Proceedings of ICAD2011
The Sixth International Conference on Axiomatic Design
Daejeon – March 30-31, 2011
ICAD-2011-05

REPEATABILITY IN DESIGN SCIENCE

Miguel Cavique
miguel.cavique@estsetubal.ips.pt
DEM,
Department of Mechanical Engineering,
School of Technology of Setúbal,
Polytechnic Institute of Setúbal,
Campus do IPS, Estefanilha,
2914-508 Setúbal, Portugal

António Gonçalves-Coelho
goncalves.coelho@fct.unl.pt
UNIDEMI,
Dep. de Engenharia Mecânica e Industrial,
Faculdade de Ciências e Tecnologia,
Universidade Nova de Lisboa
Campus de Caparica, 2829-516 Caparica, Portugal

ABSTRACT

The laws of natural science do not depend on the observer, but applications of design science depend on the designer. Therefore, it is usual to say that applications in design are subjective whereas the laws of natural science are objective.

This paper compares the asserted objectivity of a scientific experiment to the alleged subjectivity of a design. To discuss this issue, we introduce the idea of "functional repeatability" that applies to both natural experiments and design processes. In fact, if one defines a certain target to be achieved by two designs teams, the resulting design objects would be most likely different but they might repeat the same set of functions.

Over the centuries, scientists used the notion of functional repeatability to prove proposed laws of natural science. The development of a Design Science might also use the notion of functional repeatability in order to be ruled by universal laws.

Keywords: Design Science, Axiomatic Design, Experiment.

1 INTRODUCTION

The process of designing a new object is systematic and methodical, but also intuitive and disorderly, involving methodical, heuristic and creative processes [Hubka and Eder, 1996]. The formation of a new idea uses all of these processes; nevertheless the psychological process that occurs in the mind is still unknown. Karl Popper [1959] stated "there is no logical method for conceiving new ideas or logically rebuilding its process". Moreover, he said that although the process of coming up with an idea "can be of great interest to empirical psychology, it is however irrelevant to the logical analysis of scientific knowledge".

The set of psychological processes that lead to creativity have a relevant social role, although strictly outside of the definition of Science. To achieve this relevance, creativity in engineering has to take into account the required level of quality and cost [Taguchi, 1995]. Yet, quality and cost depend not only on a set of physical conditions, but also on aesthetics and other disciplines outside the scope of the Natural Sciences.

Different people will have different ideas, therefore an idea for an engineering product will certainly use different shapes and different components depending on the designer. Nevertheless, any idea that is generated must be analyzed with the help of logical and systematic procedures. These evaluation procedures lead to a total or partial acceptation, or even to the rejection of the idea, which in turn originates other psychological processes. During this analysis, the natural sciences assist in the appraisal of the physical behaviour of the design.

The engineering design process can be divided into at least three phases: the first is the identification of societal needs; the second is the creative phase where psychological processes prevail; and the third is the evaluation phase, which is analytical and corresponds to the rational evaluation of the proposed solution. In this phase, rational and empirical experiments led by applied sciences help in the decision of accepting or changing the solution that was proposed.

The current tendency of modern social sciences is to incorporate the processes of all the three phases. As most of the phenomena of the first and second phases depend on the context where they occur, such trends lead to different laws depending on the instance and/or on the participants, and are supported by constructivist theories, which use different explanations for each phenomenon according to the context where it occurs. Therefore, those explanations can never be refuted by other experiments because they apply to particular contexts. For this reason, one might question if the specific science under discussion is holistic and can explain everything, or if it is bounded. Assuming the holistic hypothesis, the science will always have a particular answer for each given question. On the contrary, the laws in the natural sciences are universal and the right combination of those laws allows an explanation for each observable fact to be deduced.

Using the natural science approach, the authors restrict the scope of this paper to the physical aspects of the solution under analysis during the evaluation phase of the design. Psychological methods of formulating ideas, such as marketing studies or aesthetics considerations are not in the scope of this paper.

2 PHILOSOPHY OF SCIENCE

Any science has a method that supports its experiments and allows the corresponding knowledge database with scientific applications to be created. In the late development stages of a scientific theory, it is possible to organize this knowledge in an axiomatic structure. One might notice that empirical tests can never be performed directly over a set of axioms to check if they express the reality. To evaluate if it is a science, the consequences of the axioms must be empirically verifiable. Only testing empirical propositions taken from the theory allows the theory to be maintained or rejected, depending on the results.

2.1 The Method in Science

Different philosophical schools have proposed different solutions on how to accept a physical law. Auguste Comte [1826] proposed the Scientific Positivism theory, a dogmatic conception of scientific laws. He said that "the combined use of reason and observation" allows the achievement of natural "effective laws or, in other words, their invariable relations of succession and resemblance".

Others decided not to accept dogmatism in science and proposed that it is possible to obtain an agreement between an experiment and a law, after subjecting the law to an exhaustive set of experiments. This exhaustive approach would lead to an infinite number of experiments. After a large number of experiments, a "sense of certainty" would occur, allowing people to believe in the agreement between the experiment and the physical law. Therefore, the agreement would come from psychological evidence, which gave the name "Psychologism" to this philosophical approach. Fries enunciated this trilemma of the method in science as choosing between dogmatism, an infinite series of experiments or psychologism.

Karl Popper [1959] solved this trilemma stating that it is possible to keep the acceptance of a physical law, until an experiment refutes it. This method, called the empirical sceptic method, sustains that the following statement characterizes the laws of nature: "a convention or decision does not immediately determine our acceptance of universal statements, but rather influences the acceptance of individual statements, i.e., basic statements" [4]. In other words, suppose that there is a universal statement, or law « t », and a basic statement, or proposition « p », about a certain experiment. Popper proposes that the scientific method should follow the *modus tollens*, i.e., using the common logic symbols:

$$((t \rightarrow p) \wedge \sim p) \rightarrow \sim t \qquad (1)$$

According to Karl Popper, only the propositions associated with experiments can be confirmed or refuted. Therefore, "an axiomatic system cannot be seen as a system of empirical or scientific hypotheses, because it can not be rejected through the falsification of its consequences" [Popper, 1959]. Only the rejection of basic propositions allows rejecting a theory.

Put in another way, the criterion for defining a science is the possibility to rebut any universal statement when a statement derived from the former is refuted. In the natural sciences, any statement should be refuted if a set of variables determines a consequence that is not supported by the relevant law. In this case, the cause-effect chain of the set of functions that describes the phenomenon leads to an unexpected result. Notice that the refutation of a natural law only depends on the non-corroboration between the predicted results of the set of functions and those taken from only one experiment. As a consequence, the knowledge that cannot undergo experimental verification is not in the scope of science.

2.2 The Scientific Experiment

As emphasized in the sections above, the development of science was made on the basis of experiments that were carried out to prove theories. These experiments are usually of a physical nature but they may also be rational, meaning that they take place just in the realm of the mind. Einstein described Science as being "an instrument by which men are able to obtain concepts of reality, verified by a systematic deduction of empirical formulations". This rationalistic construction makes use of mathematics and logic to bestow objectivity to science. Therefore, the objectivity of the scientist relies on mathematics.

For this reason, the results deducted from mathematical functions can be observed in different experiments. This means that the repeatability of an experiment does not occur in the realm of the experiment, but in the domain of mathematics. In fact, several different physical experiments can be carried out under multiple conditions as a means to verify if their results go with a certain proposed theory.

Let us suppose that we could go back to Galileo Galilei's times to observe the experiment that he supposedly conducted at the Pisa Tower. Against the long established Aristotle's law, Galileo argued that two masses dropping from the same height, would reach the soil with the same velocity. He probably has used a cannon and a musket shot because they were easy to obtain, not because he wanted to prove his theory for these two specific objects. Although the physical experiments with those two objects are different, they confirmed the law that governs the phenomenon, and Galileo's theory was found to be true, no matter what masses one uses, provided that the drag effect of the air can be neglected.

The reader can imagine different experiments to confirm Newton's second law of acceleration, Clausius' first law of Thermodynamics or the equation of state for ideal gases.

Therefore, there is no such thing as the physical repeatability of a given experiment, only the validation of the corresponding law. This means that the experiment repeatability is tested in the functional domain, a non-physical realm to which the natural law belongs.

Various design theories make use of the separation between the physical and the functional domains, as it will be seen in the next section.

3 THE DOMAINS IN DESIGN SCIENCE

The economist Adam Smith was probably the first person to suggest the notion of function applied to the social activities of different groups of individuals. More recently, Lawrence D. Miles introduced the notion of function in design, by using it in the Value Analysis (VA) theory. This theory, proposed in 1947, occurred to Miles as an answer to the need for purchasing parts for General Electric Co. The scarcity of components and raw materials led Miles to search for equipments and parts that accomplished the same functions, instead of trying to find the components themselves.

Usually, a function in VA is a verbalization labelling with one or more nouns, which expresses the ultimate aim of the effect of a certain product [EUR 16096, 1995].

Hubka and Eder [1996] regarded the functions of a technical system as the general behaviour of the system, highlighting the relation between the functions and the mechanical parts.

Pahl and Beitz's [2001] concept of function is the relationship between the inputs and the outputs of a system, which may be materials, energy or signals. They start by defining a global function during the so-called conceptual project phase, which is divided into other functions and sub-functions at deeper levels of detail. The set of functions and sub-functions creates a functional structure that helps to find a solution and answers completely the design question: "What are we trying to achieve?"

Axiomatic Design Theory [Suh, 1990], also uses the same concept of function, but describes the process of designing as a permanent dialogue between the functions and the components, the so-called physical parameters, that allow the design to be accomplished. Therefore, design uses two different domains: one that contains the achievement and the other that contains the way to achieve it. The achievement, in the form of a set of functional requirements (FRs), is decomposed in an arrangement of functions of the type father-son. The same process applies to the physical domain, where the decomposition of the design parameters (DPs) occurs. Ideally, at any given level of the decomposition process, each FR should interact with a single, specific DP at the same level, so that any chosen DP would enforce a new FR at the subsequent decomposition level. Therefore, design is a permanent zigzagging between both domains, at consecutive levels of definition, as depicted in Figure 1.

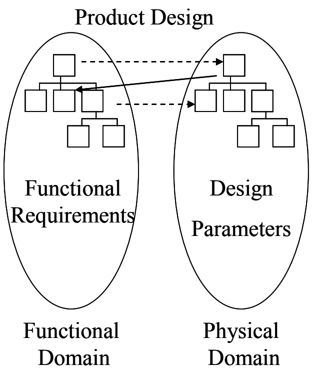

Figure 1. Domains of the design.

Each design may have constrains that could influence the choice of some DPs during the zigzagging process. These constrains, Cs, can be, a for example, the maximum weight, the minimum height, the allowable price, or any other general characteristic of the design object. The above-described domains also pertain to the world of experiments, for the physical experiment occurs in the physical domain in order to validate a proposed function. As a result, the epistemology of the experiment is similar to the epistemology of the design. Nevertheless, while science assumes experiments as appropriate to validate functions, in design, functions are known at the onset and one wants to find out the design parameters, *i.e.*, how to accomplish those functions.

4 THE EXPERIMENT AND THE DESIGN

Having verified the similarities between an experiment and a design, Eekels [2001] deemed experiments in natural science and design as "Siamese twins". Eekels diverges from Popper, in that the former accepts the use of the induction and abduction methods as a means of proving scientific theories. Although Popper agrees that those methods help create hypotheses, he only proposes the use of the *modus tollens* as a means to check the agreement between a proposition and the result of an experiment.

As for Eekels [2001], the use of propositions allows experiments and designs to be created which produce similar conclusions. To describe this similarity, he considers that a set of propositions « ri » describes the initial state of a physical experiment. Then, if « rf » describes the final state and « qe » is the set of propositions involved in the prediction of the experiment, one concludes « qe » from the propositions « ri ». Therefore, the theory is verified if the difference $|rf-qe|<\varepsilon$, in which ε is arbitrarily small, depending on the physical reality. If one conjugates « ri » with the set of propositions « exp » describing the experiment, then one obtains « rf », which is equivalent to saying that $ri \wedge exp \rightarrow rf$. Moreover, if « rf » is close to « qe », one can substitute « qe » for « rf ». This results in the following equation:

$$ri \wedge exp \rightarrow qe \qquad (2)$$

where « exp » is given and « qe » must be obtained with the support of a theory, a process that represents an increase of knowledge about a certain subject, or the process of "knowing".

In Design, a rational construction might attain the proposed design « qd » by conjugating the initial propositions « ri » with those of the design « dsgn », which is the same as saying $ri \wedge dsgn \rightarrow rf$. If one obtains the final set of propositions « rf » and if it verifies « qd », then the following equation holds:

$$ri \wedge dsgn \rightarrow qd \qquad (3)$$

where "« qd » is given and « dsgn » must be obtained", which corresponds to the process of designing, which Eekels called the process of "doing".

Therefore, "the inference « qe » and the design « dsgn » are both forms of creativity" [Eekels 2001], causing the processes of "knowing" and of "doing" to be similar. "Knowing" aims to obtain the result of the implication, taking the experiment for granted; while "doing" grants the result and specifies the premise set of the implication.

Let us suppose that someone wants to design a system to supply a specific airflow to a chamber, in such a condition that the air velocity in the occupancy zone of the chamber does not exceed 0.2 m/s. In this case, « ri » would be the set of propositions that defines the geometry of the chamber and some knowledge about the different systems that can be used to supply air to the chamber. In this example « qd » is a proposition stating the prescribed airflow and the maximum air velocity that is allowed in the occupancy area. « rf » is the result of the design: the data measured in different points of the chamber that allows deciding if the error |rf-qd| is negligible. And, « dsgn » is the set of propositions that define the kind and the location of all the air diffusers, their air velocity and the airflow direction.

5 REPEATABILITY IN DESIGN AND IN THE SCIENTIFIC EXPERIMENT

From the section above, the physical model and the scientific experiment play an important role in obtaining a solution in the world of design.

In the natural sciences no one knows, *a priori*, what physical experiment will validate the hypothesis of the theory « qe ». Therefore, the experiment « exp » has a similar role as the design, like in finding « qd » from the design reality « ri ». Scientists compare the predictions of the set of functions that describe a phenomenon, with the results of various experiments of different formats, allowing them to accept or to reject a theory. Because they use different experiments at different conditions, the confirmation of natural laws does not take place in the physical domain, but in the functional domain.

Therefore, equations (2) and (3) are equivalent and the fulfilment of the design depends on obtaining a physical prototype that can perform the required functions.

Different projects that perform the same functions will lead to repeatability, in the same sense that repeatability exists in the physical experiments. We will call the repeatability based on the verification of functions as "functional repeatability". Assuming the *modus tollens* as the support of the scientific discovery, then if « exp » has been carried out appropriately and « qe » is not verified, then either « ri » is false or some faux pas has been committed in the process of deduction.

$$\sim qe \rightarrow \sim(ri \wedge exp) \quad (4)$$

If « qd » is false, then either the initial functions are not possible or the design is incorrect:

$$\sim qd \rightarrow \sim(ri \wedge dsgn) \quad (5)$$

Applying equation (5) to the example above, and should the attained air velocity be larger than 0.2 m/s, then one could conclude that the diffuser design might have been inaccurately selected or the data concerning the chamber is incorrect.

Thus, any design object described through the functions it performs, possesses functional repeatability in the same sense that there is functional repeatability in any scientific experiment. However, there is an ontological difference between design and experiments: the aim of an experiment is to validate a proposed function, while the aim of a design is to know whether a proposed design object performs a given set of functions.

The functional repeatability criterion must rule the assessment of different physical concepts, as a given design object will be functionally equivalent to another one if it strictly performs the same set of functions.

As a result, given the same problem to solve and after establishing the functions to fulfil, one can see that different designers will produce functionally equivalent designs, although physically different.

Thus, one can apply Poper's definition of science to the design, which means that at least in the above-mentioned third phase of the design process, the behaviour of the design objects will be checked against the functions that they might perform. Additionally, although being very important in engineering, the creative process does not belong to the field of natural science. In fact, the lack of repeatability of the physical result of the creative process, *i.e.*, the design object, makes it impossible to use the method of natural science.

6 CONCLUSION

The aim of this paper is to define a design epistemology by comparing the processes that are present in design and in scientific experiments. We introduce the notion of "functional repeatability", which is common to both the design process and physical experiments. There will be functional repeatability in different design objects if they perform the same prescribed set of functions. The aforementioned repeatability also occurs in experiments of different kinds that are used in the validation of a scientific theory.

The notion of functional repeatability makes it possible to use the scientific method in Design Science, so that design objects can be objectively evaluated.

7 REFERENCES

[1] Eekels, J., "On the fundamentals of engineering design science: The geography of engineering design science. Part 2", Journal of Engineering Design, Vol 12, n. 3, pp. 255-281, 2001.

[2] Hubka, V. & Eder, W.E, *Design Science*, Springer-Verlag London Limited, 1996. ISBN 3-540-19997-7.

[3] Pahl, G. & Beitz, W., *Engineering Design - A Systematic Approach*, 2nd ed., Springer, 2001. ISBN 3-540-19917-9.

[4] Popper, K., *A Lógica da Pesquisa Científica*, Editora Pensamento Cultrix, 17th Ed., (in Portuguese, 1st ed. 1959, original title: The Logic of Scientific Discovery). ISBN 85-316-0236-x.

[5] Suh, N.P., *The Principles of Design*, New York: Oxford University Press, 1990. ISBN 0-19504345-6.

[6] Taguchi, G., *Taguchi on Robust Technology Development, Bringing Quality Upstream*, ASME, 1995. ISBN 0-7918-0028-8.

[7] Value Management, Handbook, European Commission, Report EUR 16096, DGXIII, 1995. ISBN 92-826-9534-4.