or distinguished values and valuation (Bahm 1984). *Design axiolog*y research is spontaneously developing to study the nature and the measures of the technical, economic, moral, social, and aesthetic values created by design. Rather than focusing directly on what the designer should do in order to create values, or what they are not supposed to do, it deals with what is worth pursuing and what should be avoided (Findlay 1970). Research in the trajectory of the value of products studies: (1) the type of values conveyed by products (psychological, social, logical, etc.), (2) the way of conveying the values, (3) the criterion of being or accepting a value, and (4) the reflection of the value. It subjects the value experience to empirical analysis. Research in the passion of design studies the values what the act of designing creates for people. In this context, the act of designing is considered as a means of self-expression, intellectual involvement, artistic creation, and having fun (de Wilde 1997).

9 Research in design theory

Design theories are dedicated to the organization of engineering design knowledge beyond the level of craftsmanship (Spillers 1972). The research in the category of design theory can be decomposed to the domains of: (1) design theories, (2) design semantics, and (3) design systematization (Fig. 11).

9.1 Design theories

Research in the domain of *design theories* deals with both generic theories (Love 1998) and specific theories (Takeda et al. 1992). Descriptive, prescriptive, and formal theories have been identified (Finger and Dixon 1989). Generic theories concern both the designed artifacts and design processes (Henderson and Taylor 1993). Hubka and Eder (1987) identified the content for the theory of technical systems as the total of sub-theories such as property theory, structure theory, transformation (process) theory, conformational theory, life-stage theory, evolution theory, and ecology theory. A global design problem solving theory generally serves as a scientific basis for rationalizing multi-disciplinary product development (Suh 1990; Grabowski et al. 1999). One of the proposed generic theories is general design theory (GDT) (Yoshikawa 1987), with the aim to introduce an idealized model for the evolutionary design process (Tomiyama and Yoshikawa 1986; Reich 1995).

Specific design theories are localized in scope, that is, they are connected to one or some particular problems of engineering design. A local design theory emerges when there is a testable explanation of why the method behaves as it does. Formal local theories are typically based on formalized theorems, rules and structured procedures, and are used in the automation of solution finding for design sub-problems (Braha and Maimon 1998). The generality of design theories is, to a great extent, pronounced based on domain-independence (Stegmüller 1976).

Research in the trajectory of design mappings focuses on specific problems of design such as: (1) converting ideas to formal specification (Jakobsen et al. 1991), (2) mapping requirements structures to functions and functional structures (Johnson 1991), (3) clarification of functions and functional relationships (Rodenacker 1971), (4) grasping function-to-form transition (Alexander 1964), (5) form giving and shape morphing (Muller 1997), (6) clarifying the relationships between shape and behavior, and (7) the study of concept advancement and design evolution (Gui 1990). Clarification of functions, functional relationships, and function-to-form transitions necessitate a vocabulary for functional modeling, for which proposals were given by Pahl and Beitz (1988), Koller (1994), and Roth (1974).

9.2 Design semantics

Semantics is the science of meaning (Ullmann 1972). Research in *design semantics* targets meanings and intentions in design (Akman and Surav 1996). Among the goals are: (1) understanding the meaning as it relates to design and explicating design intents (Toulmin 1972), (2) exploring design aspects and consideration of them in the design process, (3) contextual understanding of designing and designing in contexts, and (4) axiom-based approaches to design. One of the core issues has been the impact and measuring information (Meadow and Yuan 1997). Design semiotics studies the symbolisms applied to products, in the key functional activities in design, and in the related activities.

From the early 80s, the issue and scientific problems of supporting aspect-oriented enhancement of designs are known by researchers (Huang 1996). Research in design for aspects brought in various aspects such as manufacturing (Bralla 1986), assembly (Boothroyd and Dewhurst 1987), reliability (Birolini 1993), cost (Wierda 1988), ergonomics, aesthetics, recycling, and use, and advanced in the field of computer-oriented methods, models, and procedures (Redford and Chal 1994). In design for manufacturing and assembly, for instance, two major principles can be recognized behind the heterogeneous methodologies: (1) reducing the costs of the individual piece parts manufacturing and (2) reducing the assembly costs and difficulty. Conventional approaches considered design for aspects as a post-design analysis with quantitative evaluation procedures derived from extensive design practice. Now it is moving ahead to early the phases of design with qualitative techniques (Kuipers 1994). An unresolved issue remains on how to comprehend all interactions among the large number of distinct aspects and intents which influence product realization.

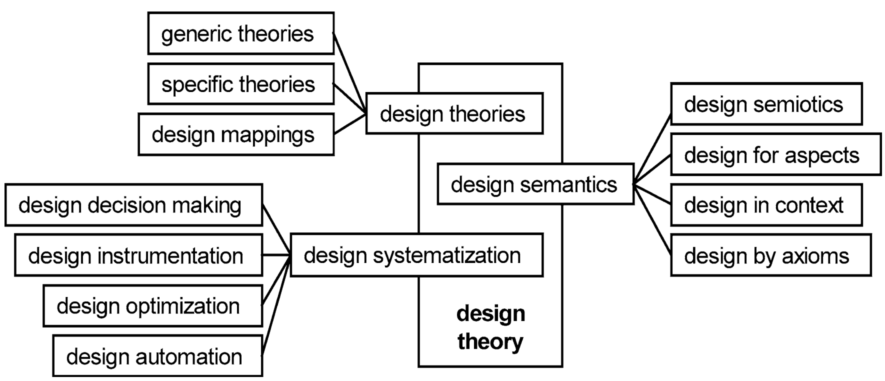


Fig. 11 Research in design theory

As "environment" became an important issue on the society level, environmentally sustainable product realization became an important issue in engineering design research. Recently, researchers clarified the concepts of green design, ecodesign, and sustainable design as activities, and system innovation, function innovation, product redesign, and product improvement as approaches (Sherwin and Bhamra 2000). Research in the trajectory of green design enforces a systems approach to the design of greener products (Ryan et al. 1992). It considers the issues of amelioration, fossil energy use, resource input, material usage, and waste emission as strategically important issues. In particular, the use of human energy and bio-degradable materials in mass-customized products received a large amount of attention. Besides environmentally friendly green products, ecodesign research is investigating the concepts of corrective products, reducing the environmental degradation, and ameliorative products, coping with the environmental effects. Design for sustainability is one approach to environmentally conscious design, with the aim to develop general theories, methods, techniques, and tools for the optimization of the interaction between products and the environment (Birkeland 2002), and the product realization technologies and the environment (Borland and Wallace 2000).

Design in context deals with the contextual understanding of designing and the relevance of design decisions and design concepts in contexts (Mitchell 2001). Design axiomatism strives for the development and application of formal reasoning frameworks from a limited number of axioms (self-evident truths), propositions (conjectures), and/or facts. Various systems of axioms have been proposed to support global and local design theories (Suh 2000). Based on the work of Russel (1912), we can conclude that there are no truths par excellence in engineering design, which makes its axiomatic definition logically unsupported.

9.3 Design systematization

The domain of *design systematization* incorporates research into: (1) design decision making, (2) design instrumentation, (3) design optimization, and (4) design automation. Design decision making investigates the cognitive and logical mechanisms behind making decisions in solution finding and representation, selection of tools and methods, and judgment of the value of designs (Wallace and Burgess 1995). Research studies individual, team, and organizational levels of design decision making (Ward et al. 1995). It investigates how the content and structure of decisions influence the design space, but also the dependencies on awareness, intents, situations, stimuli, conditions, and constraints. Design problems are often formalized as search problems in a large space for objects, to be radically shrunk by the design strategy, to find a small number of objects that constitute to satisfying or optimal solutions. Many researchers investigated the characteristics of design problem spaces (Goel 1994) and the search strategies on these spaces (Hoover and Rinderle 1989). Certain approaches to design decision making examine how the content and structure of decisions influence the design space (Morgan 1987). The significance of decision structures and the time-frame-oriented design decision making have been recognized (Little 1987). Efforts are also made towards the study of participatory design that brings together an international group of users and multi-disciplinary teams of researchers, designers, and practitioners.

Design instrumentation studies the dialectics of design tools, the dialog of design tools and design processes, humans and tools, and problems and tools (Mostow 1990). Research tries to explore what kind of tools a designer needs for their specific tasks, how tools can be integrated into the design process, in the streams of information processing, and in the environment formed by design support systems. It also investigates how improvements can be achieved by means of using tools and what kind of reengineering of design processes is needed for an optimum application of tools. Another trajectory of research considers the effects of tools on human creativity and thinking, and the possibilities of improving the interaction with tools.

Optimization means improving the design in terms of its performance parameters. Design optimization research targets both qualitative and quantitative methods of system, component, and parameter optimization (Papalambros and Wilde 2000). Typical fields of attention are shape (Bennett and Botkin 1986), structure (Bendsøe and Kikuchi 1988), and behavior (Schnack and Weikl 2000) optimization. Research in static-shape-optimization targeted methods for the minimization of the maximum stress, stress concentration, or weights. Restricted to topologies and configurations, research in structure optimization could not yet provide solutions for the structural optimization of general mechanical systems. The challenge for system optimization of complex artifacts is that subsystems must be designed in concert so that the overall system is optimized for multiple criteria. Besides analytic and numerical optimization techniques, genetic algorithms have also been widely studied in various engineering applications as means for search and optimization (Chapman et al. 1994).

Assuming that engineering design is a computable function (Fitzhorn 1988), design automation research deals with the issues of reproduction of design knowledge (Gero 1985) and problem solving capabilities in and by artificial systems (Liddament 1999). It studies computer-based problem solving strategies (Garcia et al. 1994), methods, heuristics, creativity, learning, and reasoning (Gero 1986). Its ultimate aims are formal design inference, automated problem solving, and transplantation of design capabilities (Altshuller 1984). Working towards smart or intelligent CAD systems, many researchers tried to develop combined knowledge representation and inference mechanisms (Ohsuga 1989). They are typically environments of symbolic, procedural, numeric, or declarative programming, using principle-based (Cagan and Agogino 1987), rule-based (Laurent et al. 1986), case-based (Kolodner 1993), experience-based (Wang and Howard 1994), analogy-based (Bardasz and Zeid 1991), constraints-based (Kramer 1992), logic-based (Dietterich and Ullman 1987), and/or model-based (Ohsuga 1983) inference mechanisms. Other approaches utilize the opportunities offered by evolutionary programming (LaFleur 1991) or genetic algorithms to generate populations of solutions and optimize them.

10 Research in design methodology

In its most general meaning, design methodology is the theory of design methods, activities, and techniques (Cross 1989). In a pragmatic sense, methodology is considered as a guideline, rather than a theory implying lawful relationships. My understanding is that the category of design methodology embraces the domains of: (1) methodology of design, (2) design innovation, (3) design modeling, and (4) modeling techniques (Fig. 12).

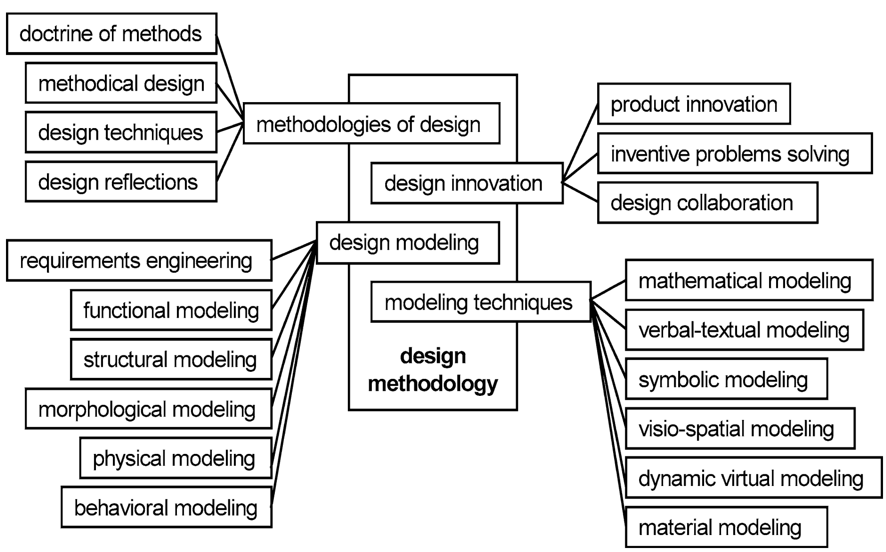
10.1 Methodologies of design

Many researchers affiliated with studying the *methodologies of design*, in particular, the principles of design methods, proposed a separation between the so-called scientific method (Davies 1968) and the design method (Cross et al. 1981). This view is well supported by the vast amount of non-scientific knowledge that is applied in engineering design (Cross 1993). When used in the pragmatic context of a methodological framework, design methodology research means: (1) methodological systematization of design processes, and (2) the employment of modeling, representation, analysis, simulation, evaluation, and/or physical testing techniques for researchers. First-generation design methodologies were to provide a set of guidelines to avoid trial-and-error techniques. Second-generation methodologies were systematic approaches involving various strategies in solving design problems (Hansen 1956; Zwicky 1969; VDI 1977a, 1993). Researchers found both limitations and benefits in structured methodologies (Jones 1963; Barkan and Hinckley 1993). Third-generation methodologies are claimed to be knowledge-instrumented collaborative techniques, though opinions are still divided. Eekels and Roozenburg (1999) introduced the notion of design methodics to differentiate the theory of methods from the development and application of methods. Design methods do not attempt to say what design is, but how human designers can achieve what they want to (Jones 1980). A design method, within a design paradigm, does not constitute a theory. Design techniques research investigates the realization of design methods by dedicated tools and technologies (Huang 1996). In the last decade, design techniques research was mostly influenced by the results of virtual reality technologies (Durlach and Mavor 1995) and multi-modal interface technologies (Weimer and Ganapathy 1989). Studies in design reflection investigate the interaction between the design task and the professional practice of a designer or a team of designers. In addition to the aspects of reflection (Schön 1983), the factors influencing natural design thoughts are also studied.

10.2 Design innovation

Design innovation research creates a scientific basis for rationalizing multi-disciplinary product development and facilitates solution finding for novel and open-ended design problems (Roozenburg 1992). Innovation has been found a complex, multi-faceted activity with a

Fig. 12 Research design methodology



system of links (Osborn 1963). Design innovation research is concerned with both innovative products and product innovation processes. It also studies the relationships between design innovation strategies and the underlying range of technical choice available to design teams (Little 1997). Along with the creative group techniques, the theory and practice of inventive problem solving have also been studied (Kim and Cochrani 2000). Design innovation research analyzes the role and emergence of discovery in innovation by humans (Hanson 1967) and systems (Langley et al. 1987). Aspects of co-located and remote design collaboration, such as knowledge sharing, collective conceptualization, tools and models sharing, team coordination and work administration, are studied.

10.3 Design modeling

The methods of modeling artifacts and processes were always at the center of design methodology research (Subrahmanian et al. 1993). With the advent of digital computers, computer internal modeling has gradually been emerging as a new field of attention in design methodology. I use the term *design modeling* to express the activities concerning the creation and processing of models of various designs in various phases of their life cycle, from different aspects and in different contexts. The objective of design modeling is to generate mental, cognitive, formal, and symbolic models of humans, artifacts, processes, and knowledge (Anderl 1997). It investigates the role of models in externalization, communication, and testing of design ideas. Design modeling covers the research trajectories of requirement engineering, functional (Chakrabarti and Bligh 1994), structural (Fujita 2000), morphological (Vergeest and Spanjaard 2002), physical (Cartwright 1997), and behavioral (Breedveld et al. 1991) modeling of products. Product modeling appeared as an integrative branch of research and development (Eastman et al. 1991). Expectations coming from various phases of the life cycle of products are investigated. Research in design modeling endeavors to improve the outcome of design not only based on mathematical and virtual analysis, modeling, simulation, and evaluation, but also based on physical concept modeling and testing, enabled by material scale models, mock-ups, and rapid prototypes (Campbell 2002).

10.4 Modeling techniques

The research domain of *modeling techniques* deals with mathematical, verbal–textual, symbolic, visio-spatial, virtual, and material methods of representation of humans, artifacts, processes, and knowledge, and their integral use in engineering design. Verbal–textual modeling comes along, among other things, in requirement specification, initial product description, functional specification, and design specifications. Mathematical modeling ranges from simple algebraic modeling through numerical modeling to computational behavioral models based on parallel computing. Symbolic modeling techniques are loosing significance due to their abstractness and inherent limitations. Visio-spatial techniques concentrate on the methods of modeling shapes and geometry-related concepts. Research in virtual modeling and prototyping techniques seeks for all-embracing computer internal representations of products (Flaig and Thrainsson 1996). It has not been possible to offer solutions for all-embracing product modeling. The integration of design models is difficult not only because of the difference in the contents, but also because of the variety of the applied representations. Actually, what is available is an extensive set of aspect models of products supporting various applications and syntactic relationships between the descriptive data. This is the way to connect drawings and part geometry models to assembly and behavioral models, and to models of downstream applications. Linking mental, virtual, and physical models in design synthesis is solved neither from a methodological, nor a technological point of view, although the use of editable and reshapeable physical concept models to support shape, structural, and functional synthesis of artifacts is recognized (Horváth et al. 2001).

11 Research in design technology

Science philosopher Ziman (2000) said that science in application is technology. Engineering design is the primary mover behind producing technological solutions. Cross et al. (1981) asserted that design is more a technological activity than a scientific activity, therefore, it has to be seen from the more practical and stable technological model of human action. Pulled by the industrial need and pushed by rapidly evolving computer technology, involving digital computers in design has actually lead to the emergence and unexpectedly rapid progress of the concept of *design technology* some 60 years ago. In my opinion, design technology is the most characteristic channel category that converts the general knowledge of engineering design to explicit product models and representations (Horváth 1998). With the advent of computers, design technology has become an intensively studied research category of engineering design. The specific research domains are shown in Fig. 13.

11.1 Design informatics

Research in the domain of *design informatics* aims at studying all specific aspects of handling design data, information and knowledge related to humans, methods, tools, and products (Salustri and Venter 1991). It concerns acquisition, representation, structuring,

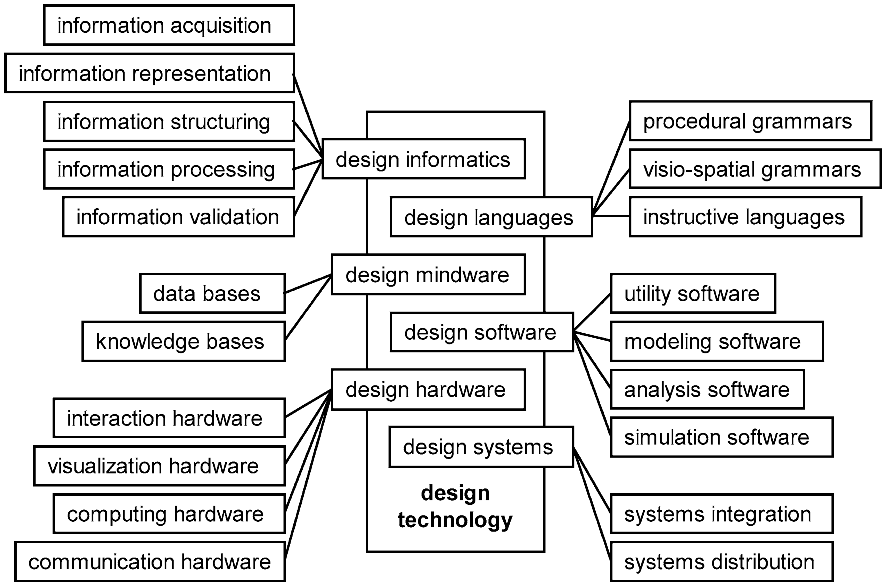


Fig. 13 Research in design technology

processing, and validation (Court et al. 1996). It studies the issues of information selection (Newland 1987), use (Kuffner and Ullman 1991), and re-use (Baya et. al. 1992) of information and knowledge in design processes (Khadilkar and Stauffer 1996). The primary issue has been processing visual and spatial information, which is enabled by the methods and techniques offered by computer graphics research and image processing (Foley et al. 1990). Image processing is concerned with the recognition and structuring of design images in the context of the design activity. The intentions to apply automated techniques based on artificial intelligence in design support systems have gradually weakened since the end of 80s, although earlier this paradigm seemed to be very popular. The emphasis shifted to knowledge-intensive systems without built-in problem solving capabilities.

11.2 Design languages

Research in the domain of *design languages* targets formal product definition languages as well as product description languages of neutral formats. Shape grammars were invented in the early 80s by Stiny (1980). In addition to shape grammars, formalisms were introduced to express, for instance, structures (Woodbury et al. 1988), functions (Lai and Wilson 1987), assemblies (Takase and Nakajima 1985), and constraints (Vemuri et al. 1988) as algebras of design (Stiny 1991). Design syntax research sprang off computational linguistic research (Brown 1997). It also studies language-level representation of design knowledge for knowledge-intensive and knowledge-based systems (Coyne et al. 1990). My perception is that the research interest towards formal languages has weakened as the real opportunities of design automation became known.

11.3 Design mindware

Another research domain, *design mindware*, deals with the issues of structuring and archiving design data, information, and knowledge in digital repositories in textual, numeric, visual, and multimedia forms (Buchmann 1984). The aim of research in product data management systems is to explore theories and methods, to develop tools for product description, organizing the information that designers need, making the product information available for the downstream processes, to coordinate and facilitate the interaction of design tools, documentation, and archiving the product data, product-related data, and product-independent design data, and to reduce the informational complexity designers need to face. Research in knowledge bases for design studies topics such as developing knowledge items, preserving knowledge, using knowledge and sharing knowledge. Conventional representation schemes, taxonomical ontologies (Logan 1989), and multimedia representation as well as knowledge asset warehousing are all studied. Knowledge management for engineering design investigates not only the issue of creating and managing knowledge items and assets, but also the processes that act upon these items and assets (Owen and Horváth 2002). As common vocabularies and semantic taxonomies of design knowledge, researchers studied various forms of design ontologies (Albers 1994).

11.4 Design software

The research domain of *design software* comprises the study of: (1) computer-mediated internal representations of numerical, textual, symbolic, graphical, and geometric information, (2) the exploration of supporting theories and methods, and (3) the development of efficient algorithms for computational and presentation tasks, and intuitive visual interfaces for the interaction with the designers and computers users in the design process. This category splits up into the research in various kinds of software, such as (1) design utilities, (2) graphics-based modeling software, (3) analysis software, (4) simulation software, and (5) optimization software (Lee 1999). Analysis software tools typically compute and investigate an actual status of an artifact or a process. Simulation software tools model and investigate the changes and the nature of changes in artifacts and processes, while optimization software tools are concerned with the improvement of the qualities of products and processes. Design utilities are for collecting and processing user information and requirements, storing information about past products, competitor products, and design documentation and archiving. Computer internal modeling focused on both simplified design representations and true modeling of the geometry, structure, materialization, behavior, and appearance of products. Graphics-based modeling software is represented by conceptual design tools (Hsu and Woon 1998), geometric modeling tools, assembly modeling tools, and manufacturing modeling tools (McMahon and Browne 1998).

Geometric modeling systems are the most settled category of design tools and the related research is one of the scientifically best supported (Mortenson 1985) The intensive research in computational geometry also favored the development of geometric modeling systems (de Berg 1997). A wide variety of three-dimensional modeling techniques has been availed for the representation of shapes such, as wireframe (Rooney et al. 1987), surface (Hosaka 1992), solid (Hoffmann and Rossignac 1996), parametric (Piegl and Tiller 1995), constraint-based (Bilgic and Fox 1996), feature-based (Shah and Mäntylä 1995), non-manifold (Masuda 1993), deformable (Metaxas and Terzopoulos 1995), fuzzy (Martin 1994), and vague (Guan et al. 1997) geometric modeling. Various manufacturing-technology-oriented software have been developed based on geometric models, for example, for molding, milling, turning, and forming (Dong and Vijayan 1997). Research advanced in theory, algorithm, and software development for assembly modeling and planning, as well as for tolerance handling (Salomons et al. 1993). Immersive, semi-immersive, and non-immersive technologies of virtual reality have been studied (Jayaram et al. 2001) to attain supportive environments for methods and activities (Dani and Gadh 1997). Some research addressed software development for redesigning and reverse engineering of designs.

The aim of the design analysis systems research is to provide effective and reliable software means for predicting the static behavior of design in terms of measures such as stress, temperature distribution, deflection, flow characteristics, buckling, fatigue, wear, and lubrication. The trajectory of analysis systems research shows a dual face as far as the direct and numerical analysis techniques are considered. The former type of systems is typically dedicated to particular types of application, while the latter type of systems is applied for general problems, which are application-independent. Remarkable results have been achieved with finite element modeling and analysis systems in various applications (Zienkiewicz and Taylor 2000). Dynamic and static mesh generation and analysis techniques for linear and non-linear applications have been proposed. Research has also been looking for effective solution algorithms such as frontal technique or various forms of direct integration algorithms (Le Tallec 1994). Geometric idealizations (Szabó 1988), automated and adaptive mesh generation (Ho-Le 1988), and techniques for mesh restructuring have been studied. Research in design simulation splits its attention between simulations based on detailed geometries and assemblies, and on initial models (Barber and Ciavarella 2000). Working models are based on detailed geometric models, and the mechanical parts are treated as either rigid bodies or deformable solids. Fast physics-based approximate animations are used in conceptual design.

11.5 Design hardware

Facilitating the development of design support systems on the computational side, historically: (1) interaction (Hand 1997), (2) visualization (Grover 1977), (3) computing, and (4) communication hardware research formed the four trajectories in *design hardware* research. Research into graphical hardware grew out in parallel with the research of graphical input and output means (Hubbold 1984). In the light of the existing concepts and achievements of all-purpose hardware research, the importance of the computing and communication trajectories of design hardware research is fading away. Supporting multi-channel natural communication and true 3D presentations are in the focus of current hardware research in the interaction and visualization trajectories.

11.6 Design system

Part of design research is orientated to working out frameworks for design systems. On the one hand, research in *design systems* aims at the integration of various design tools into a single holistic system, local or distributed, that is able to support all actions of designers. From the concept of multi-functional systems (Zeid 1991), through model-based integrated systems (Eppinger et al. 1994), research has gotten to the realm of collaborative virtual product development environments (Tay and Ming 2001). As a base of integration, several concepts, such as centralized databases, associative models, multiple feature views, shared product models, remote collaboration management (Park and Cutkosky 1999), and tele-presence, have been tested

(Navon et al. 1996). On the other hand, research is also engaged with automated problem solving systems and decision support systems (Forbus 1988). Part of the specialized research followed the paradigm of knowledge-based expert systems (Brown and Chandrasekaran 1986) using some forms of artificial intelligence (Doyle and Dean 1996).

12 Research in design application

Design application means the utilization of generic design knowledge and specific design information in designing products and product-related services. Design application research, as the only sink category, studies the ways of deploying artifact and process knowledge as well as design theories, methodologies, and technologies in solving concrete design problems. The related research domains and trajectories are shown in Fig. 14.

12.1 Design praxiology

Engineering design became a subject of praxiological research and analysis at the beginning of the 70s (Gasparski 1979). Coined by Kotarbinsky (1965), *design praxiology* research has a broader and a narrower interpretation, which is still a matter of debate. In its broader interpretation, it is towards the theory of efficient design action (Usher et al. 1998), and in its narrower meaning, it focuses on design problem solving, organization, and instrumentation in specific technical domains (Ulrich and Eppinger 1995). The influences of design on various environments and products, as well as the internal and external experiences of designing are also dealt with (Smith and Reinertsen 1995).

12.2 Design assurance

Design assurance research concerns both the quality of design actions and the quality of deliverables (Ughanwa 1988). One trajectory of research creates norms and measures of design quality, and the other is involved in the deployment of quality (Sullivan 1986). Design quality research orientated itself to creating reasoning models about quality (Kano et al. 1984), and pursued to study the factors influencing optimal execution of product development and production processes (Clausing 1994). Product quality research studies the factors that influence the resultant quality of the artifacts (Taguchi 1986).

12.3 Design standardization

Design standardization research targets the increase of efficiency and quality of design by investigating the principles of standardization, stating the requirements and characteristics of artifacts, processes and methods, and generating codes and norms with pronounced relationship to design technology (Toms 1988). Besides generating normative regulations (ISO 1994a, 1994b), design standards research also studies the principles of standardization (Owen 1993). Design metrology investigates the qualitative aspects of measurement.

12.4 Design sustenance

Receiving amplified interests in the last decade, research in *design sustenance* deals with the capacity management issues of design projects and looks for strategies and principles for outsourcing of designing, for design knowledge brokerage, and for conducting collaborative product development (Hardagon 1997). The principles of outsourcing and brokerage provide extra dynamism for design activities in virtual enterprises.

12.5 Design management

Finally, research in the domain of *design management* investigates the methods of the low-level organization of designing, exploitation of design tools for particular products, and verification and reviews of evolving de-

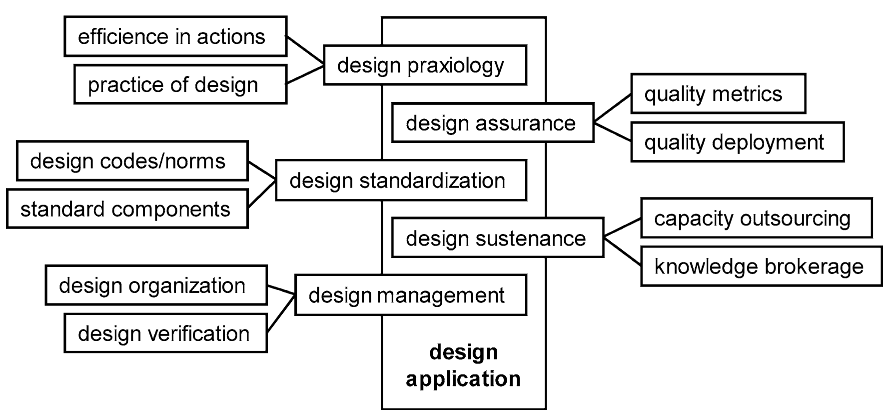


Fig. 14 Research in design application

sign. Design management research involves the study of: (1) design office management, (2) design project management, (3) organization of design management, (4) management training for designers, and (5) design training for managers. Design organization refers to a purposeful and systematic arrangement for the design activity in connection with a product and/or an environment. It also concerns the act of conducting and supervising design, and the dexterous use of design means to accomplish design ends. Along with the innumerable organizational issues involved in complex product development, these are topics for design management research. Design management plays a role in the competitiveness of new products and investigates the provisions to achieve it (Hegde et al. 1992). Design verifications research deals with authentication, certification, and warranty issues.

13 Concluding words

"Our knowledge can only be finite, while our ignorance must necessarily be infinite." This statement of Popper (1963), the Austrian-born British philosopher, is true and especially relevant to this paper. And it is important to note, since I had to face several limits. The first limit originated in the engineering design research itself. Although I was always aware of the fact that this has been extremely wide, the real distances became clearly visible for me when I managed to deepen a bit more in the ocean of research approaches. Up to now, I have not been able to cover all fields and aspects of engineering design research, just the most characteristic ones. For this reason, I expect that many domain researchers will contact me. There is one thing however that I have certainly learnt: dealing with the order and structure of the entirety of engineering design research is an enormous challenge for everyone. The second limit comes from the fact that subjectivism cannot completely be avoided in forming reasoning models. The presented reasoning model reflects my understanding and view. Striving after some level of objectivism, I tried to find evidence that could support my statements, but omissions or impreciseness in the contemplation of research issues cannot be excluded. Consequently, the presented framework of reasoning must be considered just as a proposal, rather than as an ultimate theory. Nevertheless, I believe works like this create a platform for further discussions and a clarification that I believe is the most important. The third limitation is down-to-earth. I have made every reasonable effort to collect significant books, reports, papers, and other publications. However, due to the space limitation in this paper, I could not refer to all I would have liked to. I tried to include two kinds of publications: the fundamental ones, which established a research trajectory, and the contributing ones, which reflect the current state-of-the-art. Again, the choice of references might not stand all trials owing to the involved personal judgment. I recognized that the latter mentioned publications are actually just one of many, and they might not reflect sufficient consistency due to their random nature.

Putting it all together, I still believe that the proposed teleology-inspired framework lends itself to a better understanding of the disciplinary articulation and intrinsic relationships of engineering design knowledge and research. With possible and necessary refinements, it might become a basis of a shared understanding. Then, it can help researchers to locate their work in the global picture of engineering design, managers to see the interconnections of the contents of research programs, granters to make decisions about the possible fields of investments, and educators to organize subject materials for various design courses.

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