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THE 'VALIDATION SQUARE'
– VALIDATING DESIGN METHODS –

by

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ABSTRACT

Validation[2] of engineering research has traditionally been anchored in the scientific inquiry tradition. This tradition demands "formal, rigorous and quantitative validation" (Barlas and Carpenter 1990), which is based primarily on logical induction and / or deduction. Since much engineering research is based on mathematical modeling, this kind of validation has worked – and still works – very well. There are, however, other areas of engineering research that rely on subjective statements as well as mathematical modeling, which makes 'formal, rigorous and quantitative' validation problematic. One such area is that of design methods within the field of engineering design. In this paper, we explore the question *how does one validate design research in general, and design methods in particular?*

Being anchored in the scientific inquiry tradition, research validation is strongly tied to a fundamental problem addressed in epistemology: *what is scientific knowledge and how is new knowledge confirmed?* Thus, we first look to epistemology for 1) answers to why the traditional approach of 'formal, rigorous and quantifiable' validation constitutes a problem, and 2) for an alternative approach to research validation. Having presented a new validation procedure, namely, the 'Validation Square', we validate it by means of itself. This is in correspondence with validating mathematics by means of mathematics.

We recognize that no one has *the* answer to the questions we pose. To help us converge on an answer to these questions we "think aloud" and invite you to join us in doing the same. It is our hope that in so doing we, the members of this design research community, will all be the richer for it.

Keywords: philosophy of science, epistemology, engineering design, research validation.

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[2] As a philosophical term, *validation* refers to internal consistency (i.e., a logical problem), whereas *verification* deals with justification of knowledge claims. In modeling literature, on the other hand, these terms are swapped, and in this paper we use the terms as used in the modeling literature; i.e., *verification* refers to internal consistency, while *validation* refers to justification of knowledge claims (Barlas and Carpenter 1990).

1. WHAT IS SCIENTIFIC KNOWLEDGE?

– SEARCHING FOR A NEW APPROACH TO DESIGN METHOD VALIDATION –

In this section we address the question: what problems does formal, rigorous and quantifiable validation constitute for research in general, and for research within the field of engineering design in particular? We do so by going to the roots of epistemology to evaluate the applicability of the fundamental assumptions upon which 'formal, rigorous and quantifiable' validation rest. Then, based on the literature, we propose new assumptions where old assumptions fail, before proposing a new approach to research validation based on a new set of assumptions.

1.1 The Historical Roots of Modern Epistemology

Epistemology (the theory of knowledge) started in ancient Greece with Phyrro and his skeptics. They tried to produce 'a criterion for truth', a search that was strongly influenced by Plato and Aristotle. Plato, who defined knowledge as "that over which there cannot be error", confided knowledge to a particular realm of perfect and unchangeable entities referred to as "Forms" (Honderich 1995). Plato later acknowledged that "correct belief can be turned into knowledge by means of a reason or cause", something Aristotle picked up on. He refined this thinking by stating that "knowledge entails understanding objects in terms of their reason" and that "this understanding can only come from experience". Plato supported this view by claiming that "we are all born with knowledge", hence, "learning is a process of recollection based on experience" (Honderich 1995). This constitutes the basis for foundationalism, where knowledge of the world rests on a "foundation of indubitable beliefs from which further propositions can be inferred to produce a superstructure of known truths" (Honderich 1995). And it is from this foundationalist basis modern epistemology emerged in the seventeenth century, starting with Rene Descartes and rationalism.

1.2 The Foundationalist/Formalist/Reductionist School of Epistemology

The rationalists asserted that "the truth is innate and prior to all experience" and that "human knowledge about the truth is based on reasoning" (Descartes [1641] 1931). The empiricists agreed on the innate nature of the truth, but asserted that "all human knowledge about the truth is based on experience rather than reasoning" (Locke [1690] 1894). Both views, however, are based on the fundamental assumption that *truths are absolute and innate*, which links them to Plato and Aristotle, and hence, to **foundationalism**.

The foundationalist view was brought forward by Bertrand Russell who introduced logical atomism, and by his student Ludwig Wittgenstein. With his "Tractatus Logico-philosophicus" Wittgenstein brought the atomist and foundationalist tradition to full fruition by asserting that the "function of philosophy is to monitor the bounds of sense, and to show that attempts to traverse the bounds of sense are futile" (Honderich 1995; Wittgenstein [1921] 1961). This became the basis for logical positivism, a movement holding high grounds in the scientific community until the 1960's. Their doctrine was centered around the 'verification principle' asserting that "knowledge can only be claimed if judged true by meaning [analytically true] or true by virtue of experience [synthetically true]" (Honderich 1995). Hence, non-quantifiable synthetically propositions are neither true nor false, i.e., they are meaningless. From this it follows that unless statements can be formalized for analytical and/or empirical investigation, they are meaningless. Hence, most positivists consider metaphysical, religious, aesthetic, and ethical claims as inferior to those produced by science, resulting in an extreme focus on science in general and mathematical proofs in particular. This 'urge' to formalize statements into mathematics (to allow analytical judgements) links logical positivism to **formalism**, a view that is integral to many different philosophical schools. Although being different, these schools share the fundamental assumption that *rational knowledge is the only valid knowledge*.

Logical positivism became 'obsolete' in the late 1960's, however, many of the basic ideas of atomism and foundationalism live on in what later has been known as **reductionism**. Reductionism is a wide term and is normally split into ontological, methodological and theory reduction. Ontological reductionists postulate that the whole of realities consists of a minimal number of materialistic substances. Hence, they deny the existence of immaterial phenomena and advocate "biological organisms to be no more than complex functioning machines". Methodological reductionists postulate that the properties of the whole are the sum of the properties of the parts. Hence, analysis of the parts is sufficient to gain knowledge about the whole. Theory reductionists assert that new theories absorb old theories rather than replace them. From this it follows that biology, for instance, will in the end be totally explained by chemistry and/or physics. In modern science, methodological reductionism has been the most influential reductive approach with the discovery of DNA as perhaps the most important triumph. Although successful, building on the assumptions that knowledge is innate and absolute and can only be verified by reason, reductionists are totally dependent on objective quantification. Hence, reductionism is based on the fundamental assumption that *objectivity exists*

In the preceding we have documented that the tradition of scientific inquiry demanding 'formal, rigorous and quantitative' validation is anchored in the **foundationalist/formalist/reductionist school of epistemology**. From this it follows that 'formal, rigorous and quantitative' validation is based on the fundamental assumptions that 1) *truths (knowledge) are innate and absolute*, 2) that *only rational knowledge is valid*, and 3) that *objectivity exists*. Having identified 'formal, rigorous and quantitative' validation as problematic when validating research that is based on subjective statements, we assert that the fundamental assumptions (1 through 3 above) are at the core of the problems. To substantiate this assertion we turn to the literature.

1.3 The Relativistic/Holistic/Social School of Epistemology – Challenging The 'Ruling' Fundamental Assumptions of Knowledge

The notion of *innate and absolute truths* was first challenged by Thomas Kant who synthesized rationalism and empiricism in a search for knowledge on neutral ground by asserting that ”all knowledge starts with experience” however, "not all knowledge arise out of experience" (Kant [1781] 1933). Hence, he suggested that not all truths are innate and absolute – there are some that might be added by the mind. This rises the question: *who is to determine what is given (i.e., innate and fundamental) and what is derived/added?* This question is referred to as "the myth of the given" in (Sellars 1963). Hegel, on the other hand, rejected the whole idea of innate truths and introduced a new logic in which conflict and contradictions are regarded as necessary elements of truth (thesis, antithesis, and synthesis). As a consequence Hegel regarded truth as a process rather than a fixed state of things. In his view knowledge is socially, culturally, and historically dependent, hence, there are no neutral foundations of knowledge, and entirely objective verification of knowledge claims is not possible (Hegel [1817] 1959). This view was supported by Thomas Kuhn who presented a historical analysis of how science progresses, and he argued that at any given epoch scientists work within and against the background of an unquestioned theory or set of beliefs (a paradigm). To say it with Capra: "scientific facts emerge out of an entire constellation of human perceptions, values, and actions – in one word, out of a paradigm – from which they cannot be separated" (Capra 1996). Based on this **we assert that scientific knowledge is not innate nor absolute, but rather a socially justifiable belief**.

Science progresses, according to Kuhn, when the ruling paradigm cannot provide adequate explanations to scientific problems under investigation, and this inadequacy makes way for new paradigms. Central to Kuhn's view is that the change to a new paradigm cannot be based on strictly logical reason (Kuhn [1962] 1970). This is supported by Quine who argues that "we choose a particular way of doing it [i.e., accommodate a new theory to an experiment] not because some absolute scientific principle [i.e., based on rationality] but because it is convenient, causing minimal disturbance in the existing theory". (Quine 1953). This links validation to preferences based on usefulness, which is important since it challenges the notion that *only rational knowledge is valid knowledge*.

Rational knowledge, or rational beliefs, is arrived at by accumulating and evaluating an adequate body of relevant evidence (Honderich 1995). The accumulation and evaluation of scientific evidence is addressed in the Scientific Method, where Sir Francis Bacon suggested that scientific knowledge is gained and claimed by a process of induction. This again requires rigorous rules, where formal logic and/or mathematics are preferred. The underlying assumption is of course that following the rules is a rational act in itself. This assumption fails, since determining which rules to follow also requires rules. Hence, total rational assessments are based on an infinite regress and therefore impossible. In reality the choice of rules is contextual as pointed out in the previous paragraph (i.e., dependent on the ruling paradigm). Hence, our ability to be rational depends on a basic ability to exercise intelligent judgement that cannot be completely captured in systems of rules, i.e., they are not accessible to investigation through the senses or calculation. This is the definition of intuitive knowledge, and it is ironic that hypotheses (the cornerstone of the scientific method) often are proposed as a result of intuitive processes (Honderich 1995). As Albert Einstein expressed this point:

> *"The justification (truth content) of the system [physics] rests in the proof of usefulness of the resulting theorems on the basis of sense experiences, where the relations to the latter to the former can only be comprehended intuitively" (Einstein 1950).*

Based on this **we assert that scientific knowledge is based on 1) rationality for facts, and 2) on intuition for values; hence, intuitive knowledge becomes linked to the application of rational knowledge through the determination of purpose.**

The impossibility of total rational assessments also challenges the very *existence of objectivity*, the last of the fundamental assumptions upon which formal, rigorous and quantifiable validation rest. This assumption is also challenged by Werner Heisenberg who claims that a procedure for acquiring knowledge will affect the acquired knowledge itself (Capra 1991). Albert Einstein was also aware of this problem and he stated that "one may compare these rules [related to the scientific method] with the rules of a game in which, while the rules are arbitrary, it is their rigidity alone which makes the game possible. However, the fixation will never be final. It will have validity only for a special field of application". *What about the objectivity of mathematics?* Wittgenstein addressed the issue of objectivity in mathematics, and claimed that "logic [mathematics] is merely a tool consistent only within itself and hence content free" (Wittgenstein [1921] 1961). This view was supported by Kurt Gödel who claimed in his "Incompleteness Theorem" that "every formal number theory contains an indecisive formula, i.e., neither the formula nor its negation is provable in the theory" (Gödel 1931). From this it follows that attempting to prove something formally and/or objectively is an illogical and hence, an invalid act since the underlying axiom of such an approach, i.e., that objectivity exist, is already logically refuted by Wittgenstein and Gödel. Ultimately this leads to the proposition that a conversational, contextual and subjective validation approach is more logic, and therefore more formal, since it does not refute its own axioms, i.e., that subjectivity is unavoidable. Based on this **we assert that total objectivity does not exist, and hence, that knowledge validation must be linked to contextual usefulness**.

A new school of epistemology is based on the refutation of the fundamental assumptions upon which the foundationalist/reductionist/formalist school of epistemology rests, namely, the **relativist/holistic/social school of epistemology** (Barlas and Carpenter 1990). Needless to say, we adhere to the relativist school of epistemology, and hence, we adopt a relativist view on scientific knowledge. What remains, however, is to evaluate what impact the different views on scientific knowledge has on research validation, which we do next.

1.4 Different Views on Knowledge: The Impact On Research Validation

The logical empiricist validation is a strictly formal, algorithmic, reductionist, and 'confrontational' process, where new knowledge is either true of false. The validation becomes a matter of formal accuracy rather than practical use. This approach is appropriate for closed problems that have right or wrong answers associated with them, like mathematical expressions or algorithms. The relativist validation, on the other hand, is a semiformal and conversational process, where validation is seen as a gradual process of building confidence in the usefulness of the new knowledge (with respect to a purpose). This approach is appropriate for open problems, where new knowledge is associated with heuristics and non-precise representations.

As stated, the principal objective in this paper is to synthesize a framework for validating design methods, an endeavor which intuitively is assumed to belong in the open problem category. There are no right or wrong answers to this problem, there are lots of heuristics involved, and there are lots of non-precise representations. Based on this assumption the relativist validation is adopted, and the validation strategy is based on the following statement.

We define scientific knowledge within the field of engineering design as socially justifiable belief according to the Relativistic School of Epistemology. We do so due to the open nature of design method synthesis, where new knowledge is associated with heuristics and non-precise representations. Thus, Knowledge Validation becomes a process of building confidence in its usefulness with respect to a purpose.

2. THE ‘VALIDATION SQUARE’

– A PROCESS OF BUILDING CONFIDENCE IN USEFULNESS –

In the previous section we asserted that research validation is a process of building confidence in its usefulness with respect to a purpose. As stated in the Introduction, the purpose of this paper is to develop a framework for validating design methods. Based on this we associate usefulness of a design method with whether the method provides design solutions ‘correctly’ (effectiveness), and whether it provides ‘correct’ design solutions (efficiency). Correct in this context are design solutions with acceptable operational performance, that are designed and realized with less cost and/or in less time. Hence, the process we present aims at evaluating the effectiveness and the efficiency of the method, based on qualitative and quantitative measures respectively. This is illustrated in Figure 1, where the **‘Validation Square’** at the bottom is the synthesis of this process, and this process is detailed next according to the numbers (1) through (6).

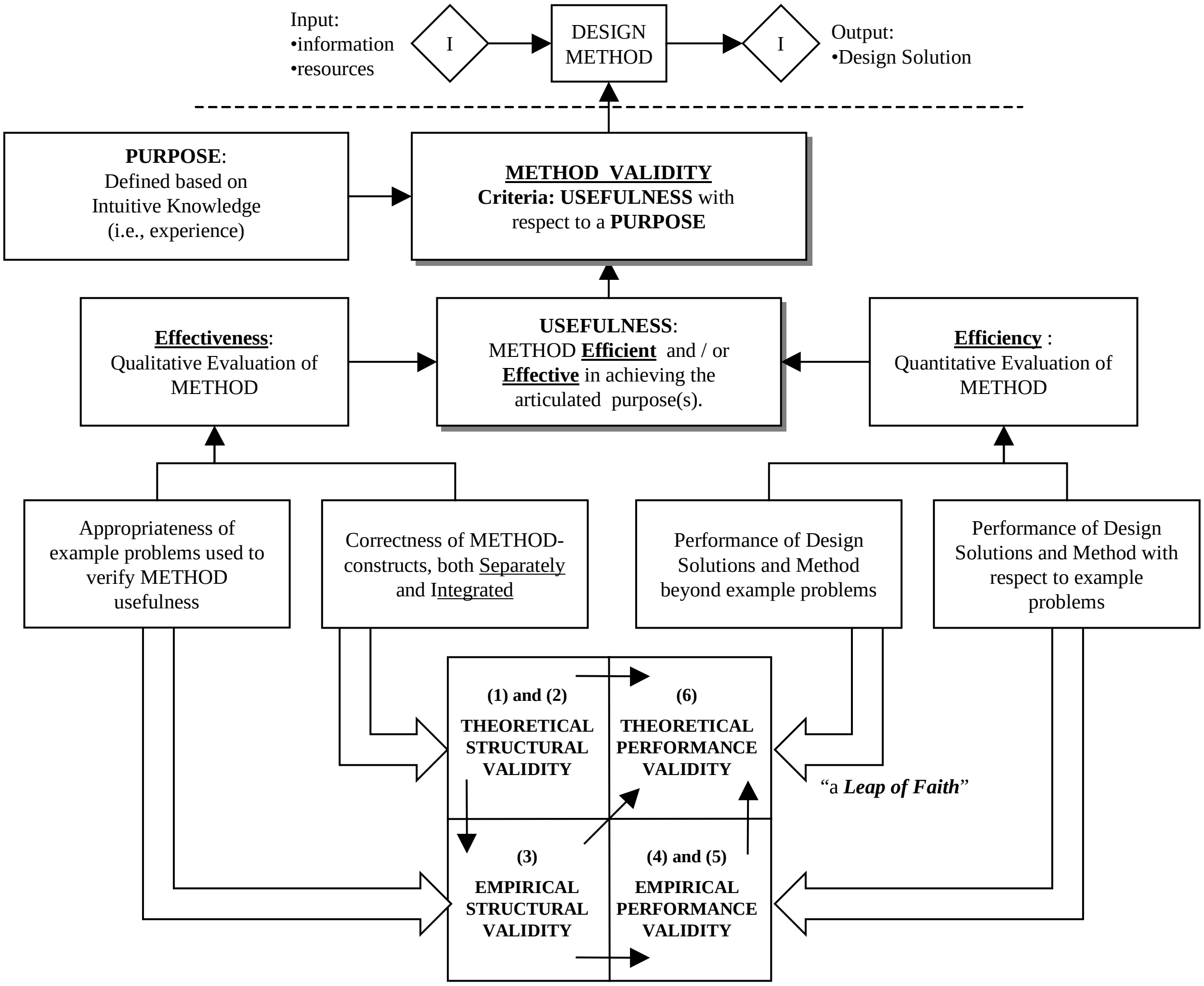


Figure 1

Design Method Validation: A Process of Building Confidence in Usefulness

2.1 Structural Validation – A Qualitative Process

As can be seen from Figure 1, being effective implies three things. (1) It implies accepting the individual constructs constituting the method; (2) accepting the internal consistency of the way the constructs are put together in the method; and (3) accepting the appropriateness of the example problems that will be used to verify the performance of the method.

(1) Accepting the construct's validity: In order to build confidence in the validity of the individual constructs constituting the method, we suggest using the literature. Based on the name of the author and publisher, the number of references associated with the construct, how long the construct has been referenced, and so, an inference towards acceptance can be built. In addition, if the constructs are being used as benchmarking for new constructs, they must be regarded as highly accepted and valued

(2) Accepting method consistency: In order to build confidence in the way the constructs are put together in the method (i.e., in the method's internal consistency) we suggest using flow-chart representations focusing on information flow. In this way it can easily be demonstrated that for each step (construct) there is adequate input available, that the anticipated output from the step (construct) is likely to occur based on the input, and that the anticipated output is an adequate input to another step (construct). Further, identifying the information flow unveils what information is assumed to be readily available, hence, facilitates evaluation against reality. Method inconsistency refers to generating information that is inadequate or not necessary, or invalid assumptions upon which the method rests.

(3) Accepting the example problems: In order to build confidence in the appropriateness of the example problems chosen for verifying the method performance, we suggest documentation through viewpoints. First, document that the example problems are similar enough to the problems for which the method-constructs are generally accepted. Then, document that the example problems represent the actual problem for which the method is intended. Finally, document that the data associated with the example problems can support a conclusion.

As can be seen, the validity of the method constructs – individually (1) and integrated (2) – deals with the structural 'soundness' of the method in a more general sense, and are therefore denoted Theoretical Structural Validity. The validity of the example problems for which the method is to be tested (3) deals with the structural 'soundness' for some particular instances, and are therefore denoted Empirical Structural Validity, However, both 'validities' are evaluated qualitatively.

2.2 Performance Validation – A Quantitative Process

As can be seen from Figure 1 being efficient implies three things. (4) It implies accepting that the outcome of the method is useful with respect to the initial purpose for some chosen example problem(s); (5) accepting that the achieved usefulness is linked to applying the method; and (6) accepting that the usefulness of the method is beyond the case studies.

(4) Accepting usefulness of method for some example problems: To build confidence in the usefulness of the method, we suggest using representative example problems. In this way, the outcome of the method can be evaluated in terms of its usefulness. As indicated, metrics for usefulness is linked to which degree an articulated purpose has been achieved. However, the purpose of proposing a design method may vary; from an industrial perspective the purpose is typically linked to reducing cost and/or time and/or improve quality. From a scholarly perspective, the purpose is augmented to include addition of scientific knowledge that can help produce more scientific knowledge.

(5) Accepting that usefulness is linked to applying the method: To build confidence that the usefulness of the resulting example problem solutions is linked to applying the method, we suggest evaluating the contributions to usefulness from each construct individually. This is done by comparing the solutions with and without the construct, allowing a quantitative evaluation.

(6) Accepting usefulness of method beyond example problems: To build confidence in generality, we suggest induction based on the following. In (1) we demonstrate that the individual constructs are generally accepted for some limited applications. In (2) we demonstrate the internal consistency of the way the constructs are put together in the method. In (3) we demonstrate that the constructs are applied within their accepted ranges. In (4) we demonstrate the usefulness of the method for some chosen example problems, which in (3) are demonstrated to be appropriate for testing the method. And finally, in (5) we demonstrate that the achieved usefulness is due to applying the method. Based on this we claim generality, i.e., that the method is useful beyond the tested example problems. However, as shown in Section 1.3, every validation rests ultimately on faith. Hence, the purpose of going through the 'Validation Square' is to present 'circumstantial' evidence to facilitate a leap of faith, i.e., to produce belief in a general usefulness of the method with respect to an articulated purpose.

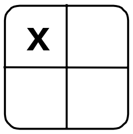
If the method is deemed useful for some limited instances (4) and (5), we denote this Empirical Performance Valid. Similarly, if the method is deemed useful beyond some limited instances (6), i.e., useful in a more general sense, we denote this Theoretical Performance Valid.

Having proposed a framework for validating design methods, namely the 'Validation Square', this framework itself needs to be validated. Being in the open problem category we want to validate the Validation Square by means of the Validation Square, which is dealt with next.

3. VALIDATING THE 'VALIDATION SQUARE'

Since a validation framework in itself is in the open problem category, it should be applicable to validate itself. This goes along with validating mathematics by means of mathematics, which is regarded as scientifically legal and acceptable. Hence, we start with evaluating the <u>Theoretical Structural Validity</u> of the 'Validation Square'.

3.1 The <u>Theoretical Structural Validity</u> of the 'Validation Square'



The <u>Theoretical Structural Validity</u> (TSV) of the 'Validation Square' refers to accepting the structural/logical 'soundness' of its constructs, both individually and integrated. The constructs of the 'Validation Square' are represented by the four internal squares as illustrated in Figure 1: the <u>Theoretical Structural Validity</u> (TSV), the <u>Empirical Structural Validity</u> (ESV), the <u>Empirical Performance Validity</u> (EPV) and the <u>Theoretical Performance Validity</u> (TPV). Hence, accepting the TSV of the 'Validation Square' implies accepting the structural/logical soundness of each of these 'validities' in addition to accepting that they are put together in a logical and consistent manner.

(1) Accepting the individual 'validities': It should not be hard to accept that any tools/constructs/etc. to be used in a design method has to be individually valid, and that the tools/constructs/etc. has to be organized in a way that creates internal consistency. Hence, we assert that TSV as outlined in Section 2.1 is a structurally (logically) valid proposition.

This view is supported in (Hazelrigg 1999?). However, Hazelrigg asserts that "validation of a design alternative selection method can be done <u>only</u> mathematically, and <u>only</u> through validation of the procedure, not by verification through results", a view based on (Barzilai 1998). We find it difficult to accept the preceding statement. Both Hazelrigg and Barzilai must be viewed as advocating 'rigorous, formal, and quantifiable' validation, an approach based on fundamental assumptions which we have questioned. Further, .Hazelrigg argues that "only if all steps in a procedure are valid, that is, rational, self-consistent, and derivable from axioms, is it possible for a method [as a whole] to be valid". This is based on the view that rational assessments yield universal and necessary results; hence, if methods produce significantly different results with identical input, at most one of the methods can be logically valid. This view is challenged by bounded rationality, where human cognitive limitations are viewed to yield a considerable scope for rational disagreement (Honderich 1995). Hence, we suggest that the presented axioms in (Hazelrigg 1999?) can be challenged and logically refuted by using a different set of rules.

Finally, we contend that the total disregard for using results (i.e., evaluating usefulness) as part of validation as suggested by Hazelrigg to be illogical to say the least. Let us explain. The purpose of an 'alternative selection method' is to recommend the best alternative based on some criteria. Hence, what is really important is to have a) a good set of alternatives, and b) the right set of criteria for what is best. Both of these aspects cannot be addressed by rational assessments, hence, the usefulness of having a totally rational selection process becomes limited; the process with which an alternative is recommended is valid, but the alternative may not be valid. This is very well demonstrated by 'the battle' between Windows 3.1 and IBM's OS2 operative system; most experts deemed OS2 to be a better operative system, however, the OS2 lost the competition.

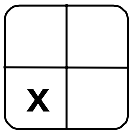
Based on this we assert that internal consistency alone does not assure external relevance, hence, we feel that validation has to be augmented to address external relevance by evaluating usefulness. In this context it should not be hard to accept that any example problem used to verify a method’s usefulness has to a) be similar to the problems for which the tools/constructs/etc. are generally accepted; b) be representative of the problems for which the method is intended; and c) provide sufficient data to support a conclusion. Hence, we assert that ESV as outlined in Section 2.1 is a structurally valid proposition.

Accordingly, it should not be hard to accept that unless a design method is able to produce useful results (i.e., design solutions) for a particular problem it cannot be deemed valid for that particular problem. (It does not mean, however, that the method is invalid in general.) Hence, we assert that EPV as outlined in Section 2.2 is a structurally valid proposition.

Finally, the TPV-validity is based on the other three internal ‘validities’ being accepted, as well as accepting that the induction presented in Section 2.2 (6) is logically valid. The first is given in the previous paragraphs, while the latter is dealt with next.

(2) Accepting the ‘Validation Square’ consistency: We assert that the induction given in Section 2.2 (6) is logically valid. To substantiate this claim we turn to the literature. The consistency of viewing validation as a process of building confidence in usefulness (with respect to a purpose) is demonstrated in Section 1.3. Here we argue that a conversational, contextual and subjective validation approach is logic, and therefore formal, since it does not refute its own axioms, i.e., that subjectivity is unavoidable. This view is fully supported in (Emblemsvåg 1999), and is based on a tradition of building confidence based on posits, see (Chen 1995; Lewis 1996; Koch 1997; Peplinski 1997; Simpson 1998) for more details. Further, splitting this process of building confidence in one structural (qualitative) and one performance (quantitative) part, and in one theoretical (general) and one empirical (particular) part comes from the area of system dynamics (Richardson and Pugh 1981). This area has been heavily criticized for not employing ‘formal, rigorous, objective and quantitative’ model validation procedures (Barlas and Carpenter 1990; Barlas 1996), which makes this approach even more interesting from the perspective of design method validation. The first time we have noticed these validation aspects used in the area of engineering design is in (Bailey 1997), where they are put into a ‘square’. However, the prescriptive and comprehensive ‘Validation Square’ as presented in this paper is first presented in (Pedersen 1999), where it was used to validate that the presented doctoral research contributed with new scientific knowledge to the field of engineering design. Finally, it has been used in (Siddique 1999) to validate doctoral research as well. Based on the previous, we assert that the ‘Validation Square’ is Theoretical Structural Valid.

3.2 The Empirical Structural Validity of the ‘Validation Square’



As stated in Section 2.2, any example problem intended for method testing has to be validated itself and deemed appropriate. As mentioned in the previous paragraph, the ‘Validation Square’ has been used to validate a design method, namely, the “Hierarchical Product Platform Realization Method”, or the HPPRM for short (Pedersen 1999). Hence, we use the HPPRM as our example problem to test the usefulness of the 'Validation Square' and show in the following its appropriateness.

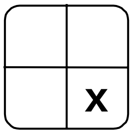
(3) Accepting the HPPRM as an example problem: The HPPRM is a design method intended for realizing large and complex made-to-order systems that are very expensive and produced in small numbers. The outcome of the HPPRM is a so called Hierarchical Product Platform (or HPP for short), which is a product platform serving as a basis for products addressing different market segments. The HPPRM consists of three phases, namely, Define, Model, and Solve. Each of these phases is centered around an independent construct, namely, Numerical Taxonomy, Technology Diffusion, and the compromise DSP, see Figure 2.

- Numerical Taxonomy (Sneath and Sokal 1973) is used to identify the potential for standardization in an existing design portfolio by means of clustering. The clustering itself is 'objective' whereas interpreting the clusters is based on subjective judgements.
- Technology Diffusion (Silverberg, Dosi et al. 1988; Silverberg 1991; Hall 1994) is used to discount the performance of alternative technologies according their maturity and leverage potential to existing technology. Application of the discounting factor is 'objective' whereas decisions regarding learning rates and leverage potentials are based on subjective judgements.
- The compromise DSP (Mistree, Hughes et al. 1993) is used to enable designers to minimize the distance to their goals for the total system with respect to operational performance, time and cost. Solving the compromise DSP is 'objective' whereas deciding on scenarios as well as making the final decision is based on subjective judgements.

Applying the HPPRM is preparing 'subjective' input to 'objective' mathematical constructs that produces output which is judged 'subjectively'; hence, it complies with the kind of problems for which the 'Validation Square' is intended.

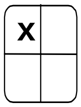
Further, in (Pedersen 1999) HPP's were developed for a family of gravitational separators and a family of marginal field vessels, which constitutes two instances for which the HPPRM is tested. Hence, we claim that this is sufficient data to support a conclusion regarding the usefulness of the HPPRM, and thus, regarding the usefulness of the 'Validation Square'. Based on the following we assert that the HPPRM is an appropriate example problem to test the usefulness of the 'Validation Square', i.e., using the HPPRM is Empirical Structural Valid.

3.3 The Empirical Performance Validity of the 'Validation Square'



The purpose of applying the 'Validation Square' to the HPPRM is to build confidence in its validity. Hence, the usefulness of the 'Validation Square' is linked to which degree confidence is built (4) and to which degree this confidence is due to applying the 'Validation Square' (5).

(4) Accepting usefulness of 'Validation Square': In order to build confidence in HPPRM validity we applied the 'Validation Square' in the following manner.



- We demonstrated by means of the literature that the core constructs of the HPPRM are generally accepted for their intended applications. Further, we demonstrated by means of flow chart representation that (1) there is no redundant information being generated and (2) the underlying assumptions are valid. Based on this we asserted Theoretical Structural Validity.

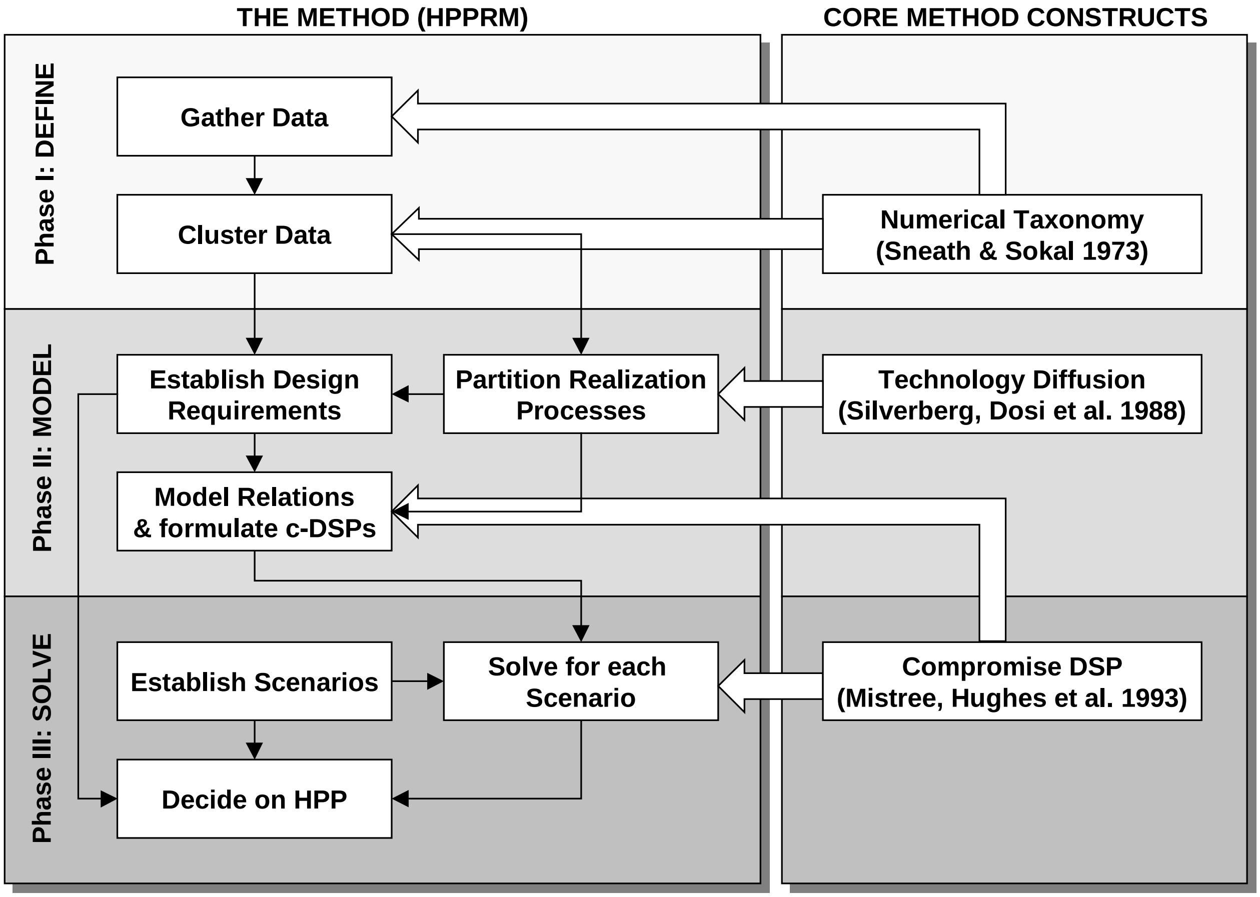


Figure 2
The HPPRM and its Constructs, An Overview

- We demonstrated by means of induction that the (1) *Gravitational Separator* example problem was appropriate for exemplifying and illustrating the HPPRM in detail, and (2) that the *Marginal Field Vessel* example problem was appropriate for testing the usefulness of the HPPRM. Based on this we asserted Empirical Structural Validity.

- We demonstrated by means of the example problems that (1) the resulting HPPs represented feasible solutions realizable in less time with less cost, and (2) that each construct contributed to usefulness; Numerical Taxonomy by reducing the combinatorial problem to a manageable size, Technology Diffusion by advocating a continuous improvement approach, and compromise DSP by advocating robust and adaptive solutions. Based on this we asserted Empirical Performance Validity.

- Based on the outcome of the previous steps in the 'Validation Square' we inferred general validity of the HPPRM based on the following. (1) The key method-constructs are applicable for problems beyond the example problems, (2) the example problems are representative of the general problem, and (3) the HPPRM is useful for the representative example problems. Based on this we asserted <u>Theoretical Performance Validity</u>.

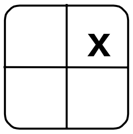
Based on the fact that a seven member doctoral reading committee accepted that the HPPRM added new knowledge to the field of engineering design, we assert that the ‘Validation Square’ as applied in (Pedersen 1999) built confidence in usefulness with respect to a purpose. What remains is to evaluate whether this confidence was due to the ‘Validation Square’.

(5) Accepting that usefulness is linked to applying the ‘Validation Square’: Being <u>Theoretical Performance Valid</u> implies that all other ‘validities’ are accepted, and hence, each of the ‘validities’ is necessary but not sufficient. However, confidence can be built with very little ‘evidence’ presented, it all comes down to faith as pointed out in Section 1.3. Nevertheless, we claim that the likelihood of accepting something as valid increases with the amount of relevant and accepted ‘evidence’. Based on this we assert that due to applying the ‘Validation Square’ the reading committee was provided with sufficient relevant ‘evidence’ to accept the HPPRM.

We have now demonstrated that applying the ‘Validation Square’ provided a sufficient amount of ‘evidence’ to build confidence in validity for at least one instance, namely, the HPPRM. Based on this we assert that the ‘Validation Square’ is <u>Empirical Performance Valid</u>.

3.4 The <u>Theoretical Performance Validity</u> of the ‘Validation Square’

The general validity of the ‘Validation Square’ is based on accepting its usefulness beyond the example problem, which is presented next.



(6) Accepting usefulness of ‘Validity Square’ beyond the HPPRM example:
We assert that the ‘Validation Square’ is useful to validate design methods with mixed ‘subjective’ and ’objective’ statements beyond the presented HPPRM example, and we substantiate this claim as follows.

- As long as a design method can be evaluated for its likelihood of ‘producing’ the wanted outcome, it can be deemed <u>Theoretical Structural Valid</u>.
- As long as an example problem can be evaluated for its appropriateness regarding method testing, it can be deemed <u>Empirical Structural Valid</u>.
- As long as a design method can be evaluated in terms of how well the resulting design solutions performs compared to design solutions arrived at by other methods, it can be deemed <u>Empirical Performance Valid</u>.
- And finally, as long as inference can be made towards a design method’s general usefulness, it can be deemed <u>Theoretical Performance Valid</u>.

Based on this, we assert that the ‘Validation Square’ is generally applicable for validating design methods in particular, and for validating research in general. The latter is based on expanding the previous induction in the following way.

- As long as any research result can be evaluated in terms of the likelihood of fulfilling its intended application, it can be deemed <u>Theoretical Structural Valid</u>.

- As long as any test of research usefulness can be evaluated for its appropriateness, it can be deemed Empirical Structural Valid.
- As long as any research results can be evaluated in terms of its usefulness for some particular applications, it can be deemed Empirical Performance Valid.
- And finally, as long as inference can be made towards the general usefulness of any research results, it can be deemed Theoretical Performance Valid.

Based on this we assert that the 'Validation Square' is Theoretical Performance Valid, hence, it is deemed valid for validating new knowledge associated with heuristics and non-precise representations. From this it follows that we have achieved the principal objective of this paper, namely, to synthesize a framework to validate design methods in particular and research results in general. And we have done so according to the relativist/holistic/social school of epistemology, where scientific knowledge is defined as socially justifiable belief, and research validation is viewed as a process of building confidence with respect to a purpose.

4. CLOSURE

In this paper we have questioned the fundamental assumptions upon which 'formal, rigorous and quantitative' validation rest, and suggested a new set of assumptions leading us to a new view on knowledge validation, namely, a relativist/holistic/social view (see Table 1)

Table 1

Old view on knowledge validation	Fundamental assumptions	Refutation based on	New emerging assumptions	New view on knowledge validation
Foundationalist	Knowledge is absolute/innate	Kant, Hegel, Sellars, Quine, Kuhn	Knowledge is socially justifiable belief	Relativist
Reductionist	Rationality only valid basis for knowledge	Honderich, Einstein	Intuition valid basis for defining purpose for application of knowledge	Holistic
Formalist	Objectivity exist	Hegel, Kuhn, Wittgenstein, Gødel, Einstein	Research validation linked to usefulness	Social and conversational

Based on the changed view, we assert that validating a design method is a process of demonstrating usefulness with respect to a purpose. Based on this assertion we present a framework for guiding this process, namely, the ‘Validation Square’ (see Figure 3). This framework builds on research in systems dynamics, and a tradition of using posits in engineering design. However, the ‘Validation Square’ as presented in this paper extends all these efforts by offering a prescriptive approach that is more comprehensive and systematic.

The ‘Validation Square’ has been used to validate a design method for realizing large and expensive made-to-order systems, namely, the HPPRM (Pedersen 1999), and to validate a method for product platform configuration (Siddique 1999). Based on this paper we assert that the ‘Validation Square’ is appropriate for validating research results in general, as long as it can be subjected to qualitative and quantitative evaluation as outlined in Section 2.

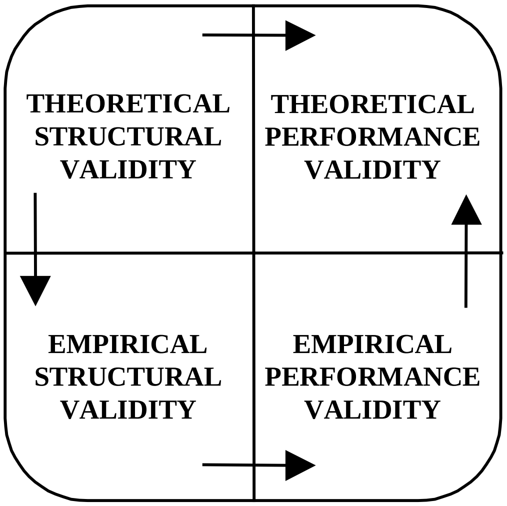


Figure 3
The Validation Square

As we wrote in our abstract, we recognize that no one has the answer. We trust that you enjoyed thinking aloud with us. We now invite you to comment upon what we have presented so that we together can create something of value not only to us but to our student colleagues - the next generation researchers!

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