

THE VALIDATION SQUARE:

HOW DOES ONE VERIFY AND VALIDATE A DESIGN METHOD?

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ABSTRACT

Validation⁵ of engineering research has traditionally been anchored in the tradition of scientific inquiry. This demands formal, rigorous and quantitative validation, 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

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⁵ 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]).

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 corresponds to the idea of 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.

Word count:

1– SEARCHING FOR A NEW APPROACH TO DESIGN METHOD VALIDATION –

How should a design method proposed in a MS thesis /PhD dissertation be validated? What should we get our students to do to validate their work? What are the characteristics of a high quality MS thesis / PhD dissertation? These are questions that are important to both faculty and students who are involved in researching and documenting their findings in the scholarly literature and provides the impetus for writing this chapter. Answers to the first two questions are provided in the body of this chapter whereas an answer to the third question is forthcoming in the appendix.

Validation of engineering research has traditionally been anchored in the formalism of scientific inquiry, which demands “formal, rigorous and quantitative validation”, Barlas and Carpenter, 1990 [1]. In this formalism logical induction and / or deduction plays a key role, which makes it particularly useful in validating internal consistency within the framework of the scientific method. 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. The work presented here has evolved from a paper by Pederson, Emblemståg, and co-authors, 2000 [2].

In this area, validating internal consistency does not guarantee external relevance, i.e., that the design solution is useful for its intended purpose. Hence, we need to *augment* the traditional

validation methods in order to ensure external relevance. In order to do so, we go to the roots of epistemology for alternative ways of looking at design knowledge.

1.1 The Historical Roots of Modern Epistemology

Epistemology (the theory of knowledge) started in ancient Greece with Pyrrho, Plato and Aristotle who had a foundationalist view of knowledge. According to this view 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, i.e., that all truths are absolute and innate, Honderich, 1995 [3].

From this foundationalist basis modern epistemology emerged in the seventeenth century with the introduction of rationalism by Descartes, 1641, [4] and empiricism by Locke, 1690, [5]. The foundationalist views were brought forward in the twentieth century with the introduction of positivism by Wittgenstein, 1921, [6]. Positivism was centered on the verification principle which asserted that unless statements can be formalized for analytical and/or empirical investigation, they are meaningless. This created a need to formalize statements into mathematics which links positivism to formalism. Although being different, these schools share the fundamental assumption that rational knowledge is the only valid knowledge.

Positivism became outmoded in the late 1960's, however, many of the basic ideas of atomism and foundationalism live on in what later became known as reductionism. Reductionism is a wide term, however, in modern science methodological reductionism has been the most influential reductive approach. 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. 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*

From this we see that formal, rigorous and quantitative validation is anchored in the foundationalist/formalist/reductionist school of epistemology. Accordingly, this school 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*.

As previously stated, “formal, rigorous and quantitative” validation of research that is based on subjective statements becomes problematic. Based on the above, we assert that the fundamental assumptions (1 through 3 above) are at the core of these problems.

1.2 The Relativistic / Holistic / Social School of Epistemology

The notion of *innate and absolute truths* was first challenged by Kant, 1781, [7], followed by Hegel, 1817, [8]; Kuhn, 1962, [9]; and Sellars, 1963, [10]. In their 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.

This also challenges the notion that *only rational knowledge is valid knowledge*. Kuhn, 1962, [9] and Quine, 1953 [11] observed that science progresses when the ruling theories cannot provide adequate explanations to scientific problems under investigation, making way for new theories. The new theories are then accommodated to experiments not because they satisfy some absolute scientific principles but because they are convenient, causing minimal disturbance in the existing

theory. Hence, our ability to be rational depends on a basic ability to exercise intelligent judgment that cannot be completely captured in systems of rules, i.e.; they are not accessible to investigation through the senses or calculation.

The impossibility of total rational assessments also challenges the very *existence of objectivity*. This assumption was also challenged by Wittgenstein, 1921 [6]; Einstein, 1950 [12]; and Gödel, 1931 [13] among others. Einstein 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”. Wittgenstein addressed the issue of objectivity in mathematics, and claimed that “mathematics is merely a tool consistent only within itself and hence content free”.

This view was supported by Kurt Gödel who claimed that, “every formal number theory contains an indecisive formula, i.e., neither the formula nor its negation is provable in the theory”.

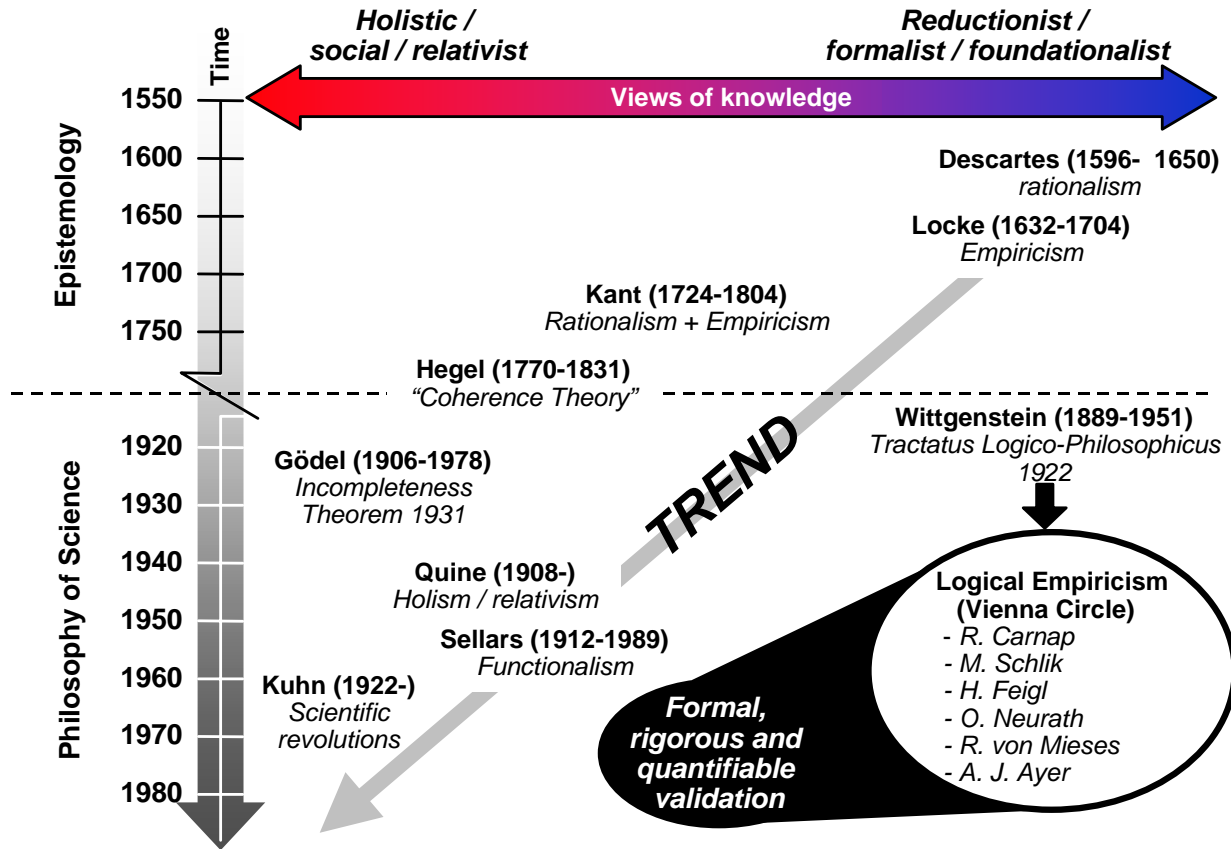


Figure 1: The evolution of thought

As can be seen in Figure 1, the refutation of the fundamental assumptions upon which the foundationalist/reductionist/formalist school of epistemology rests, led the way for a new school of epistemology, namely, the relativist/holistic/social school of epistemology. The impact these different views of knowledge have on research validation is dealt with next.

1.3 The Impact of Different Views on Knowledge on Research Validation

Foundationalist / formalist / reductionist validation is a strictly formal, algorithmic, reductionist, and confrontational process, where new knowledge is either true or 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, such as mathematical expressions or algorithms.

Relativistic/holistic/social 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 acknowledges the mathematical part of engineering design as well as acknowledging the significance of subjectivity. This makes a relativist validation procedure appropriate for open problems, where new knowledge is associated with heuristics and non-precise representations as well as mathematical modeling.

Hence, in order to ensure external relevance, i.e., that the design solution is useful for its intended purpose, a relativist validation procedure is asserted, based on the following definition:

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 Section 1, we asserted that research validation is a process of building confidence in its usefulness with respect to a purpose. 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 design solutions efficiently with acceptable operational performance which 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 2, where the Validation Square at the bottom of the diagram represents the synthesis of the validation process.

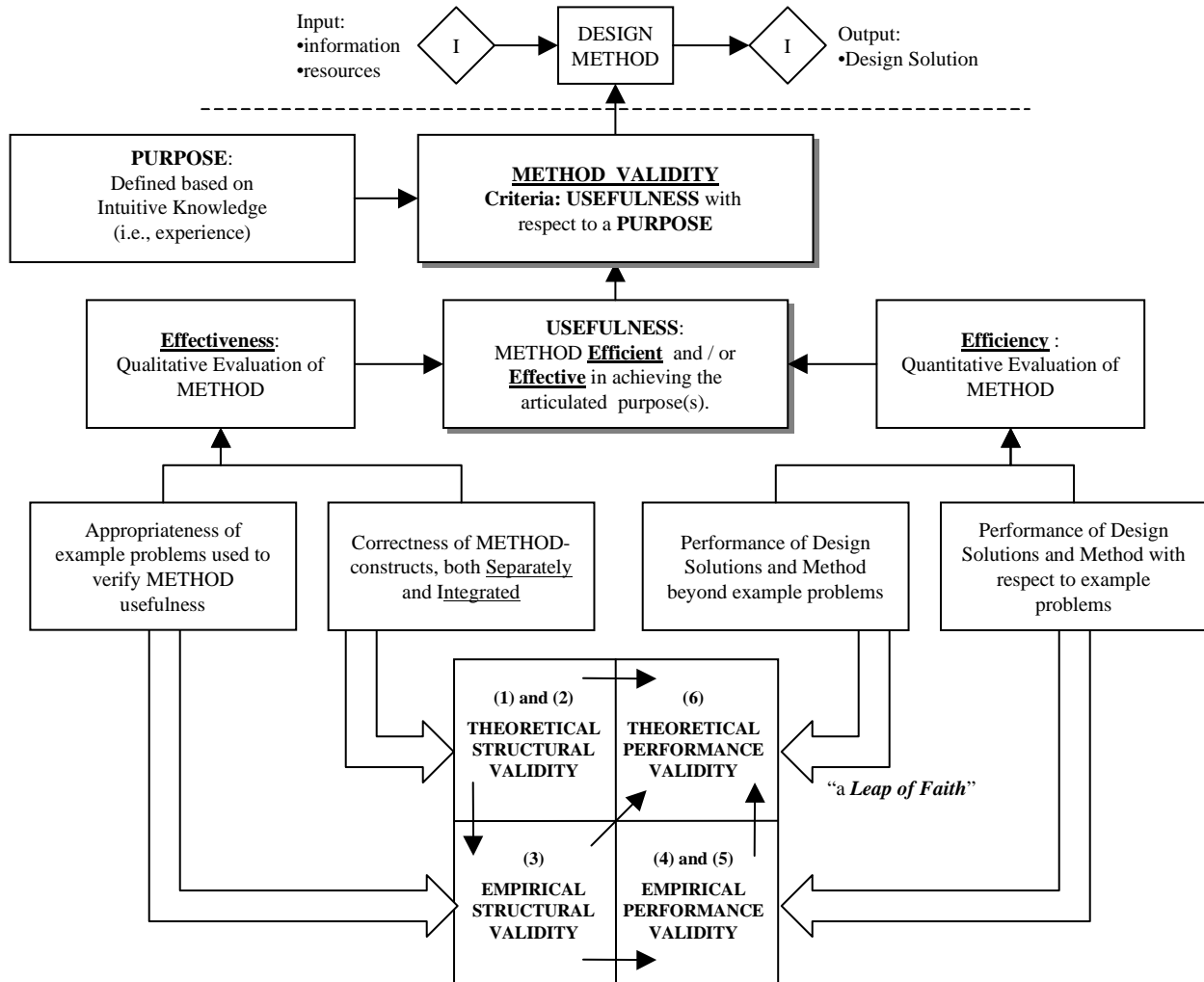


Figure 2
Design Method Validation: A Process of Building Confidence in Usefulness with Respect to a Purpose

2.1 Structural Validation – A Qualitative Process

As can be seen from Figure 2, being *effective* implies three things. It implies: (1) 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 critically evaluating the literature. If the constructs are being used as benchmarking for new constructs, they must be regarded as widely accepted and valued

(2) Accepting method's consistency: In order to build confidence in the way the constructs are assembled 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, specifying the information flow unveils what information is assumed to be readily available, and helps the designer insure that that information is actually available.

An inconsistent method generates information that is inadequate, not necessary, or is based on invalid assumptions.

(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

different 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 problems for which the method is intended. Finally, document that the data associated with the example problems is adequate to 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 of these types of validity are evaluated qualitatively.

2.2 Performance Validation – A Quantitative Process

As can be seen from Figure 2, efficiency 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 are linked to the degree to which 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 improving 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(s) solution 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) have been demonstrated to be appropriate for testing the method. And finally, in (5) we demonstrate that the usefulness achieved is due to applying the method. Based on this we claim generality, i.e., that the method is useful beyond the example problems which were tested. 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 as Empirical Performance Validity. Similarly, if the method is deemed useful beyond some limited

instances (6), i.e., useful in a more general sense, we denote this as Theoretical Performance Validity.

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’

3. Applying the Validation Square for Validating Engineering Design Research

In this section, we offer examples and advice for practical application of the validation square for engineering design research. The examples are drawn from research to establish methods for designing robust, multifunctional cellular materials (c.f., Seepersad, Dempsey and coauthors, 2004 [14]; Seepersad, Kumar and coauthors 2004 [15]; and Seepersad, 2004 [16]. As illustrated in Figure 3, the materials are ordered, metallic cellular materials with extended prismatic cells. The materials can be produced with nearly arbitrary two-dimensional topologies and dimensions, metallic base materials, and wall thicknesses as small as 50 microns via a thermo-chemical extrusion fabrication process developed at Georgia Tech by Cochran and coauthors, 2000, [17]. The design challenge is to tailor the topology and dimensions of the materials for multifunctional applications, such as the gas turbine engine combustor liner illustrated in Figure 4. These applications require adequate performance in multiple, functional domains—such as heat transfer and structural load bearing—that place conflicting demands on the material structures. A Robust Topological Preliminary Design Exploration Method (RTPDEM) has been established for

exploring and generating robust, multifunctional cellular topology and other preliminary design specifications, Seepersad, 2004, [16]. Aspects of the validation process for the RTPDEM are highlighted in this section as examples of applying each facet of the validation square strategy. As illustrated in the validation square diagram in Figure 2, validation is a four-phase process in which it is established that the design method provides solutions correctly (structural validity) and provides correct solutions (performance validity). This must be shown for the example problems of interest (domain-specific) and for broader classes of problems or applications (domain-independent). Each phase is discussed sequentially in the following sections.

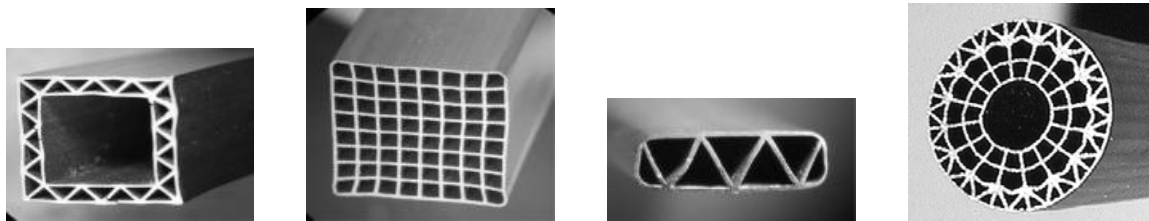


Figure 3 – Ordered, Prismatic Cellular Materials

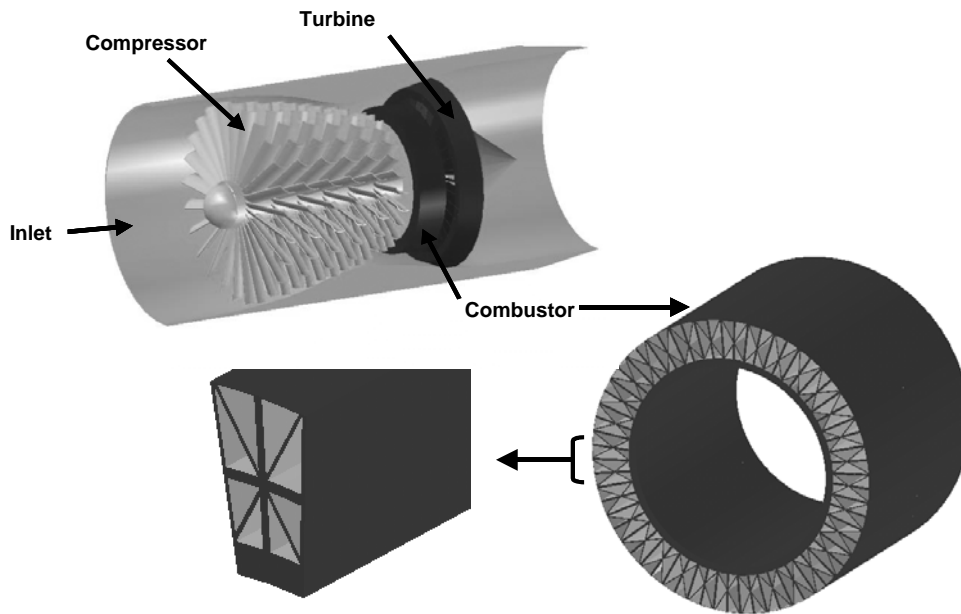


Figure 4 – Cellular Materials for a Multifunctional Application within the

3.1 Theoretical (Domain-Independent) Structural Validation

The primary consideration for theoretical (domain-independent) structural validity is the logical consistency of the proposed design method. Often, a design method is at least partially a synthesis or assembly of parent methods or constructs. In this case, internal consistency must be established not only for the overall method but also for the *individual* parent constructs that comprise it.

The first step is to determine the requirements for the design method. At least two categories of requirements should be enumerated:

- (1) requirements for the *outcomes* of the method, such as the functional, behavioral, and structural characteristics or quality of the resulting products. For example, the RTPDEM is intended to facilitate the realization of families of designs that are manufacturable and exhibit a range of tradeoffs between multifunctional performance objectives and robustness to dimensional and topological variation.
- (2) requirements for the *process* by which the method generates the outcomes. Examples include the efficiency of the method, computational requirements such as distributed versus local computing or supercomputers versus desktop PCs, the knowledge and experience levels required of the intended user, the ability to accommodate multiple designers, and intended designer interactions with one another and with the computing framework.

These requirements provide the foundation for metrics that are used to evaluate the usefulness of the method throughout the validation process. Sample high-level requirements for the RTPDEM are listed in Table 1, Seepersad, 2004 [16]; these high-level requirements are decomposed into a

hierarchical set of more specific requirements. Often, the requirements are identified most easily by considering the intended context for application of the method (e.g., multifunctional cellular materials). Characteristics of the intended domain of application should be enumerated and may include details of the intended physical domains (e.g., structural mechanics, thermodynamics, electromagnetics), types of performance parameters, classes of variables (i.e., continuous, discrete, binary), and product architectural characteristics (e.g., degree of modularity, size, user interfaces).

Table 1 – High-Level Requirements for a Sample Design Method

- | |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ol style="list-style-type: none">1. The method should facilitate exploration and generation of <i>families</i> of multifunctional or multiobjective compromise solutions.2. The method should facilitate systematic modification of topology.3. The method should facilitate consideration and maximization of robustness and flexibility with respect to many sources of variation, including tolerances and topological imperfections.4. The method should be systematic, efficient, and effective relative to ad-hoc methodologies. |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

After the requirements for the design method have been established, the next step is to search the technical literature related to each parent construct and critically evaluate them with respect to their established advantages, limitations, and accepted domains of application. For example, because the RTPDEM is founded on topology design techniques, robust design methods, and multiobjective decision support, relevant literature is critically reviewed in each field in the context of the design method requirements documented in a previous step. The limitations of currently available constructs and methods can be used to confirm the need for the proposed design methods.

At this stage, it may be necessary to apply the parent constructs or methods to small example problems to build familiarity with the methods and more concretely establish their capabilities and limitations. This is especially important for two sets of conditions: (1) the parent

methods/constructs have not been used for applications similar to the intended domain of application of the proposed design method, or (2) the performance of the parent methods/constructs have not been adequately documented in the literature. For example, topology design methods for the RTPDEM are applied to a standard example problem and coupled with various search/optimization algorithms to ascertain the relative performance of each alternative algorithm. A sample diagram of processor time versus problem size or resolution for three different algorithms is illustrated in Figure 5.

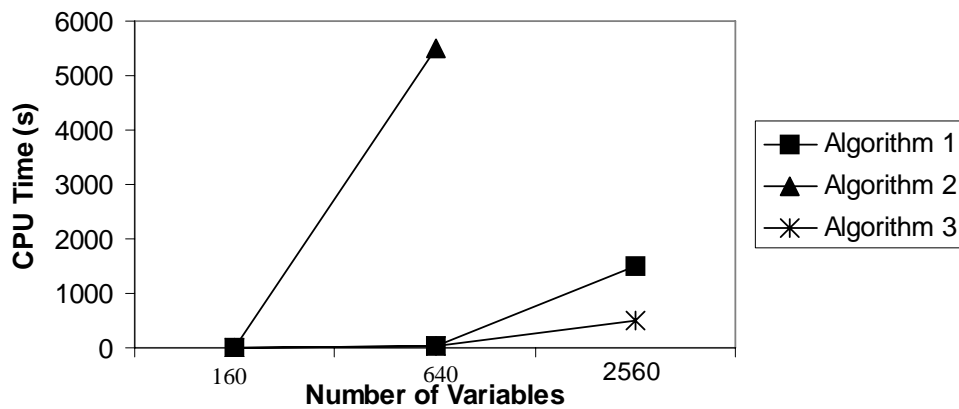


Figure 5 –Investigating Performance Capabilities to Support Theoretical Structural Validation of Algorithms that are Foundational Constructs Within a Design Method, Fernández, 2003 [18].

Next, it is important to establish the internal consistency of the proposed design method in its entirety. This can be accomplished both logically and empirically. Techniques include logical arguments, formal or informal mathematical proofs, and flowcharts. Flowcharts are especially useful for verifying that there is adequate input for each step in a design process and that adequate output is provided for the next step. Empirical techniques include very small example problems designed to test a specific capability of the method. These experiments are especially useful when empirical results can be compared with well-established or theoretical data.

Finally, it is important to compare the capabilities and limitations of the proposed method and its parent constructs with the design method requirements established previously. Based on this exercise, the structural validity of the design method is confirmed independently of *specific* example problems or domains of applications. However, the intended domain of application serves an important role of providing context for domain-independent structural validation — a role that is particularly prominent in prompting the requirements by which the design method is evaluated.

3.2 Empirical (Domain-Specific) Structural Validation

Empirical (Domain-Specific) Structural Validation involves building confidence in the appropriateness of the example problems selected for illustrating and verifying the performance of the design method.

The first step in establishing domain-specific structural validity is to document that the example problems are similar to the problems for which the design method and its constituent constructs are generally accepted or intended. An important aspect of the previous validation phase—Theoretical (Domain-Independent) Structural Validation—is establishing the accepted domain of application of the design method. The domain of application is typically described as a list of characteristics of the design problems for which the design method is intended. In the empirical (domain-specific) structural validation phase, the characteristics of the example problems are documented and compared with those for which the design methods are intended.

The investigator should check that the example problems together exhibit *all* of the critical characteristics of the design problems for which the method is intended. It is appropriate to have multiple example problems—several of which possess subsets of the characteristics and one or

more of which possess a broader or unified set of characteristics. Such an approach enables detailed, independent investigation of specific aspects of the design method with targeted, small-scale examples as well as broader investigation of important interactions and other system-level issues with holistic, all-encompassing examples. Table 2 includes a sample list of design problem characteristics for which the RTPDEM is intended and indicates the subset of characteristics shared by each of three example problems used to validate the RTPDEM. It is extremely important for each example to fulfill a role in the validation process that is not fulfilled by other example problems. Otherwise, efforts are simply duplicated, and the example should be discarded. Conversely, if one or more of the critical characteristics of the design problems (for which the method is intended) are missing from the example problems, it is important to identify additional examples or to expand one or more of the planned examples to include the missing characteristics.

TABLE 2 –Design Capabilities Demonstrated in Each Example, Seepersad, 2004 [16]

	<u>EXAMPLE 1</u>	<u>EXAMPLE 2</u>	<u>EXAMPLE 3</u>
	STRUCTURAL HEAT EXCHANGER	ROBUST STRUCTURAL MATERIALS	COMBUSTOR LINERS
MULTIFUNCTIONAL DESIGN EXPLORATION			
SINGLE DOMAIN	✓	✓	
MULTIPLE DOMAINS	✓		✓
DISTRIBUTED MULTIFUNCTIONAL SYNTHESIS	✓		✓
ROBUST DESIGN EXPLORATION			
VARIATION IN CONTROL FACTORS		✓	✓
VARIATION IN TOPOLOGY		✓	✓
VARIATION IN MATERIAL PROPERTIES		✓	
VARIATION IN OPERATING CONDITIONS			✓
ROBUST DESIGN METHODS TO SUPPORT DISTRIBUTED, MULTIFUNCTIONAL DESIGN			✓
TOPOLOGY DESIGN			
STRUCTURAL		✓	

MULTIFUNCTIONAL (STRUCTURAL AND THERMAL)			✓
COUPLED WITH ROBUST DESIGN METHODS		✓	✓
DISTRIBUTED			✓

The next step involves documenting that the data from the examples can be used to support conclusions with respect to the performance of the design methods. One aspect of this task is to determine whether the example problems represent *actual* problems for which the design method is intended. Simplifying assumptions are made in any design example with respect to the quantity of data, the number and type of variables, the extent to which broader aspects of the system are considered, and many other characteristics. The investigator should document the simplifying assumptions embedded in the example problems and confirm that the assumptions will not affect his/her ability to draw conclusions from the example. For example, when making assumptions, an investigator must not simplify away a critical characteristic for which the design method is intended. A second aspect of this task is documenting that each example will yield qualitative and/or quantitative data that can be compared, contrasted, and otherwise processed to evaluate the performance of the proposed design method.

3.3 Empirical (Domain-Specific) Performance Validation

Empirical (Domain-Specific) Performance Validity involves building confidence in the usefulness of a method using example problems and case studies. Representative example problems are used to evaluate the results of applying the design method in terms of the outcome- and process-related design method requirements documented in the Theoretical (Domain-Independent) Structural Validation phase. For example, one of the outcome-related design method requirements for the RTPDEM is the exploration and generation of families of designs

that exhibit ranges of multifunctional performance tradeoffs. The RTPDEM is used to generate the family of cellular material designs illustrated in Figure 6. The designs are intended to serve as structural heat exchangers and balance thermal and structural performance, as illustrated on the horizontal and vertical chart axes, respectively.

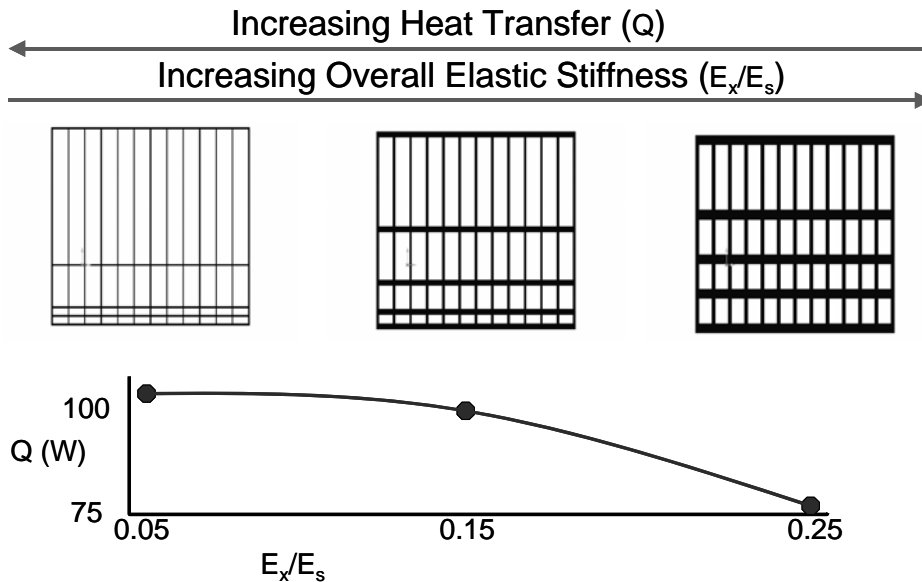


Figure 6 – Sample Multifunctional Designs Generated with the RTPDEM
Seepersad, 2004 [16]

It is also important to establish that the resulting usefulness is, in fact, a result of applying the method. For example, solutions obtained with and without the construct/method can be compared and/or the contribution of each element of the method can be evaluated in turn. When validating the RTPDEM, the multifunctional performance of the designs illustrated in Figure 6 is compared with those generated with conventional, single-objective optimization techniques and with ad-hoc designs that are generated using engineering intuition without the benefit of systematic design methods or search techniques. The objective of the comparisons is to determine whether utilizing the RTPDEM actually improves the robustness and/or multifunctional performance or provides an improved balance between multifunctional objectives

compared with single-objective or ad-hoc designs. Also, important performance measures of parametrically tailored materials are compared with the same measures for parametrically *and topologically* tailored materials and for materials designed with robustness considerations to gauge the impact of each aspect of the RTPDEM.

An important part of empirical (domain-specific) performance validity is careful review of the data used to support any conclusions. This involves establishing the accuracy, internal consistency, and quality of the data. For example, in optimization exercises, multiple starting points, active constraints and goals, and convergence can be documented to verify that the solution is stationary and robust. In Figure 7, a sample convergence plot is illustrated for the RTPDEM for one of the designs in Figure 6.

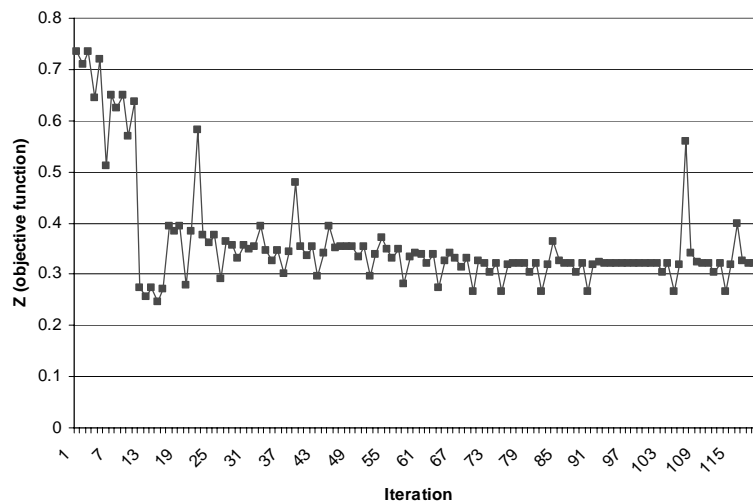


Figure 7 – Sample Convergence Plot for a Trial Run of the RTPDEM, Seepersad, 2004 [16]

If computational models are required for the examples, it is important to verify that data obtained from the models accurately represents aspects of the problem relevant to the design method being tested. Data or results from the models should be compared with experimental data, well-established theoretical results, or more comprehensive computational models. A

sample comparison between a fast, approximate thermal finite element model (utilized in a thermal application of the RTPDEM) and detailed FLUENT results for three different heat source temperatures is illustrated in Figure 8. Based on a comparison of the data, the model should be observed to react to inputs in an expected manner or in the same way that an actual system would react. A similar step is performed for the design method and its constituent constructs in the Theoretical (Domain-Independent) Structural Validation phase; here it is performed for the computational models and data needed for the specific example problem(s).

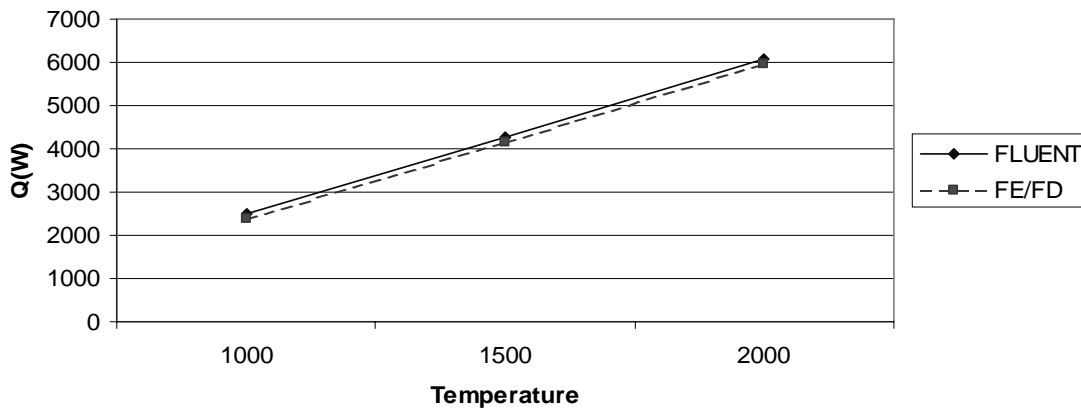


Figure 8 – A Comparison between Fast Finite Element (FE/FD) and Detailed FLUENT Heat Transfer (Q) Predictions for a Range of Heat Source Temperatures Seepersad, 2004 [16]

3.4 Theoretical (Domain-Independent) Performance Validation

Theoretical (Domain-Independent) Performance Validation involves building confidence in the generality of the method and accepting that the method is useful beyond the example problems. The first step is to revisit the intended domain of application established in other validation phases. The characteristics of the application domain are enumerated as part of Theoretical (Domain-Independent) Structural Validation and used to evaluate the appropriateness of the example problems as part of Empirical (Domain-Specific) Structural Validation. The

investigator can argue logically that the design method is useful for examples with the *precise* characteristics of the example problems used to validate the design method. An intuitive argument must be made that the design method is useful for a *more general* class of problems. The investigator should use his/her judgment and experience with the examples to clearly indicate the characteristics that a design problem *should* have and those it *should not* have in order to be eligible for utilization of the design method. At this stage, it is appropriate to list design problem characteristics and conditions for which the design method *may* be applicable but have not been explicitly tested; extending the design method and establishing its capabilities for these applications represent opportunities for future work. For example, using design problem examples, the usefulness of the RTPDEM is demonstrated for thermal and structural functional domains and for problems with observed variations in dimensions and topology. Further work is required to extend it to other functional domains and other sources of variation such as boundary conditions and material properties.

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 3.

Table 3
A New View of Knowledge Validation

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 9. 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.

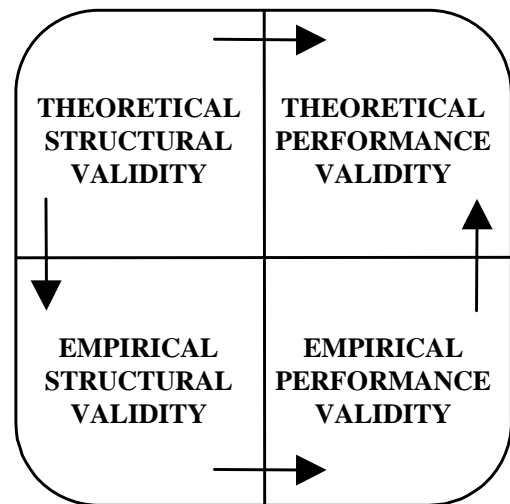


Figure 9
The Validation Square

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.

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!

ACKNOWLEDGMENTS

How should a proposed design method be validated? In our laboratory, this question was first addressed by Jon Shupe in his dissertation (PhD 1998, [19]). Warren Smith (PhD 1992 [20]), Reid Bailey (MS 1997 [21]), Jesse Peplinski (PhD 1997 [22]), Jan Emblemståg (PhD 1999 [23]), Kjartan Pedersen (PhD 1999 [24]), Reid Bailey (PhD 2000 [25]), and Carolyn Conner Seepersad (PhD 2004 [16]) all have added to the answer that we present in this chapter.

We acknowledge George Hazelrigg for putting the question *vis a vis* validation of a proposed design method to the design research community. This provided the impetus for us to provide an initial response at the ASME Design Theory and Methodology Conference in 2000.

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APPENDIX

Characteristics of Well-Written MS Theses and PhD Dissertations in Design

Farrokh Mistree

Each academic unit has a different vision of itself and the standards it sets for itself. Within an academic unit there is a diversity of opinions *vis a vis* expectations and standards. Over the years, I have observed that there is a vast difference in expectations *vis a vis* what constitutes a MS thesis. At some institutions the MS thesis involves undertaking a project and the outcome is a tad more than a term paper. At other institutions, a MS thesis is substantial. I belong to the latter category.

What is the difference between a doctoral dissertation and a MS thesis?

I expect both to be well-written and have value. The value may differ. I expect something new to emerge from a doctoral dissertation or a new interpretation given to existing data. For a MS thesis I am comfortable with a problem being solved and well-documented. Although a student may solve an industrial problem as part of the MS work, the problem must be set in a scholarly context – preferably with an explanation of the intellectual context of the problem, critical review of the literature, and thorough verification/validation of the work performed.

I recognize that there is a difference between research and development. I expect this distinction to be respected both in a MS thesis and a PhD dissertation. Finally, I expect students to have learned how to identify, formulate and resolve problems associated with research / development. I have seen some doctoral dissertations, particularly in design, where the dissertation is essentially a lot more of the same – a person is being given a doctorate for 5 years (instead of 2) of work of master’s level work and there is no contribution to advancing knowledge.

Characteristics of a HIGH quality MS thesis / Doctoral Dissertation

Content / Value: Foundation material for one or more conference papers / one paper in a quality journal is embodied in the thesis.

Framing the thesis: The question to be investigated is substantiated by the review and the question is framed appropriately within the context of the state-of-art or state-of-practice. There is a scholarly review of the literature. Commentary on the literature reviewed is insightful and is anchored in cited papers. A commentary that exemplifies the need to pursue a particular line of investigation is expected. The research question / or the question that is foundational to development is clearly articulated and is anchored in the critical review of the literature.

Development of theme: Presentation of the “story” in a manner that is connected, logical, and consistent.

Explanations: There needs to be cross-referencing between chapters and also between sections in a chapter. My comments pertaining to “standalone” chapters read “put in

context of preceding” or “put in context of research question” or “dies”. Text needs to bring figures alive; figures with limited related text result in comments from me such as “talk to figure.” Text without figures result in comments from me such as “cannot visualize.” A Table of Contents that when read “tells a story” of how the story is told in this thesis. Poor Tables of Content elicit comments from me such as “particularize title,” “jumps”, “disconnected”, “dies.”

Body: A systematic, logical, connected progression towards answering the research question / development question.

Verification and validation: This is a weak spot in both MS theses and PhD dissertations in design. Typically, a method is proposed and example problem is solved and conclusions are drawn. Solving one or two examples does not, in my opinion, allow one to claim that the method has been verified. At a minimum I expect key assumptions, limitations and ramifications to be spelled out. I expect a clear statement of why each of the examples has been chosen and what is being verified through the exercise of each these examples. I expect a clear statement as to why the results are right and argumentation to support claims / conclusions.

Closure: Claims at the end of the thesis must be consistent with what has been stated in the abstract and introduction and what is supported by the material presented in the text. Commentary associated with closing the loop between that which was promised and delivered must be included. I expect comments on next logical steps to be taken with this project; these need to be warranted by what is presented in the text.

References: The citations must be complete and accurate. The format must be self-consistent within each category (e.g., journal articles, chapters in books, books, articles in conference proceedings, etc.). I expect the names of all authors to be included and that the style is consistent; not first names for some and only initials for others.

Appendices: These must be self-contained and add value at the point where referenced in the text. An appendix is not a place to dump a solitary figure or table.

Nomenclature / glossary: Included on an as needed basis.

Acknowledgment: Credit must be given to all those who assisted and financial sources. If students work together to produce more substantial results than either one alone could produce then, an acknowledgement of collaboration and a clear discussion of the relationship between the projects is expected in the thesis.

Grammar and punctuation: I expect my students to be educated not just trained. I look for correct spelling and the correct use of words. Some common mistakes: principle / principal, method / methodology, example / case study, etc. Correct use of mathematical symbols: For example, there is a difference significant difference between \leq and $<$. I expect students not to use active verbs when inanimate objects are the subject, e.g., figures do not show anything. I expect to see a key word / key phrase being used consistently throughout the thesis; minimize the use of different words to refer to the same thing. For example, if a distinction has been made between a “design problem” and an “optimization problem” I expect the right phrase to be used at the right place. If there is no distinction between the two phrases then I expect use of one or the other.

Personality: The technical / academic personality of the author is discernable through his / her writing. In a high quality thesis I become aware of a student's curiosity, willingness to pursue leads, willingness to take risks, attention to detail, ability to frame questions and draw conclusions, spark, broader contexts, etc.