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Advancing Design Research: A "Big-D" Design Perspective

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Abstract: Advances in design research representations and models are needed as the interfaces between disciplines in design become blurred and overlapping, and as design encompasses more and more complex systems. A conceptual framework known as "Big-D" Design, as coined by Singapore's newest national university (the Singapore University of Technology and Design or SUTD), may provide a meaningful and useful context for advancing design research. This paper is an initial examination of the implications for scientific design research on using this particular framework. As part of the analysis, the paper proposes a simplified decomposition of the broader concept in order to explore potential variation within this framework. It is found that many research objectives are better investigated when the broader design field is studied than in a singular category or domain of design. The paper concludes by recommending aggressive attempts to (1) arrive at a coherent set of terminology and research methodologies relative to design research that extend over at least all of technologically-enabled design and (2) perform epistemological and ontological studies of the relationship of engineering science and technologically-enabled design science as there is more overlap between them than is generally recognized.

Keyword: Design Research, technologically-intensive design, heuristics, principles, design theory

1 Introduction

A novel concept central to future innovation economies and the fields of engineering and architecture is "Big-D Design. As created by and used as a vision for Singapore's newest national university (the Singapore University of Technology and Design or SUTD), ***"Big-D Design"*** *includes all technologically-intensive design, from architectural design to product design, software design, and systems design. It is design through conception, development, prototyping, manufacturing, operation, maintenance, recycling, and reuse – the full value chain. It includes an understanding and integration of the liberal arts,*

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humanities, and social sciences. In short, Big-D encompasses the art and science of design; for more information about the university and its concepts, see references [1,2].

The authors are all associated with the SUTD-MIT International Design Center which is metaphorically seen as the cardiovascular system of SUTD. Our research agenda aims to extend Big-D Design science and Big D Design practice through new methods, theories, principles, heuristics, pedagogy, technologies, processes, and the development of leaders in Design. This paper explores the implications on ours and any design research agenda of taking a Big-D Design perspective. Three elements of this Design perspective and the nature of the questions they lead to about design research are:

1. All technologically-enabled design: what are the advantages and disadvantages of committing to research across this breadth of fields?
2. Full Value Chain: What are the benefits and potential pitfalls of engaging the full value chain in Design research?
3. Art *and* Science of Design: Does design research entail both of these? Must it?

In order to adequately address these questions, we examine prior design research and establish criteria we are using in this examination. Our criteria are twofold: the first is to continue building a cumulative research enterprise around design so that future research builds upon a reliable base and has continually more impact on Big D Design research communities, and Big D Design education. The second criterion, which we consider equally important, is to impact design practice favorably, in new and exciting ways. Research results can impact practice favorably by development of new methods, theories, guidelines, heuristics and principles that when applied directly lead to superior results for practicing engineers and teams. Design research output can also favorably impact practice through results that point to superior education methods that can involve better basic knowledge structure to support design and better exposure to methods and experiences that are effective in design practice.

The next three sections of the paper examine, in order of the questions, each of the three aspects of the Design perspective introduced here. Each section considers the potential advantages and disadvantages based upon the criteria discussed in the preceding paragraph, relying upon examination of a wide range of design research and education literature. The final section (Section 5) draws together the separate elements in the other sections examining interactions among the three separate aspects of Big D Design. This section also discusses the relationship of “Design Science” with “Engineering Science.” It is acknowledged that when exploring Big-D Design Science, there is much overlap with engineering science.

2 All Technologically –enabled Design

The first aspect of Big D design is that it includes “All” technologically-enabled design; thus question 1 asks what are the advantages and disadvantages of committing to research across this breadth of fields. To address this question, it is necessary to define what is not in Big D Design following this definition and also about alternative ways to categorize the domains that are contained within Big D Design. This construct for design, although broad, does not envelope fields that are focused on aesthetics as the primary or exclusive criterion. It does not include design of visual art such as sculptures or paintings, or design of music or poetry, but does include technologically-enabled fields with a high aesthetic content such as architecture or product design. There are some fuzzy boundaries to any definition, but for our purposes debating specific cases is not important to our overall agenda. Design as used in the Big-D context is broad but does not include all activities that are legitimately called design.

In order to examine what might be gained or lost as one performs design research in the "Big D" perspective, it is useful to consider how one might establish categories included within Big D Design. Categories are desired that connect naturally with cognition and the cognitive science that pervades design as a process, methods, and science. Since "Big D" Design includes all engineering design and architecture, one approach is to think about design across all "typical" departments in an engineering school plus architecture. Such a listing is shown in the first column in Table 1. A second approach shown in the second column in Table 1 comes from a paper by Purao et al. (2008) [3] which reports on a workshop where a significant attempt was made to have presentations across a wide array of design domains. The domains listed are those describing the presentation disciplines at the workshop. We note only modest overlap between the lists in the first two columns of Table 1 but believe *both* are fully within "Big D" Design. The listing in the paper by Purao et al. –even though resulting from an attempt to encourage and obtain very broad design input- was organized by a MIS (Management Information Systems) group and many of the disciplines are from the area where management and engineering overlap- an area labeled systems socio-technical engineering in column 1. Interestingly, this field is one not stabilized within typical university engineering schools.

Table 1 Categorizations within "Big D" Design

Typical University Departments	Disciplines listed in [1], Purao et al. (2008)	Simplified categorization suggested here
Aerospace engineering Architecture	Computer science	Software (Algorithm and Program) Design
Biological engineering Chemical engineering Civil engineering Computer (software) engineering and science	Environmental design Human Computer Interaction Informatics	Electromechanical-architectural Artifacts and Systems Design
Electrical engineering Engineering mechanics	Information sciences Information studies Information systems	Socio-economic-technical Systems Design
Environmental engineering Industrial Engineering Materials engineering and science Mechanical engineering Nuclear engineering Systems and socio-technical engineering	Management science Production and management Software engineering	Materials and Molecular-level Design

Although there is not uniformity in choices of departments or names within all universities, the listing in the first column of Table 1 is the most objectively defined partly because accrediting boards and fields of practice dictate some level of uniformity in names and content. This stability is an argument for exploring question 1 using this list. However, taxonomy criteria (and we are in fact discussing taxonomy for technologically-enabled design) more importantly express the desirability for internally homogenous categories and for the entire taxonomy to be collectively exhaustive and mutually exclusive.

In our attempt to answer question 1, we want to know if homogeneous, mutually exclusive categories are strong enough to support a set of homogeneous principles or heuristics about design. In reality, categorization attempts rarely arrive at homogeneous, mutually exclusive categories in a collectively exhaustive set, but it is our judgment that the first two columns of Table 1 fail badly enough to make further analysis using either approach potentially meaningless. Column 2 is clearly not collectively exhaustive based upon cursory analysis of design research in an engineering school within a typical university. Because specific university engineering departments engage in a broad variety of types of design and typically have overlap in each type, the organizing approach in column 1 misses badly on mutual exclusivity and internal homogeneity. Consider, for example, software engineering that is carried out in nuclear engineering, aerospace engineering, civil engineering and in other places beyond computer engineering or science in a typical engineering school. Similarly diverse placement of materials invention, systems engineering, structural engineering, fluid dynamics, and others indicate that to consider design in any one engineering field could verge on equivalence to studying it across all of “Big D” Design. Thus decomposition to categories at the university department level –while useful for other purposes- does not seem useful to analysis of design research. Perhaps a consolidation or purification of these fields can yield categories more useful to our needs.

Thus, a further attempt to develop categories within technologically-intensive design is undertaken. Technologically-intensive design is a very broad term covering many types and types of design output. To name just a few specific examples, the act and output of such design includes halogen light bulbs, a personal water purification device for developing countries, LED lighting, improved supercapacitors, nano-materials for water purification, a new soccer robot, a new military aircraft, software for controlling air flow in a large building, a new large--scale building, the Internet, and the road system in a large city. Depending upon the specifics of the typology one might think about, it might be possible to define hundreds if not thousands of technologically-intensive design domains. For example, the US patent system has more than 400 classes of patents in its highest classification category and more than 200,000 in its most granular categorization. One must recognize that each of these hundreds and even thousands of “domains” in fact has unique characteristics that might affect how design is performed. Specifying these characteristics (or especially trying to teach or carry out research in a cohesive fashion) for hundreds or even thousands of design fields is not especially feasible and certainly not very useful.

For the purpose of condensation for this paper, our reading of the design literature-particularly the references given in the next subsections, our experience with specific examples of design we have pursued, and our discussions with a variety of technologically-intensive designers, is synthesized to suggest four prototypical classes. These categories are our attempt to capture the breadth of the field, while designating classes likely to contain similar design fundamentals and methods. In other words, it is our judgment that these classes represent some of the most important differences likely to have effect in terms of advancing research fields and performing design. The third column of Table 1 gives the following names to these four classes:

- Software (algorithm and program) design;
- Electromechanical-architectural artifacts and systems design;
- Socio-economic-technical system design; and
- Materials and molecular-level design.

We now briefly discuss each of these classes in order to summarize what the literature analysis suggests is homogeneous in each category. The brief descriptions also are meant to support our contention that these four classes are to a large degree mutually exclusive. It is also clear that no simple set represents a perfect decomposition of "Big D" Design, but these four are more useful to us than any identified alternative in considering question 1. Since we are attempting to include all technologically-intensive design within the four categories, we are using the terms more broadly than may be customary for most readers.

2.1 Software algorithms and program Design

Software design relates to the digital and not the material world, where the output of this category of design are programs, or software systems, that accomplish many different functions and have a range of sizes (usually characterized by lines of code even as all recognize the imperfections of the metric). In cases where control software is highly integrated with physical artifacts, there exists a clear connection with our next class (electromechanical-architectural artifact and system design). For very large scale software systems where the software, hardware and the users are tightly coupled (for example, an air traffic control system), we consider such design problems to be contained in our third category (socio-economic-technical system design). Thus, the category we discuss here is for relatively pure software but the descriptions connect, interact, and apply to software subsystems in our other categories.

Software design is relatively new as a practice domain but nonetheless has received a large amount of attention academically [4-10][1]. Pressman [4] has summarized the "evolution of software design" as an ongoing process that has spanned four (and now more) decades which early on concentrated on modular programs and methods for refining software structures in a top-down manner. Later work proposed methods for translation of data flow or data structure into a design definition. In the 90s (and beyond) emphasis was on an object-oriented approach to design derivation. Software architecture and design patterns have also recently received emphasis in software design. Abstraction, complexity and re-use are also fundamental concerns in software design whereas the basic knowledge needed by designers in this category centers on discrete mathematics. Representation and possibly cognitive differences between this category of design and others have not been demonstrated but would be interesting to pursue.

2.2 Electromechanical-architectural artifacts and systems Design

Electromechanical-architectural artifact and system design produces output that is generally the most visible and tangible of our four categories. As used in this paper, it includes almost all of what are commonly called products (e.g., automobiles, home appliances and furnishing, PCs, cell phones, cameras, etc.) and extends in scale and function beyond what is usually referred to as "products" to include boats, air conditioning systems, elevators, cranes, houses, buildings, locomotives, etc. In our definition, even quite large artifacts such as airplanes, electric power generation turbines

[1] These references are only a modest fraction of the books in this general area.

and plants, aircraft carriers and large buildings are included in this category. When these large scale systems include a large social, economic and human-enterprise component, they can be categorized within the third category (socio-economic-technical systems).

In our definition, human-designed physical systems that process energy are also classified as electromechanical artifacts. Thus the output of this category includes much of the human-made physical world. Possibly because of the visibility and prevalence of its output, much popular and academic thinking equates this category with the totality of what is meant by technologically-intensive design. However, Design, as defined within the Big-D Design concept and at SUTD, recognizes a much broader domain of technologically-intensive design, so we do not restrict "Big D" Design to this category. Two important sub-fields in the electromechanical-architectural design field tend to, in most instances, even more narrowly define design, using the term to focus on the actual kind of design they do: those sub-fields are industrial design and architecture. These fields which are leading areas in key sub-fields of electromechanical-architectural artifacts and systems- for example, aesthetically and spatial sensitive electromechanical-architectural systems- deserve special attention.

Electromechanical-architectural artifacts and system design has - not surprisingly- resulted in a number of textbooks that are used in universities and by practitioners. References [11-25] give a small sample of the many diverse published books that treat this category of Big-D Design. Given the physical nature of these systems, consideration of space (geometry) is fundamental to electromechanical-architectural design. However, electromechanical-architectural design goes well beyond space considerations to include energy and information feedback. Due to the wide variety of designed objects, the fundamental topics of interest include function, materials, architecture and flexibility. The basic knowledge that underlies electromechanical-architectural design is centered, in part, on physics and mathematics. Practical knowledge in this domain often includes visual representation from sketching to complex 3D geometric representation systems, it also often includes knowledge of fabrication, materials and manufacturing of discrete products and it often includes deep knowledge of systems dynamics, modeling, making, and testing.

2.3 Socio-economic-technical system Design

Of the four categories we define for this study, historically, recognition of the concept of socio-economic-technical system design occurred latest. Although interest in large-scale technical systems with major social and economic impact has existed for a few decades [26,27], it is only more recently that such a category was recognized as critical in the world of design and needing to be addressed from an engineering/technical perspective [28-34]. The boundary between socio-economic-technical systems with both large-scale electromechanical-architectural systems and large scale software systems is the inclusion within the design problem of complex social elements. At times, technical designers leave these social aspects to others, such as those from management or policy fields. Only if such problems are considered as part of the design do we consider the example to be in the socio-economic-technical design category. Here are two specific examples which might shed light on our use of the term: (1) Some might consider design of an air-traffic control system as only concerned with the radar sensing system and the software; (2) The design of a corporate control and improvement system such as the Toyota Production System (TPS) has been considered by some to only include the protocols, plant layouts and technical heuristics. In our use of the term socio-economic-technical design, however, these two examples also include: (1) the personnel, organizational and communication problems (pilot to controller, controller to controller, pilot to pilot, controller to supervisor etc.) and (2) the problem-solving approach, the redesigned role of management, cooperative teams and personnel incentives. It is the nature of socio-economic-technical systems [28-30] that if the complete design effort is constrained within the purely technical domain, the system will be much less effective than it would otherwise be.

Socio-economic-technical system design thus has prominently among its concerns considerations of stakeholders, decision processes, protocols, and standards. Because of their large scale and typically societal importance, architecture, flexibility, sophisticated design processes such as systems engineering and re-use are also top concerns in design of such systems. Representation of various types including process flow, as well as sophisticated programs for requirements and stakeholders are generally associated with this category of design. Of the four categories we have proposed, socio-economic-technical system designers have the most need for fundamental understanding of operations research and social science approaches and theories.

2.4 Materials and molecular level design

Even though a relatively large fraction of technological progress [35-37] is due to design (invention and improvement) of materials and fabrication processes, there has been relatively little attention paid to materials design research and theory as a subject of enquiry. This lack of attention occurs despite (or perhaps because) materials and molecular level design predates even engineering and science as we know them. There have been a few papers describing the expanding knowledge that underlies particularly exciting new materials [38-40], but only Olson's contribution [40] contains significant attention to materials design in a broader sense. In many design textbooks [11-25], design *of* materials is not covered. In a few of these books [11, 14], design *with* materials is discussed including the introduction of Ashby diagrams [41] that systematize materials choice in a variety of design problems. However, choosing the best available material for a given application is ***not*** the focus of what we mean here by materials design. Instead materials design is the process of changing fundamental materials, processes, and processing parameters to create novel and useful materials. Examples of these include new nano-materials processing techniques for Li-ion batteries, vapor deposition of low band-gap semiconductors on Si for solar photovoltaic improvement, new thermoforming techniques for polymeric materials, and literally many hundreds of other specific novel useful materials and processes documented in the patent literature each year. In the solar PV field alone (about ½ of one of the 400 categories in the US patent database), there are about 75 "materials design" patents per year [42].

For consistency, we do not consider design of new materials systems such as large scale materials manufacturing systems or photovoltaic arrays to be materials design, but instead categorize these in either socio-economic-technical or electromechanical-architectural system design. Thus, our definition of materials design positions itself at the relatively small end of a dimensional scale. Perhaps most importantly, materials design always is intimately involved with processing (fabrication of the material). Olsen (40) and others (35) are clear that when materials designers undertake their creative steps, processing can come first: concurrent consideration of making and creating is not a new procedure for materials and molecular level designers. Materials are used as important elements in other artifacts and systems so materials design often aims at improving properties that are known to be important rather than directly aiming to improve an end user function. The fundamental knowledge important to materials and molecular design includes physics, biology, and chemistry at multiple scales; important practical knowledge includes deep and broad knowledge of material processing approaches and understanding of functional requirements that link to properties of various kinds.

2.5 Design Research from narrower or wider perspectives

The fundamental knowledge and approaches used by the four categories of technologically-intensive designers have clear differences even in the brief discussions just presented. In addition, it seems quite reasonable to expect some cognitive processing differences even though this subject has not yet been researched. Thus, there is significant and strong rationale for conducting much design research within such domains and in even finer categories where specific methods and approaches might have value. The benefits from a narrower focus can be consideration of specific important problems (for example, flexibility –see [29, 44, 45] or very specific design methods (for example, objects that transform as part of their function- see [45]). Is there any evidence for value in research from broader perspectives? In fact, there is much work that has produced valuable output while taking a very broad view of design. Indeed, two of the most cited and most important contributors to a cumulative design research agenda are H. Simon (46) and D. Schön (47). Both of these "founding fathers" of design research considered design quite broadly. Based upon their work, the benefits from a broad agenda are deeper insights, improved generalizability and improved capacity for differentiating fundamental from contingent aspects of design.

We also used two other approaches for input to answering the first of our questions. The first additional approach was to review 56 design papers relative to differences in "Type of Theory" from publications in different design domains. The theory typology (or taxonomy) that we followed is from Gregor [48, 49] who considers Information Systems design but argues for looking at design broadly. Table 2 shows Gregor's taxonomy and Table 3 shows the distribution of theory types as a function of papers that are predominantly in the differing design domains shown. Class IV of Gregor's taxonomy is the theory type that is most consistent with the establishment of a cumulative research agenda for design. It is important that our classification of the reviewed papers shows a significant fraction in this theory type and that those papers appear in all the different design categories. Further research will extend this analysis and seek causality connections and implications on cumulative Design theory.

Table 2 A Taxonomy of theory in information systems research after Gregor [45]

Theory Type	Distinguishing Attributes
I. Analysis	Concerns what is.
	The theory does not extend beyond analysis and description. No casual relationships among phenomena are specified and no predictions are made.
II. Explanation	Concerns what is, how, why, when, and where.
	The theory provides explanations but does not aim to predict with any precision. There are no testable propositions.
III. Prediction	Concerns what is and what will be.
	The theory provides predictions and has testable propositions but does not have well-developed justificatory causal explanations.
IV. Explanation and prediction	Concerns what is, how, why, when, where and what will be.
	Provides predictions and has both testable propositions and causal explanations
V. Design and action	Concerns what and how to do something.
	The theory gives explicit prescriptions (e.g., methods, techniques, principles of form and function) for constructing an systems, artifact (product), or process.

In addition to examining theory type distributions, we also briefly examined design principles that have resulted from design research. In the spirit of design science, much research and writing on design attempts to identify principles that can be used beyond single cases. In some instances, these are called heuristics or guidelines [94] and axioms [95]. In other cases [96, 97], researchers attempt to describe overall systems of interlinked principles for invention (such systems are of potential relevance here since the most novel design outputs are inventions).

Table 3 Theory type distribution of analyzed papers (references are papers analyzed)

Theory type	Materials and molecular-level design [338-40, 50-55]	Electromechanical-architectural artifacts and systems design [43-45, 56-85]	Software (Algorithms and Program) Design [86-92	Socio-economic-technical systems design [28,37, 92-96]	TOTAL
Analyze	1	8	2	2	13
Explain	0	4	1	1	6
Predict	0	2	0	0	2
Explain, predict	6	10	2	4	24
Action, design	2	9	2	0	11

Much of the work on design principles and heuristics has been carried out within a particular design context. For two examples, we consider the 180 plus heuristics given in Rechtin and Maier's book [97] and the 201 principles discussed by Davis [101]. In the former case, the principles are clearly framed in terms of design of classes of large-scale complex technical (and socio-economic-technical) systems, while in the latter case the principles are intended to guide software development. Analyzing these carefully, one can identify a number that have wider applicability but some –not surprisingly- are clearly not relevant in other domains. Specific examples from each study –two that have potentially general interest across domains (G) and one too narrow to be general (S) are:

- Rechtin and Maier (G): The first line of defense against complexity is simplicity of design;
- Rechtin and Maier (G): You can't avoid **redesign**. It's a natural part of design;
- Rechtin and Maier (S): If social cooperation is required, the **way** in which a system is **implemented** and introduced must be an **integral part** of its architecture;
- Davis (G): The design process should not suffer from "tunnel vision;"
- Davis (G): The design should be structured to degrade gently, even when aberrant data, events or operating conditions are encountered; and
- Davis (S): The design should "minimize the intellectual distance" between the software and the problem as it exists in the real world.

Similar to these examples, most principles of design are framed within a limited context and are often judged to be useful and instructive within that context. Most research papers published –dissimilar to the textbooks just discussed- specify principles only for the intended problem and domain (examples are [42-45]). There are clear overlaps with principles between the two texts just reviewed sometimes with quite similar and sometimes dissimilar terminology (decomposition, integration, function and customer concerns are obvious ones that arise). Thus, it is worth exploring if a good starting point to examine design principles from a Big-D Design perspective already exists. As far as the authors are aware, only two attempts have been made to define general design principles and these will be considered next.

The first is the work done by Nam Suh and described in his book *The Principles of Design* [98]. The book--as opposed to the references noted in the preceding paragraphs--does not list a large number of principles or heuristics; instead it focuses on a very small number of what the book terms axioms. In fact, the two key "axioms" are the independence axiom (each functional requirement should be independent of other functional requirements) and the information axiom (among the designs that satisfy the independence axiom, the design that has the smallest information content is the best design). Suh's work in this book and other writings [67] uses these two axioms to "derive" larger numbers of theories and corollaries. On one hand, the independence concept is fairly widely applicable to thinking about designs across our full range of design domains. On the other hand- despite the terminology- the basic axioms are not as fundamental as this mathematical terminology implies. Indeed, while independence has a number of advantages, many designs that do *not* follow it are superior to alternatives that do. In this sense, it is much like the other "principles and heuristics" that have been postulated and is not in any sense truly axiomatic. The derived theories and corollaries are similar principles that can be seen as implications of the two major principles (independence and information). The strength of "axiomatic" design is that the principles apparently have wider application than others. In addition, there have been a number of conferences and workshops held on axiomatic design and some use in industry; however, at the present time this is not a fully developed set of principles for use across all Design.

The second effort that apparently attempts to develop generally applicable design principles is the work initiated by Altshuller [100,101] in the 1940s and still actively pursued today. This work, known both by its Russian acronym (TRIZ) and by English terminology (Theory of Inventive Problem Solving or TIPS), has its empirical basis in study and classification of patents. Four different aspects of TRIZ include:

1. TRIZ identifies eight "laws" of technical systems evolution which are useful in predicting the nature of desired future design changes;
2. TRIZ identifies thousands of "effects" that are characterized as domain independent;
3. TRIZ identifies 40 design "principles" for resolving contradictions (TRIZ hypothesizes that contradictions in existing solutions are the major way to specify inventive opportunities for the future);
4. TRIZ identifies ~ 75 "standard solutions" that deal with identified problems.

The translation of TRIZ to "Big D" Design is challenging because the TRIZ literature does not discuss the breadth of applicability and tends to not recognize what aspects of "technologically-intensive design" that it may be neglecting. Moreover, most of the examples shown in the literature are from the electromechanical-architectural design field which may be a result of the background of practitioners and supporters of TRIZ.

The TRIZ laws of evolution are largely descriptive and some may seem difficult to make operational. For example, evolutionary law number 2 ("increasing ideality") simply says that output per resource increases over time. This is better stated by the exponential improvements seen in various output per resource as first documented by Moore [102] and now known to be much more general [103,104]. Nonetheless, many of the design principles appear quite general and can be imagined to apply across all "Big D" Design domains. For example, principle number 13 "the other way around" suggests the powerful heuristic to examine the problem in a reverse (or with the inside out or in different temporal order or). However, many principles appear to be more limited in their application across domains (examples include #7 "Nesting", #8 "counterweight", #18 "Mechanical vibration", #28 "Replacement of a mechanical system", #29 "pneumatic or hydraulic construction", #32 "Changing the Color", #35 "transformation of the chemical or physical states of an object", #37 "Thermal expansion"). Although these apparent limitations may relate to terminology and translation from the theory's source language, research and advancement of TRIZ are needed to understand this system's application for all technologically-intensive design.

Recognizing exceptions such as the relatively general #13, neither the TRIZ principles nor the solutions appear to have direct application to software or socio-technical design –perhaps because of the scarcity of such solutions in the patent database that underlies the approach. It is also not clear how well the approach covers materials design despite its prevalence in the patent database. The principles with clear materials content are about materials change or substitution, not about inventing new materials (as examples, #30 "Flexible membranes or thin films" and #31 "Use of porous materials"). Thus, despite some uptake in practice and ongoing documented work [105], TRIZ is also not a fully developed set of Big-D Design principles.

Overall, based upon this preliminary analysis, it appears that sets of broadly applicable design principles are potentially derivable which gives tentative support for a positive answer to question 1. However, the current general approaches do not seem adequate. From the commonality seen in the lists examined, one infers that by some work an overall listing might be developed giving principles in an organized framework but doing this (or even proving its value) will require significant additional work.

3 The Full Value Chain

Question 2 in the first section asks: What are the benefits and potential harm of engaging the full value chain in design research? There are clear practice benefits from considering the full value chain in design as the extensive practice-oriented work done on concurrent engineering signals. There are also clear educational benefits both from a leadership education and understanding design in context viewpoint. Thus, from a university such as SUTD, there is great value in defining design as broadly across the value chain as it does. However, from a research perspective, there may be only a few research objectives that benefit from the wider lens- design for sustainability, value, manufacturability [106, 107] and other DFX areas are examples. Since the full value chain differs in the categories we consider (software does not have physical facilities or tools, materials processing is mostly continuous vs. the discrete product or system manufacturing in the other categories, the nature of customers, clients and stakeholders are different), Design for manufacturability research naturally occurs in narrower domains than ***all*** technologically-intensive Design. Based on these examples, care must be taken in understanding how to develop and engage in design research from the broader Big-D context in regard to the value chain.

4 Art *and* Science of Design

The question of interest in this section is whether design research must involve both the art and science of design. Our criteria for assessing design research state that such research must impact practice in order to be of value. Since the practice of design is essentially about creating something that has not previously existed, an irreducible element of art is involved in the practice of all technologically-intensive design. This conclusion combined with our criterion for research value and the fact that research is the process for developing new science dictates that all design research includes both the art and science of design.

While almost no-one would disagree with design practice having at least some artistic aspect, there are some [10] who object to a Science of Design (thereby implicitly or explicitly arguing that design research is not viable). This position seems indefensible given the progress that has been made in design research. In our study of design principles (Section 2), we find some principles that apply quite widely (modularity or independence of function) and much opportunity exists to explore others. Moreover, there is much more understanding of the importance of expertise [108] than there was when the cumulative design research agenda was initiated almost 50 years ago. Similarly, the importance of analogical transfer in design has been much more strongly established [109, 110] including some work [111] that points towards the best "knowledge structure" for enabling this process.

5 Concluding Remarks

Although we have chosen to discuss the three elements of "Big-D" Design separately (1-all domains of technologically-intensive design, 2-full value chain and 3-art/science combination), there are clear and important interactions among these dimensions. One example of the interconnectedness of these elements is that when research is performed that combines the art and science of design, valuable work has been done that examines design in essentially all domains [46, 47] as well as by looking at more specific problems within a domain [43-45]. A second example of the interactions among the elements is that when research is carried out on the full design value chain, more practical (or art content) is introduced as well as more scientific content [106]. A third example –among many that can be noted- is that as mentioned in Section 3, the full value chain has very different content in the different domains that we have described.

Our consideration of the impact of taking a "Big-D" perspective in design research has in all cases shown potential value for broader viewpoints while clearly avoiding any requirement to do so. A 2008 paper by Kuechler and Vaishnavi [93], that argues for broadening the scope of Information Systems Design Research (ISDR), criticizes ISDR for missing important contributions from the "designerly way of knowing" schools [112] and that the ISDR literature contains little in citations to design work outside ISDR. This is not apparently so in all design research domains, but a tendency to fragment might be working to overcome the early start by Simon and others in a broader way. In addition, there are valuable results in the literature that come from considering design beyond technologically-intensive domains. In regard to combining art (practice) and science (research), we have already argued that this is a natural outcome of carrying out research with one objective being to impact the practice of design favorably. However, we do not believe that all design research must involve designing something new as this would amount to the methodological straightjacket (elimination of valuable research projects) noted by Purao et al. [3]. Research on the art of design can uncover theory that is at least partly scientific, but this can be accomplished by a variety of methods beyond designing something new- for example by systematic study of much design output (empirical studies) [43, 141, 113] or by systematizing observed designer methods [59, 81].

Arguing as we have for a broader (technologically –enabled) perspective for much design research introduces two issues that can limit the value of the work. The first issue is one articulated well in Purao et al. [3] after participating in presentations and extensive discussion among the fields of design shown in the second column of Table 1; one participant said:

> "The lack of a common language constitutes a danger to the nascent design sciences. The danger is that our joint efforts will dissolve into incoherence, as exemplified by the myth of the ill-fated Tower of Babel."

Analyzing a wide variety of literature from across design research domains reinforces this point. As one example, many in software design consider design only the creative core of the process so design as used by them does not include specifying, coding or testing; whereas in most electromechanical-architectural design literature, design includes specifying and testing and often manufacturing. Multiplying this example by the many other words that are used quite differently shows that the Tower of Babel danger is real and present (even within domains there is surprising variety in terminology). Thus, one necessary step in pursuing a broader and effective design research agenda is a serious attempt to arrive at a more coherent terminology.

A second major issue in pursuing a research agenda across all technologically-intensive design is the epistemological relationship of such design research to "Engineering Science" –the reigning academic standard in engineering schools worldwide. There is extensive discussion in the design science literature about the epistemological relationship of design to natural science, and there is significant discussion of its relationship to the social sciences. However, there is almost none discussing the relationship of engineering science with technologically-intensive design science. This silence is almost surely related to the fact that the epistemological basis of engineering science has not been considered very deeply. In fact, the arguably best and perhaps only serious consideration of engineering science – Vincenti's 1990 book "What Engineers Know and How They Know it" [114] – does not use the term engineering science despite discussing knowledge that most engineering scientists would consider appropriate to the term. Most interestingly, the major conclusion by Vincenti appears to be that the difference in the science that engineers do compared with natural science, is that "[engineering] science" is fundamentally oriented to make the findings of natural science useful in *design*. Thus, one can probably consider "engineering science" and "design science" intertwined and one possibly a sub-set of the other. An aggressive attempt to clarify this relationship would have great value in setting an agenda for pursuing design research- particularly over the broad spectrum of "all technologically-enabled design."

As a conclusion to this paper, it is clear that we have only examined a small fraction of the issues and foundations needed to create a Big-D perspective of Design research. At the core of our analysis is an understanding of technologically-intensive design as categories, as the study, identification, formalism, and use of design principles and heuristics, as the full value chain, and inclusive of art and science. While the supporting literature of this paper generally supports this view, significantly more analysis is needed on this literature, in addition to integration with design research methodologies and other segments of the design research literature, including [115-124] and beyond.

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