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ON METHODOLOGICAL CHARACTERISTICS OF ENGINEERING DESIGN RESEARCH

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1. Introduction

Engineering design contributes to sustaining human existence and well being by virtual creation of artifacts and services. Parallel with the growth of importance of design in technologies and in the society, more and more efforts are being made in order to understand design not only as a practical exercise, but also as a formal branch of learning [Braha and Maimon, 1998]. Design research is the engine of the inquiry as well as the instrument for exploration, description, structuring, rationalization, utilization and validation of knowledge for design science and praxis [Archer, 1981]. No one can deny that there is a shift in the foundations of engineering design from intuition to reason. The act of designing and the discipline of design have been investigated from ontological, epistemological, methodological, technological, social, and praxiological aspects, and a shared view seems to have been formed [Cross, 1993]. At the same time, there is a lack of clarity about what constitutes engineering design research, what its characteristics are, and what to do with these characteristics [Blessing, 2002]. The origin of the problem is that design research cannot be taken as an offspring of research in sciences, since design science significantly differs from natural sciences [Willem, 1990]. Additional difficulties come from the premature nature of design science that concerns both the scientifically grounded study of design as a phenomenon and as a discipline, and the use of scientific knowledge about and in design through scientifically validated methods and tools [Hubka and Eder, 1996].

Various interpretations have been given to design research. [Eckert et al., 2003] argued that design research *has no unique features* besides its subject matter, but it has two defining characteristics that differentiate it from the contributory disciplines: (i) it is concerned with the explanation of a complex heterogeneous human activity, and (ii) it is concerned with finding practical ways to improve human performance in intricate tasks. The aim of engineering design research is to support the industry by developing knowledge, methods and tools, which can improve the chances of producing a successful product. This interpretation emphasizes *research in design*. Design research has to achieve a deeper understanding of both the science and the praxis of design that requires a multidisciplinary approach involving research in natural science, engineering and technology, and to some extent, in philosophy of science. This interpretation puts the emphasis on *research for design*. One can consider design as a process and means of constructing and exploring new knowledge, both quantitative and qualitative. This way, design research is placed in the context of *research by design*. Eventually, design research combines these three variants in one - something that has no parallels in scientific or engineering research. In addition to this, the teleological nature of design implies a specific order of design knowledge, which is also reflected on the research in/for/by design [Horváth, I., 2003]. If anything, the above-mentioned things make design research a specific subject matter.

The still existing uncertainties about the nature of engineering design research stimulated the author to go into further investigations. His concrete goal was to identify and analyze the methodological characteristics of science research and design research, and to make it clear in which sense the characteristics of design research differ from the characteristics of research in natural, social or technical sciences. The presumption was that if design research does not share all intrinsic properties of science research, then there must most probably be characteristics that are (i) relevant to both, (ii) forming a kind of counterpart of, or complementing each other, and (iii) valid either for scientific research or for design research only. The comparative study confirmed the existence of three categories of characteristics, which have been called 'common', 'coupled' and 'unique'. The common characteristics are unconditionally valid to all approaches to research, no matter if they are purely scientific or not. Three other characteristics of scientific research have been found that have counterparts in design research. In addition, having nothing to do with the two unique methodological characteristics of research in sciences, three unique characteristics of design research have been found. We have to note that this kind of dissociation of the characteristics is artificial for two reasons: (i) in reality the characteristics are holonic (synergetic) rather than distinct characteristics, and (ii) some counter and unique characteristics of scientific research are also applicable to design research, but to a much lower scale, and vice versa.

2. Unique characteristics of natural science research

2.1 Driven by paradigms

Though it is not without paradoxes, the majority of science philosophers accept the theory of paradigmatic evolution of natural sciences. According to the original definition, paradigms are *comprehensive theoretical and methodological frameworks* reflecting a particular state of aggregation of knowledge and a view formed based on it. The Kuhnian theory of paradigms explains that paradigms are the results of revolutions in science. This theory however only weekly circumscribes how normal science goes to the pre-paradigmatic status, how can multiple paradigms be coexistent, and how can a part of a former paradigm be preserved in a new paradigm resulting in a shift rather than a crisis in the paradigms. For this reasons new explanations of the concept of paradigm have been proposed. Paradigms are to describe and explain observed and inferred phenomena, past or present, aimed at building a testable body of knowledge open to rejection or confirmation. On the other hand, we cannot talk about any epistemological paradigm of design science, or about forming the order of design knowledge by such a paradigm, since nothing like that is known to exist. This can be understood as a consequence of the current stage of development of design science and of the epistemological nature of design knowledge. It does not however exclude thinking of strong governing theories (local paradigms), something contrasting the standard view on paradigmatic evolution of sciences. An unfavorable outcome of the lack of a governing paradigm in engineering design science is a large number of small-scale research actions that are difficult to integrate.

2.2 Predictive capacities

Factual sciences are progressing from description to explanation. The final stage of development of factual sciences is progress from explanation to prediction. Prediction is a projection of research hypotheses and theories towards *verification at a different time*, usually in the future. If the projection is to the past, we talk about retrodiction, i.e. reconstructing the past based on present evidences. With simple terms, prediction is the derivation of a not known fact from a given hypothesis under given circumstances (conditions). Predictions, that are typical in natural and social sciences, acquire credibility from the research practice they inspire. In the process of forming a prediction, scientific research always uses the available scientific results as premises and derives conclusions by *formal reasoning*. Empirical predictions of sciences are based on, for instance, statistics and computations. Theoretical predictions are derived by interpolating or extrapolating existing facts and theories. On the one hand, a reliable prediction assumes a proper body of knowledge, on the other hand, a prediction should be considered underdetermined if multiple predictions can be constructed based on a body of knowledge. Following from its teleological nature, design research has nothing to do with prediction, except in a philosophical context.

3. Common characteristics of scientific research and design research

3.1 Pluralism in terms of methods

The methodology of scientific inquiry features a special scenario that includes problem isolation, hypothesis forming, systematic investigation, theory formulation, and theory validation. Being based on rational or experimental principles, the methods are the means to attain knowing in research. Research comes along with (i) *methodical doubt*, which regards the suspension of decision on the acceptance of hypotheses unless they have been demonstrated true by means of proper methods, and (ii) *methodological diversity*, which is the consequence of having nothing like a single universal method in research. Instead, what exists is a wide variety of methods that are exemplified in each specific branch of sciences and can be chosen depending on the nature of the research problem, the hypothesis, the research questions, and the preferred strategy for verification of the concepts. This is a characteristic of all genres of research and is referred to as *methodological pluralism*. It accepts that the methods of design research cannot be reduced to one due to their uniqueness. The methods have been categorized as (i) rational (discursive, synthetic, ascetic, empirical, critical, dialectical, intuitive, historical, reflexive, psychological), (b) deductive (axiomatic, logical), and (c) inductive (nomological, descriptive, statistical, experimental, comparative) methods. Research methods can be of quantitative and qualitative nature. In engineering design research both rational and inductive methods, and quantitative and qualitative methods are applied, alone or in combination with one another.

3.2 Implicate ordering of knowledge

In the development of a scientific discipline, the aggregation of the body of knowledge is always accompanied by the formation of the order of knowledge. Order defines the *categories of thoughts* and the *accommodation of facts and theories* in the body of knowledge. The order is holistic if it mutually enfolds all relationships of knowledge. On the basis of results of the seventies, science philosophers assume that research works and validates facts and theories according to a governing theoretical and methodological framework (a paradigm). They believe that also the order of knowledge is determined by the governing paradigm. It means that normal science explores and adds on new knowledge, as it is the most rational under the influence of the prevailing paradigm. Any new order of knowledge is possible only if normal science provides sufficient evidences for the necessity of a shift of, or a change in the paradigm. For these reasons, research has a specific relationship with the order, which is typically described as *implicate*. Design research is only indirectly influenced by the paradigms of natural and other sciences, i.e., as far as it reflects the influences of the prevailing paradigms through the body of general knowledge that is shared by design science. The author’s understanding has been that there is currently no other paradigmatic framework for design science than that is originating in its *teleological nature*. Nevertheless, it serves merely as a reasoning platform in the current formation phase of design science rather than as an orderly system of theories. This reasoning platform is nevertheless reflected on both the goal setting and the conduct of the contemporary design research. This fact however reconfirms the implicate relationship which exists in between engineering design research and the order of engineering design knowledge.

3.3 Verification by evidences

The principal value category of sciences is *truth*. Indisputably, scientific research endeavors achieving sufficient amount of trustworthiness in the elements of new knowledge. To this end, it employs various methods and procedures to verify hypotheses, facts, laws, theories, and explanations. The form and degree of verification may change in the various disciplines, but not the endeavor to produce true knowledge. Other issue is that the twentieth century science philosophy took up various attitudes to verification towards truth. The truth of a proposition is usually established by observation in natural and social sciences. It does not matter if experimentally or logically, the truth can only be verified to a *certain degree of confidence*. Leaving out the technical difficulties, a particular hypothesis is said to be in principle verifiable, if a positive or negative confirmation is possible under suitable conditions, and a hypothesis is properly confirmed to a certain degree, if a sufficient amount of *experimental or rational evidences* is available. Verification is a shared characteristic of scientific research and design research, although with different suggestions. According to the view of rationalist science philosophers, neither the scientific, nor the non-scientific part of the engineering design knowledge can be conclusively proved, or conclusively disproved. Hence, the goal of verification in design research is the demonstration of coherence and usefulness. It normally employs rational (either common-sense) proving in terms of the validity of the explored and/or constructed knowledge, theories, methods, tools and processes. Probability is normally considered to qualify the truth of propositions.

3.4 Disciplinary organization of inquiry

Disciplinary articulation of research means that the inquiry takes place in *various fields of interests* and usually appears in specific context. For these reasons, there are specializations in research, higher levels of which are called *disciplines*, and the lower levels *departments*. The ontological and historical status of the branches of sciences is reflected on the disciplinary structure. Astronomy, physics, chemistry, biology, psychology, sociology, economy and politics have developed to be a kind of fundamental disciplines. The study of these and other disciplines define the decomposition to multiple levels of mono-disciplinary, interdisciplinary and/or multidisciplinary subfields, called departments. The departmental specialization is influenced not only by the interests in inquiry, but also by the sources of knowledge. The departmental dissection can be observed in design science as well as in fundamental and applied sciences. Here the major departments are design knowledge, design theory, design methodology, design technology, and design application. Research in design knowledge is concerned with improved understanding, in design theory with proper reasoning, in design methodology with correct use of knowledge, and in design technology with effective application of design knowledge. It has been generally accepted that design science is a federation of sub-disciplines having design as the subject of their interests. Thinking in departments gives way to the raise of a variety of reasoning and descriptive models.

3.5 Relying on enabling infrastructure

Historically, the inquiry was first enabled by simple means and by various experimental apparatus later on. The development of the research apparatus was made possible by the scientific discoveries and inventions as well as by the development of applied sciences, in particular, of technology. During the last century the research apparatus has developed into a comprehensive *research infrastructure*. The major functions of the research infrastructure are (i) observation, (ii) measurement, (iii) reproduction, (iv) computation, and (v) communication. The enabling infrastructure and the progress of inquiry are mutually dependent. On the one hand, there is a need for a proper research infrastructure in order to go deeper into the still unknown. On the other hand, the available research infrastructure determines what research can study, investigate and experiments with. For natural sciences it may sound obvious, but design research is not an exception. It also introduces means to enable inquiry, but the nature of the means differs from that used in fundamental research. The enabling infrastructure of design research is actually a *mixture of research means* typically used in human and social sciences and in applied sciences and technologies.

3.6 Research has been socialized

For a long time, dealing with sciences was separated from the everyday life. Doing research in sciences was the privilege of some mindful and devoted individuals, who pursued knowledge for the beauty of learning, feeding their curiosity, and the satisfaction of knowing. They insisted that the practical aspects of sciences could only appear as by-products. In our modern life the situation has been completely different. Changes in the society accelerate the creation of new knowledge (societal pull), and new knowledge drives changes in the society (scientific push). Science has been *socialized*: its goals are to a growing extent derived from the actual needs of the society, and its results are directly used in the society [Dilnot, 1982]. Socialization does not only mean putting research in a social context, but also executing it according to the demand of the society. With simple words, both science and design must act as *benefactors* of the society. In socialization of research the major issues are such as (i) moving away from the traditional pipeline concept to an innovation cycle concept, (ii) finding the place of sciences in given cultures, (iii) proper use of the results of research, (iv) forming policies for conducting research, and (v) providing resources for research. The penetration of science into our everyday life is taking place in front of our eyes. The boundaries between natural and technical sciences, as well as between design and technologies are gradually dissolved. This corroborates that scientific research is much *more than just an enlightened exercise* of personal curiosity. Engineering design is one of the best examples how far science extends into praxis. Each appearance of design is permeated with scientific knowledge: all artifacts obey the laws of natural, technical and even social sciences. At last we can say that, being the engine for sciences, the systematic inquiry empowers solving industrial problems through design.

4. Counter characteristics

4.1 Generalization towards absolute versus multiple aspects of relativity

The goal of sciences is identifying and explaining the regularities of nature with universally applicable fundamental laws. Sciences are based on the observation of specific cases, but what is typically considered to be *scientific knowledge is generalization* of the individual cases. With other words, generalization extends the concrete experiences beyond the observable experiences. Research in sciences follows the doctrine of scientific generalization that signifies the endeavor of sciences to get close to the *absolute knowing and truth*, without exception, approximation, and qualification. The doctrine of absolute in epistemology is related to the assumption that truth is possible, and involves the rules of induction. It is difficult to justify philosophically, but there appears to be no alternative. In science philosophy, absolute has traditionally been a notion expressing perfection, completeness and universality. In modern thought, however, absolute is used to express that the body of knowledge or part of it is complete of its kind, rather than absolutely unconditioned (perfect) truth. A statement is true at least in part in virtue of contingent facts about the world. Another aspect of absoluteness is the *general applicability*. For scientific research the issue of general applicability appear in terms of both the knowledge and the methods. Generality of knowledge means that all basic scientific laws are generally applicable. That is, a claim is true for the type of things and true for each individual of that type. Scientific research applies methods and procedures that are case independent, that is, reusable whenever obtaining new knowledge emerges as a goal in a context.

Opposing absolute, relative refers to the *non-perfection or non-completeness* of the act of knowledge inquiry and, consequently, the scientific knowledge. Epistemic relativism is the thesis that there are no propositions knowable, except relative to a point of view. The truth associated with one point of view has no grounds from another point of view. Relativism is also the position that there is no one correct view of things. This is a typical characteristic of design research, in which the view varies among different researchers and research communities, and there is no objective criterion of deciding which the right one is. The term relative also refers to the *ad hoc nature* of design research, meaning that research is typically made not in general, but specifically for one purpose. Moreover, design research is much more driven by local philosophies than the research in any other scientific discipline. It brings about alternative local theories, qualified bodies of knowledge, and unverifiable but useful methods and tools, chosen a fortiori based on the hypothesized strength. Consequently, engineering design to a large extent is grounded on approximate truth.

4.2 Asserting knowledge through reduction versus constructive knowledge building

The ultimate goal of sciences is to come to a simple set of connected, fundamental laws from which the special laws in the different branches of sciences can be deduced. This analytical rationality, called *reductionism*, labels the relationship of scientific theories to one another and it is typically strong in natural and abstract sciences. Reductionism contributes to revealing more special theories as special cases or derivatives of more general theories in a domain of a discipline. Usually *logical derivation* is applied to get the (approximate) truth of the less general theory from the laws of the more general one. However, if the laws are not translatable, then there is no possibility of reduction or there will be explanatory losses when moving one theory to another. The concept of reduction is not unknown in design science, but it *has different flavors* over there. It claims that the properties of any system can be understood by knowing what it is made of and how those parts interact with each other. Reductionism is also about looking at the concerns of the design discipline from different abstractions, viewpoints and aspects, and investigating them with different purposes. Both methodological and theoretical reductionism has been criticized for not being supportive to holism. Reductionism goes so far in engineering design as *decomposition* of the global tasks, functions and solutions to intuitively and individually manageable components in order to cope with totality and complexity.

Design research tends to form a basis for the design science by adapting the doctrine of positivism. The doctrine of design research is not exhausted in the systematic description of empirical rules; it intends to build new knowledge structures. The knowledge exploration and aggregation program of design research is supported by the *thesis of constructivism*, which creates synthetic truth by fitting parts of knowledge together on purpose. Synthetic truth cannot be known a priory. The inductive-statistical model of reasoning, which employs probabilistic generalizations instead of strict laws, is typically used to support constructing new knowledge. Design knowledge is inherently multi-faceted. In the most general sense, the source of design knowledge is, on the one hand, formal scientific knowledge, and, on the other hand, tacit human knowledge that appear in synergism. Design research associates parts of universal knowledge (from fundamental research) with specific disciplinary knowledge (from applied and operational research). Validation of elements of design knowledge is through *confrontation of meaning and usefulness*. Multiple 'weak' theories are created if the theories alleged to be underdetermined by observational data.

4.3 Reasoning to the best explanation versus model-induced interpretation

Scientific research observes the existing world and predicts what is going to happen. Research provides us not only with facts and theories, but also with *explanations on phenomena* and problems. Explanations of cognitive sciences are supported by various methods. The most fundamental form of scientific explanation is based on the deductive-nomological model. This is a form of reasoning in sciences, which assumes at least one empirically tested or testable fact or law. Actually, all other forms of explanation can be traced back to it. *Inference to the best explanation* is employed to infer the existence of facts or laws, which are not directly observable or detectable otherwise. In these cases inductive or abductive reasoning is used in argumentations. In design research, usually the nature of knowledge is what prevents reasoning to optimum explanation. For this reason, explanation in design research is *interwoven with pragmatism* that claims that usefulness of knowledge is a function of its contribution to rational conduct.

From an epistemological point of view, interpretation is the matter of giving scientific knowledge empirical context. Methodologically, interpretation is a *semantic assumption* by which an element of reality is substituted. Being the basis of interpretation, mental conceptions are transformed to knowledge structures, called *models*, which are idealizations or simplifications of reality.

Interpretation is often referred to as *model-induced explanation*. This form of construction and/or reconstruction of knowledge structures is backed by and validated against background knowledge. Interpretation mainly concerns the theoretical elements of knowledge, but empirical facts can also be target. Applying abstract theories of factual basis results in factual models, while abstract theories produce formal models on formal basis. Normative models used in design research are derived from factual and formal models, respectively, or from the combinations of them. Interpretation in design research is often based on axiomatic models. What the models of interpretation usually suffer from is the complexity of reality, which leads to a non-exhaustive framing of knowledge, and this way, to a kind of lack of scientific rigor.

5. Unique characteristics of design research

5.1 Purpose driven

Cognitive and formal sciences are for a genuine exploration of generally applicable knowledge. Operative sciences are to exploit fundamental knowledge and to generate new knowledge about applications. Besides proper understanding, the specific purpose of design science is providing knowledge for creation of artifacts. This implies *a flow of design knowledge* from the status of scientific/theoretical comprehension to the status of technical/pragmatic deployment. As a vehicle, design research contributes to exploring, structuring and utilization of design knowledge. What it actually does is transferring knowledge from general to specific as well as from abstract to concrete for the act of designing. This is an indication that engineering design research is of *teleological nature*. Eventually, teleology can be seen from the aspect of conducting design research and of the knowledge produced. The epistemological understanding of teleology is that the mind is guided or governed by purposes, values, interests, instincts, and intents in its pursuing of truth. Teleology of design research entails research in categories (departments) reflecting a *natural streaming* of design knowledge. Teleological nature of design knowledge means that it is used in a purposeful manner. Traditionally the disciplinary part (understanding) and the practical part (application) of design research were at least contrasted, if not confronted. However there is nothing like two distinct domains in engineering design research, neither in engineering design, since the teleological nature brings together these contextually different domains. Constructivism provides for problem solving in artifact development in addition to aggregation of knowledge. From the teleological purpose of design science short knowledge cycles come out for engineering design research that has influences on its methods.

5.2 Multi-focal in concerns

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 observed situation in design [Blessing, 2002]. A specific characteristic of design research is that it has a *compound focus* in terms of knowledge inquiry. It concurrently studies (i) *humans* concerned with research and influenced by design, (ii) design *knowledge*, (iii) designed *artifacts*, and (iv) design related *processes*. Also investigated are the interrelationships between these aspects. Design science on the one hand intends to understand the human aspects of design through a statistical prediction of aggregate human behavior, even though any detailed prediction of the course of individual behavior is impossible. It studies the heterogeneous human activity concerning design as well as finding practical ways to improve human performance in complex design tasks. Design knowledge has *two sources*, which are the factual and formal knowledge (both scientifically verified and ordinary) and the human related (tacit) knowledge. Design knowledge is studied with the aim to improve its functional utility. The study of artifacts has *multiple aspects*, i.e., artifacts as: (i) realized, distributed and utilized products and services, (ii) technical systems with functions, structures, materials and behaviors, (iii) things having influences and reflections on humans and society, and (iv) objects coexisting in and with the environment. The investigation of design related processes concerns (i) perceptual and cognitive processes, (ii) creation and removal processes (both virtual and physical), (iii) existential processes (both operation and use), and (iv) implied processes (e.g., economic, social, technology, industrial). In addition, interrelationships such as knowledge in products, knowledge intensive processes, development of tools, and optimization of applications, are getting growing attention in design research and stimulate the development of new research methods.

5.3 Normatively instrumental

As discussed above, design research in general generates *prescriptive and normative*, rather than descriptive and explanatory, knowledge. The first two terms have to do with norms about the ways things ought to be, as opposed to 'descriptive' or 'explanatory' having to do with the ways things actually are. In philosophical discussions, normative is used as a standard, a rule, or principle to judge or direct human conduct as something to be complied with [Dimarogonas, 1997]. An endeavour related to knowledge aggregation and construction for engineering design is to establish a standard of correctness by the prescription of evaluative rules in order to promote directives for a proper conduct of designing. Methodologically it concerns both the synthesis of an artifactual system and the carrying out of designing. Consequently, the normative nature of design research in terms of design knowledge has *two dimensions*: (i) studying the physical correctness of application of design knowledge by which it signifies either a 'desired' average or a usual level of attainment or performance in designing, and (ii) investigating the morally correctness of using design knowledge. In order to fulfill its purpose, design science has to produce a body of knowledge that simultaneously embodies natural laws as well as human reason. Paradoxically enough, much of our ordinary knowledge dealt with in design research (and used in design) does not belong to the category of scientific knowledge due to *lack of generality*. Therefore, design knowledge is often regarded as instrumental for design science. Instrumentalism regards the provision of knowledge for design science and for design praxis. The peculiar *normatively instrumental* nature of design research allows us to make meaningful claims about unobservable, but does not deny the skepticism towards these claims.

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