TheATLAS

MODULE SERIES

TRANSDISCIPLINARY ENGINEERING & SCIENCE

FOUNDATIONS FOR A TRANSDISCIPLINARY APPROACH TO ENGINEERING SYSTEMS RESEARCH BASED ON DESIGN & PROCESS

Derrick Tate
Atila Ertas
Murat M. Tanik
Tim T. Maxwell

ISSN: 1933-5423

TAM-Vol.2-No.1, 2006

The Academy of Transdisciplinary Learning & Advanced Studies
TheATLAS Publications

TheATLAS Book Series on Transdisciplinary Engineering & Science

SERIES EDITOR-IN-CHIEF
A. ERTAS

TRANSDISCIPLINE: Integrating science and engineering principles

"...Today, complexity is a word that is much in fashion. We have learned very well that many of the systems that we are trying to deal with in our contemporary science and engineering are very complex indeed. They are so complex that it is not obvious that the powerful tricks and procedures that served us for four centuries or more in the development of modern science and engineering will enable us to understand and deal with them. We are learning that we need a science of complex systems, and we are beginning to construct it..."

Nobel Laureate Herbert A. Simon
Keynote Speech, 2000 IDPT Conference

TheATLAS Publishing

ISSN: 1933-5423

Published in the United States of America by

TheATLAS

www.theatlas.org

Abstract

Within many fields, such as medicine, biosciences, and cognitive science, there is growing awareness of the need for *transdisciplinary* approaches. Likewise, engineering education and research needs to be supplemented by a fundamentally new way of addressing the multidimensional, complex problems that society faces today. Because of the nature of modern engineering systems, traditional disciplinary approaches have proven inadequate, and researchers and educators are transcending traditional disciplinary boundaries to explore complementary approaches. In this paper the authors propose a framework for transdisciplinary education and research drawing upon the experience of implementing a graduate program over the past eight years, primarily, for the aerospace industry. Furthermore, the authors describe modern challenges in engineering system design and propose an approach to address them using the transdisciplinary framework presented. The paper also shows that design and process are fundamental to this transdisciplinary approach, presents an exemplar of a design tool that can be used in transdisciplinary engineering, and proposes further extension of this approach to education and research.

Keywords: transdisciplinary, design, process, axiomatic design, engineering systems.

1 Introduction

Having a fundamental understanding of engineering systems has become increasingly important as the pace of technological development has accelerated due to global collaboration and competition. Technology has driven changes in design and development processes for engineering systems. [1] Products have become integrated engineering systems, and design and production requirements cross disciplinary boundaries. This requires input from multiple disciplines within engineering as well as other disciplines outside of science and engineering, such as business, social sciences, medicine, etc. Knowledge from many disciplines must be integrated into an effective system or product—such as a transportation system based on hydrogen-fueled vehicles, a new space shuttle, or optical backplanes. As the pace of development of new technical systems has continued to accelerate, the need has shifted from interdisciplinary or multidisciplinary design teams to trans-organization, trans-national, or even trans-continent work.

The authors argue for the need of a transdisciplinary research and educational framework to address large-scale, modern engineering systems and to prepare the engineers, designers, and researchers of the future. Three critical attributes of this new system are:

- The clarification of theoretical issues involved in crossing disciplinary boundaries.
- The development of a more comprehensive understanding of large-scale problems.
- The integration of concepts and methods from other disciplines which share similar levels of analysis.[1]

This paper is structured as follows: Section 1 introduces the challenges faced in engineering systems and the need for a transdisciplinary approach to engineering systems. Section 2 shows inadequacies of current disciplinary approaches and defines the transdisciplinary program. Section 3 shows the application of the transdisciplinary approach to engineering education and research and draws an analogy with other fields such as biology and cognitive science. Section 4 presents a framework for transdisciplinary engineering based on design and process and shows that design and process are fundamental to transdisciplinary endeavors in engineering. Section 5 presents axiomatic design as an exemplary transdisciplinary tool to be used across engineering disciplines and presents an overview of results from a graduate-level Master's program that has been taught in the aerospace industry for the past eight years. Section 6 outlines the future work and challenges in creating a transdisciplinary science for engineering. Section 7 presents a summary and conclusions.

2 Challenges in engineering systems

During the last decade, the number of complex problems facing engineers has exploded, and the technical knowledge and understanding in science and engineering required to attack these problems is rapidly evolving. A few examples are the groundbreaking advancements in semiconductor and software technologies, the bio-sciences, and nanotechnology.

The last two decades of designing large-scale engineering systems taught us that neither mono-disciplinary nor inter- or multi-disciplinary approaches provide an environment that promotes the collaboration and synthesis necessary to extend beyond existing disciplinary boundaries and produce truly creative and innovative solutions to large-scale, complex problems.

2.1 Need for transdisciplinary approach

If the history of science is a guide, technological innovations have often preceded and led to the establishment of new scientific fields. [2] Today, attempts to design modern engineering systems create the need for a "transdisciplinary" model for

[1] For example, the fields of pharmacology, brain imaging, and neuroscience share a bio–behavioral perspective (focusing on phenomena at molecular, cellular, and organismic levels).

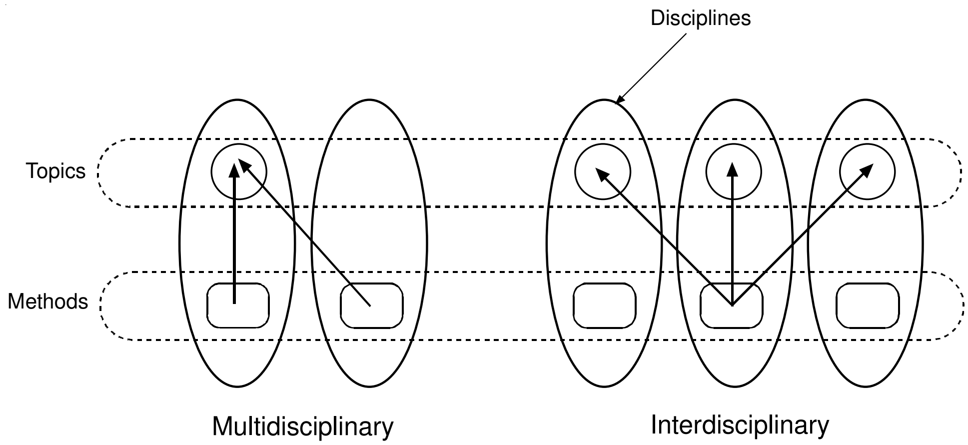

Figure 1. Distinction between multidisciplinary and interdisciplinary work. A multidisciplinary approach uses methods from two or more disciplines to examine a common topic while interdisciplinary work involves the application of a method from one discipline to topics studied by other disciplines.

education and research that can transcend traditional disciplinary or organizational boundaries to enable the solution of large problems by teams of people from diverse backgrounds. [3]

2.1.1 Discipline vs. transdiscipline

The difference between multidisciplinary and interdisciplinary is illustrated in Figure 1. A multidisciplinary approach uses methods from two or more disciplines to examine a common topic. In general, researchers from different disciplines work independently, each from his or her own discipline-specific perspective to address a common topic. Interdisciplinary work involves the application of a method from one discipline to topics studied by other disciplines. In other words, interdisciplinary research concerns the transfer of techniques (methods) between disciplines. Both multidisciplinary and interdisciplinary activities cross disciplinary boundaries, but their goals remain within the framework of disciplinary research.

Sperber [4] describes the challenges faced in interdisciplinary work and recognizes that current efforts do not go far enough in promoting understanding and cooperation between disciplines. While "grant proposals...have built in interdisciplinary rhetoric and describe future collaboration among people from different disciplines,...this is mostly done in order to meet the criteria for the grant. The actual scientific content generally consists in the juxtaposition of monodisciplinary projects with some effort to articulate their presentation." Sperber believes that the easiest way to have interdisciplinary work received is not to present it as such, but "to produce different versions of it for each of the disciplines concerned." [4]

Much of the difficulty of interdisciplinarity is due to the fact that attention, recognition, and authority are channeled by disciplinary institutions, yet researchers should recognize that "disciplines are artificial 'holding patterns' of inquiry whose metaphysical significance should not be overestimated." Researchers should not have a "providential view of the history of science [that] science is normally as it ought to be." This view "refuses to consider that science (or a particular science), had it pursued a different course of inquiry earlier in its history, would have ended up in a better epistemic position than it is in today. It simply take[s] for granted that [there could be no better outcome than that resulting from the choice] to dump Aristotle for Newton, Newton for Einstein, etc.– and at roughly the times and for the reasons they were dumped." [5]

2.1.2 Definition of transdisciplinary

According to the Oxford English Dictionary, the term "transdisciplinary" appeared in 1972 and may be defined as "Of or pertaining to more than one discipline or branch of learning" From its earliest usage, *transdisciplinary* indicates greater cooperation and integration between disciplines in contrast to *interdisciplinary* or *multidisciplinary* [6]:

> **1972** E. JANTSCH in *OECD: Interdisciplinarity* II. i. 105 The ultimate degree of co-ordination in the education/innovation system,..which may be called *transdisciplinarity*, would..depend on a common anxiomatics [sic]... The whole education..system would be co-ordinated as a *multi-level, multi-goal* system, embracing a multitude of..interdisciplinary two-level systems, which..will be modified in the transdisciplinary framework.

Transdisciplinary goes beyond *multidisciplinary* and *interdisciplinary* to mutually share methods and subjects between disciplines. [3] Transdisciplinary education and research take collaboration across discipline boundaries a step further than do multidisciplinary and interdisciplinary programs. In following the transdisciplinary concept, researchers representing diverse disciplines work jointly to develop and use a shared conceptual framework that draws upon discipline-specific concepts, theories, and methods, but addresses common problems through a new synthesis of a common ontology, theories, models, and methodology.

2.1.3 More than just a jargon

To create a new approach to research and education, an appropriate theoretical framework must be established to deal with cross-disciplinary interaction. This framework should be constructed upon a sound basis of philosophy and sociology of science consistent with the historical record.

So far, “the vast majority of scientific publications belongs squarely to an established discipline, as does the quasi-totality of academic and research jobs.” Nor has inter- or trans-disciplinary work been much studied within philosophy of science. “[M]ost people who have written on interdisciplinarity have done so from the point of view of science policy rather than from the point of view of philosophy, history or sociology of science....[T]he disciplinary organization of the sciences as we know it is not a mere reflection in scholarship of everlasting natural divisions among levels of reality. It is a historical product which, in its present form, goes back to the nineteenth century and to the development of modern universities and research institutions.” [4]

In addition to understanding the history of disciplines, there are conceptual questions that must be addressed. This section discusses developments in philosophy of science in order to provide a background for understanding the structure of a discipline and a theory of transdisciplinary endeavors. This enables us to examine questions such as

- What is a discipline?
- What are the methods of a discipline, and how do disciplines advance?
- How are intellectual networks structured with respect to disciplines?
- What are the challenges to transdisciplinary communication?
- How can research methods from multiple disciples be combined?
- How can results from transdisciplinary work be evaluated?

The establishment of a disciple or transdiscipline can be distinguished by its paradigm or research program and its research community. According to Kuhn a *paradigm* for research is a unifying view of a discipline (“the entire constellation of beliefs, values, techniques, and so on shared by the members of a given [research] community” [7, p. 175]) that is brought about *exemplars* (“the concrete puzzle-solutions which [are] employed as models or examples...as a basis for the solution of the remaining puzzles of normal science” [7, p. 175]). Thus, for example, Newton’s *Principia* is a treatise which served as a unifying vision for the paradigm of Newtonian mechanics, and Dobzhansky’s *Genetics and the Origin of Species* provides an exemplar for the paradigm of neo-Darwinian biology.

A *research program* can be defined as “a sequence of theories representing the development of a central idea.” [8, p. 54] Similarly, for Laudan, a *research tradition* consists of “(1) a set of beliefs about what sorts of entities and processes make up the domain of inquiry; and (2) a set of epistemic and methodological norms about how the domain is to be investigated, how theories are to be tested, how data are to be collected, and the like.” [9, p. 83]

Therefore, a paradigm or a research program consists of

- *ontology*: an identification of the fundamental concepts that make up the field of study

· *aims*: an articulation of the scope of the field in terms of both problems that have been solved (*exemplars*) and problems remaining to be solved (*anomalies*) which should be covered by the program—and are expected to be—but have not yet been
· *methodology*: guidelines for further developing the program—particularly in a manner consistent with the problem-solving approach that the program has been following
· *theories*: relationships between fundamental concepts of the field and application to specific problems

2.1.4 Current transdisciplinary programs

Some examples of transdisciplinary programs that have been recently established include the transdisciplinary tobacco use research centers and the Bioengineering Consortium (BECON) funded by the National Institute of Health (NIH). [10] Additional programs have begun appearing in other areas: spatial information architecture; behavioral science; project management, leadership, education and training, arts, and professional studies; geographic information systems; cancer research; and aging.

2.1.5 Holistic vision for design and process

There is much discussion these days about interdisciplinary and multidisciplinary research, but efforts at cooperation between disciplines are often ad hoc, driven by the desire to secure funding for a particular project. [4] What is the underlying connection between the disciplines? A scientific reason and basis for cooperation needs to be identified, and the authors believe that design and process can provide such a basis for cooperation between disciplines in engineering systems.

The semantics of process and design constitute a set of information that is common across multiple disciples and belongs to them all. Transdisciplinary design integrates knowledge about various subsystems that is contained within multiple separate disciples and synthesizes this into a new generalized conceptual framework with its own topics of interest and methods.

The Society for Design and Process Science was founded in 1995 "to foster, to identify and to extend a core of science that deals with design and processes across a broad spectrum of human, technological, and economic endeavors: a spectrum that covers the traditional disciplines of communications, computer sciences, economics, engineering, management, manufacturing, mathematics and statistics, and physical and social sciences." [11]

Likewise MIT has recognized the importance of fundamental research into engineering design of complex systems. "Engineering systems is a field of study taking an integrative holistic view of large-scale, complex, technologically-enabled systems with significant enterprise level interactions and socio-technical interfaces." In December 1998, MIT established an Engineering Systems Division (ESD) in order to help "the engineering profession create a meaningful place for itself in the broader, multidisciplinary approach required to solve society's problems" by creating "solutions at the macro scales" and "includ[ing] the context of each challenge as well as the consequences of technological advancement." [12, 13]

The emerging transdisciplinary vision for design and process can be distinguished from "engineering science." It will have an enterprise-level perspective, adopt a holistic approach, deal with macro-scale design, and combine qualitative and quantitative approaches in understanding both technical and social-organizational contexts. [12]

Scientific theories comprise fundamental knowledge areas in the form of perceptions and understandings of different entities, and the relations between these fundamental areas. The fundamental knowledge areas are at a more abstract level than observations of real-world data. These perceptions and relations are combined by the researcher or practitioner to produce specific consequences, for example, predictions of observations. The role of design researchers is to develop new design theories and to verify these. Design as a discipline contains its own paradigm, covering several fundamental knowledge areas. Additionally as a natural transdiscipline, design must interact with various other disciplines.

Knowledge in engineering systems can be abstracted into fundamental areas. When knowledge is related between or within these fundamental areas, a theory of design and process is generated. The areas of fundamental knowledge which are covered within design theory can be abstracted as shown:

- the design process
- the design object (the product of the design process)
- designers
- specific field knowledge
- resources (such as time, money)

This abstraction agrees with fundamental areas advanced by other researchers. According to Dixon [14], the areas of fundamental knowledge which are required for "a descriptive cognitive theory of design" are the designer(s), the problem, the organizational environment, the design environment (including information resources and computer-based and other tools), and time. In the TIPS (theory of inventive problem solving) school—researchers following the work of Altshuller—the fundamental areas modeled are a process of design and products of this process [15]. In praxiologic design science, from Poland, the elements considered are designers, the design object, and the design process. [16]

Specific design theories are then concerned with one or more of these fundamental areas. For example, axiomatic design (AD) relates the design object to decisions in the design process [17]. The theory of technical evolution within TIPS is an abstraction of the evolution of engineering systems, from many fields; as such, it is concerned with only design objects. Similarly other design theories provide insight about one or more of the above fundamental areas.

A sound transdisciplinary science of engineering systems needs, of course, to incorporate knowledge from many different areas. The core of knowledge centered on design and process will be augmented based on discipline-specific knowledge depending on the problem at hand. The core of design and process knowledge will also be necessarily broad and incorporate concepts and methods from what are today separate individual disciplines. The core transdisciplinary areas of design and process can be described as the following.

Design process activities and decision making

The design process model consists of a collection of distinct activities with clear start and end points. Each activity is a transformation of inputs to outputs. These activities can be sequenced in many ways and fit together into a project-specific design process. Each project will have its unique sequence, depending on its scope and goals.

Research in engineering design concerns the interplay between the design process and the design object. How does the design process produce a design object? Research which addresses this question produces a descriptive model of design. If instead of a description of how the design is done, research produces a prescriptive model of design, then the model answers questions subsumed under this: how should the design process be performed?

Communication, individual, group psychology, cognitive science, leadership

In addition to the activities and decisions made during design, another topic for research are the designers themselves. How do they work individually and collectively?

A key aspect of personal interaction in design projects and elsewhere is leadership. Transdisciplinary science should take into account the multiple roles played by leaders in different contexts. For example, coordinating international projects, leading a research group, collaborating, or even serving in a supervisory role—each of these has aspects of leadership. The best characteristics and activities of leaders will be different in different situations, cultures, and roles.

Leaders may be gifted in different ways and through their characters exhibit the best qualities of leadership in different ways. Transdisciplinary education should seek to equip people from diverse backgrounds with the necessary skills and experiences to enable them to contribute positively in building up institutions and others.

Resources and cost

An important criterion for evaluating the success of a design is the expenditure of resources that have been made in producing it—from development cost and time to manufacturing cost, cost of ownership, and recycling or disposal. A true transdisciplinary design applies to the whole product lifecycle and pull in relevant economic models and data.

Intercultural factors

In the global economy there is a need for designers to work across multiple cultural contexts. For successful transdisciplinary design, cultural factors must be accounted for. For example, recently a question was raised with the author whether a tool like Design For Manufacturing (DFM) could be developed for low-income countries. Would the guidelines for best design and manufacturing practice be contextually determined?

Some parts of engineering are becoming global commodities. Universal sharing of knowledge cannot take place without the application of the transdisciplinary attitude, which implies the practice of trans–cultural, trans–religious, trans–politic, and trans–national vision.

For an example of a program in global engineering design see, [18] and [19].

Models of the design object

Design produces an output. Transdisciplinary design must include models of the objects being designed. In the most general sense, a model may be defined, following Ross [20]: A is a *model* of B if A may be used to answer questions about B.

3 Application of transdisciplinary science to engineering education

Previous papers have argued that a transdisciplinary approach is needed in engineering education and research. An example is the design of an Embedded Cruise Control System (ECCS)—which can only be the best ECCS if components (and knowledge) from the disciplines of mechanical engineering, electronics engineering, and software engineering are integrated. [3, 21]

Table 1 shows the emergence of transdisciplinary approaches in generating and disseminating knowledge. Several key features of this emerging transdisciplinary approach are the need for systematic methods to dynamically generate new knowledge (a process termed *meta-fusion*), the transition to a facilitative approach to teaching, the integral need for automation to solve relevant problems, and the emergence of integrated institutes and university programs.

The institutes will be larger than traditional interdepartmental programs, such as the work done at Microsoft R&D Centers and big research groups that design computers. Universities are helping, but they do not have the long memories of corporations. Clearly, more comprehensive and integrative collaboration strategies have to be developed between industry and universities.

Table 1. Knowledge Generation and Dissemination Methods

Method	Era	Teaching	Automation Need	Social Machinery	Research – Education
a. Deductive reasoning (Plato) b. Observation and logic (Aristotle)	Platonic – Aristotelian	Primarily based on authority and regurgitation	Minimal	Plato's Academy Aristotle's Lyceum	Ad hoc
Experimentation (Descartes)	Cartesian – Mechanistic	Primarily based on instruction	Increased	Universities	Primarily disciplinary
Meta–fusion (systematic knowledge generation)	Combinatorics – Integration	Primarily based on facilitation	An integral part of the method	Integrated universities and polytechs guided by institutes of technosciences in the technopolicies of the next century	Primarily transdisciplinary

3.1 Comparison with other fields

For engineering systems, design theory provides a general explanatory framework for a research program that covers basically anything that could be regarded as design. In biology, a broad range of fields have been brought together under the overarching heading of the new-Darwinian synthesis, and in cognitive science researchers from various disciplines have drawn together to jointly investigate the mind.

The success of the neo-Darwinian paradigm was due to the conceptual framework provided by Dobzhansky in his book, *Genetics and the Origin of Species*. Biology under the neo-Darwinian synthesis ranges from laboratory-based genetics and computer-based simulations to paleontologists and natural historians who study animals and plants in the field. "Yet neo-Darwinism was able to bring together all of these vastly different fields under one umbrella theoretical framework in a way which never happened in the social sciences." [22]

Howard Gardner, an early proponent of the "cognitive revolution" wrote in 1985: "At present most cognitive scientists are drawn from the rank of specific disciplines—in particular, philosophy, psychology, artificial intelligence, linguistics, anthropology, and neuroscience. … The hope is that some day the boundaries between these disciplines may become attenuated or perhaps disappear altogether, yielding a single unified cognitive science." [4]

4 Fundamental nature of design and process for transdisciplinary science

Nobel Laureate Herbert Simon stated [23]

> Today, complexity is a word that is much in fashion. We have learned very well that many of the systems that we are trying to deal with in our

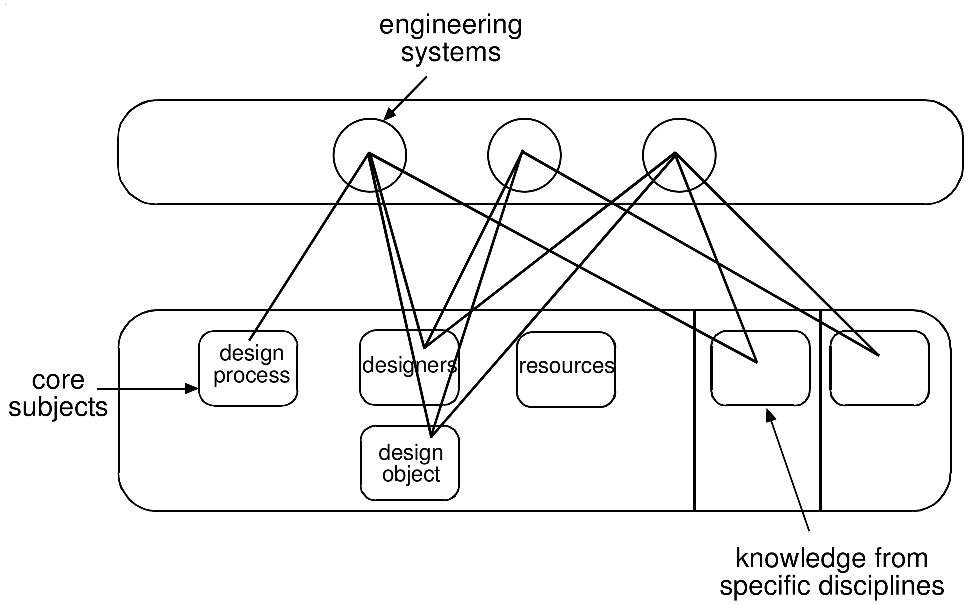

Figure 2. Transdisciplinary engineering consists of a core of knowledge and tools about design and process plus dynamically accessed knowledge and tools from other disciplines.

> contemporary science and engineering are very complex indeed. They are so complex that it is not obvious that the powerful tricks and procedures that served us for four centuries or more in the development of modern science and engineering will enable us to understand and deal with them. We are learning that we need a science of complex systems, and we are beginning to construct it...

The essence of the transdisciplinary approach is "a foundation of design fundamentals and process development and management....This core is then surrounded by knowledge and skill 'tools' selected from various disciplines. These tools can be updated as needed to keep pace with developing technology." [1]

The process envisioned for achieving transdisciplinary engineering starts with "extract[ing] the common elements, design and process, from existing disciplines and synthesiz[ing] them into the foundation of the new transdiscipline...The transdisciplinary approach provides an umbrella of the core design, process, systems, and metrics common to all disciplines that is necessary for problem solving." [21]

In addition to this core knowledge about the design process, models of the design object, etc., specific application information from other disciplines must be integrated into design activities in a transdisciplinary way. This is illustrated in Figure 2.

4.1 Design and process as fundamentally transdisciplinary subjects

What is design? Design can mean the process which is followed to produce an output. The design process may entail the creation of a new solution, the selection of an existing solution, or a combination of the two. Design can also mean an object. A series of activities are performed by which the customers' perception of a design task is transformed into an output—the design object, which is any satisfactory solution to this task.

In this paper the authors will use the term *design process* (or *process*) to refer to the sequence of steps by which designers develop or select the means to satisfy a set of objectives, subject to constraints, and the authors will use *design object* (or *design*) to refer to the product, that is, the output, of the above process.

The transformation—from customer perception to a design object—occurs by means of designers working with design tools, with their knowledge of discipline-specific information, and with a set of available resources. Thus, the areas of fundamental knowledge that are covered within design theory are these: the design process, the design object, designers, resources (time, money), and specific disciplinary knowledge.

In addition to these fundamental areas, transdisciplinary design must draw upon knowledge arising from multiple additional disciplines. This knowledge is not formally part of the design discipline, but must be used in the context of transdisciplinary utilization to bring into realization specific engineering systems.

4.2 Nature of design and process science

A main objective in transdisciplinary design and process is to provide a framework to dynamically assemble relevant information. The main challenges in creating a scientific basis for transdisciplinary design and process science are two:

1. Design is inherently intentional. In this way it is distinct from other sciences, especially natural sciences, whose goal is to objectively model and understand existing phenomena. Design, though, can be thought of as a way to organize and manage the interrelationships and interfaces between other disciplines.

2. Traditional disciplinary boundaries promote and enable work within the discipline, but make meaningful cross-disciplinary work difficult. Design is fundamentally transdisciplinary because the scope is open-ended.

Design can exist as a—broad, but separate (as discussed below)—body of knowledge, but to deal with specific problems at hand, discipline-specific knowledge must be brought in, which necessitates a transdisciplinary approach.

4.3 Characteristics of transdisciplinary design and process science

All key characteristics of design and process must be included in the transdisciplinary approach to enable engineers to make effective use all available resources, methods, and tools in the development of large, complex systems.

Design and process are fundamental to transdisciplinary approach to engineering systems. The essence of the transdisciplinary approach is a foundation of design fundamentals and process development surrounded by knowledge and skill 'tools' selected from various disciplines.

Design should be scalable to large, dynamic engineering systems. Functional Requirements change over time. Moreover, the design process deals with problems at multiple levels: levels of scope (a measure of the amount of impact the problem has on the overall design) and levels of abstraction (a measure of how conceptual or how detailed the problem is).

Engineering systems are a challenge of integration. Engineering disciplines can efficiently create components, but have great difficulty combining them because there is no systematic approach, for example, the design of the Hubble space telescope, optical backplanes, and the space shuttle. With a systematic approach, engineers can assume a component with certain interfaces, farm out components to disciplinary people, and when done, assemble the components together.

Engineering relationships in design should drive the development process. Although the individual activities performed are similar throughout the design process, they may be sequenced in different ways. Performance of the design process is evaluated against the quantity of resources (time, costs) used to satisfy the objective (i.e., solve the design problem). An activity is evaluated against the resources expended to produce completely its outputs.

Designers need rules for process. The purpose of the design process is to make decisions, specifically to find a solution (in terms of a design object) to some design problem. Thus, clearly defined decision points and decision criteria (and/or rules) must be visible in the process.

Engineering systems include uncertainty and variation. Variation and uncertainty are potential problems for engineering systems. A transdisciplinary approach to design and process must include means to deal with multiple sources of noise—such as the environment, manufacturing variation, and usage and wear—in producing engineering systems that provide robust functionality.

Engineering systems include socio-technical interfaces. Socio-technical systems require insights from social science in defining and tackling problems.

Computers and automation are necessary. Automation is necessary because humans alone cannot deal with the number of components and the amount of information necessary.

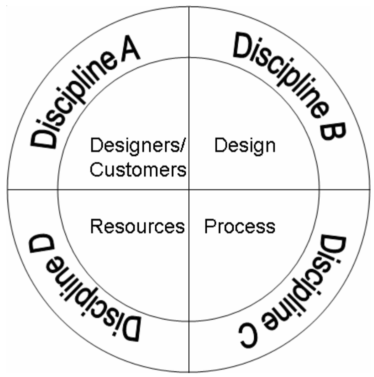

Figure 3. The transdisciplinary approach to engineering consists of core subjects dealing with designers, design artifacts, design process, and resources. These are combined with disciplinary knowledge in creating new systems.

4.4 A framework for transdisciplinary engineering

Figure 3 shows that the transdisciplinary approach to engineering consists of core subjects dealing with designers, design artifacts, design process, and resources. These are combined with disciplinary knowledge in creating new systems.

4.5 Relationship of design and process science to other areas needed for transdisciplinary engineering

Considering the four knowledge areas of transdisciplinary engineering in a pairwise fashion shows that other relevant disciplinary knowledge is relevant that can be integrated into a fully transdisciplinary approach to engineering systems as shown in Figure 4.

5 Tools for transdisciplinary design and process

Worldwide universities are adjusting their visions of education and research. For example, seven years ago the Texas Tech University College of Engineering had the vision to develop the first transdisciplinary graduate engineering program, and thus, initiate transdisciplinary education and research in engineering systems. A Transdisciplinary Master of Engineering Program in Process and Systems Design was developed for a company in the aerospace industry. As of 2006, approximately hundred students have completed the program, and the program has been very well received by the company and by the students.

The program offers two tracks: Design, Process, and Production and System Design and Integration. [24] In the program, the students take one course per month,

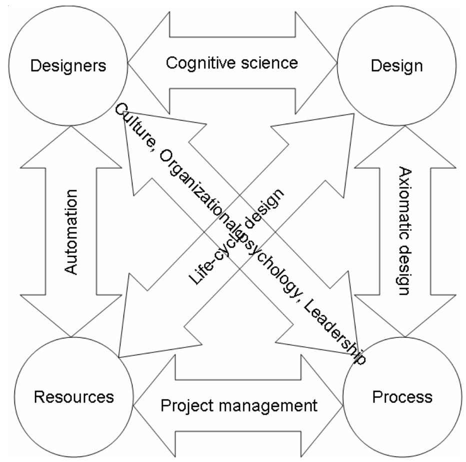

Figure 4. The links between the core subjects in transdisciplinary engineering draw upon various types of knowledge.

until they have accumulated the 36 units needed for the degree. In addition to the 11 courses for the degree, the students are required to complete a Master's Research Report, worth 3 credit hours.

The program is structured around a set of core courses that present the fundamental basis of the transdisciplinary approach, and then specific disciplines are taught as knowledge bases for the students to draw upon and use in their applications.

The coursework includes the areas enumerated above as fundamental to design—design process (fundamentals of transdisciplinary design and process), design object/modeling (engineering modeling and analysis), designers (creativity), resources (project management), and discipline knowledge (mechanical engineering, software engineering, etc.).

"Fundamentals of Transdisciplinary Design and Process" is one of four core courses in the program—along with Systems Engineering Principles, Technical Management and Creativity, and Engineering Modeling and Analysis. As one of the core courses of the program, Fundamentals of Transdisciplinary Design and Process is intended to present "the fundamental aspects of design and process, which cut across the boundaries of all disciplines [and] provide a means for solving complex problems." [24] The bulk of the material presented in this course has been based on axiomatic design principles. [25]

5.1 Axiomatic design principles for transdisciplinary engineering systems

Axiomatic design is an example of the type of design theories and tools which can play a foundational role in transdisciplinary design and process. To create a scientific foundation for transdisciplinary engineering that is useful in systems design, axiomatic design provides discipline-independent representations of designs, a general design process, general criteria for effective decision making, and scalability for complex systems.

Scope: Axiomatic Design (AD) was created by Suh in order to create a science base for design and manufacturing. [26] The theory has been further developed by Suh and others [27] and detailed in two books [17] and [2]. Axiomatic design was originally taught as a graduate-level course at MIT by Suh starting in the 1987-88 academic year using a draft of his book *The Principles of Design* [17]. Next it was taught as a summer course at MIT during the 1990s. For a description of the outline of summer courses in axiomatic design at MIT, see [28]. By the late 1990s, Suh was writing his second book on axiomatic design, Axiomatic Design: Advances and Applications [2], and the organization of the class changed accordingly. Recently, we taught AD at Texas Tech and University of Alabama at Birmingham to graduate students.

The starting point for axiomatic design, as stated by Suh, is that "there exists a fundamental set of principles that determines good design practice". [17] p. 18] These principles, the axioms, are to be used in a design process that consists of at least three activities: problem formulation, concept generation, and concept evaluation and selection.

Suh's primary motivation for developing axiomatic design is education; he wants designers to learn how to make good design decisions. Suh's goal is to establish an "academic [discipline] for design and manufacturing" [17, pp. 21-22]. The reason is found in the following: "[i]n order to obtain better performance, both engineering and management structures require fundamental, correct principles and [methods] to guide *decision making in design;* otherwise, the ad hoc nature of design can not be improved" [17, p. 5]. To be effective "the student must be taught to see the big picture and [be taught] the ability to conceptualize a solution, as well as how to optimize an existing product or process" [17, p. 22].

Suh's view of the scope of design may be summarized by the following: "Design, as the epitome of the goal of engineering, facilitates the creation of new products, processes, software, systems, and organizations through which engineering contributes to society by satisfying its needs and aspirations" [17, p. 5]. In contrast to Clausing [29], Suh does not describe how to connect design activities to the company's general activities; Suh's theories and methods are focused on decision making in the design process.

The scope of applicability of the theory is broad. This theory has been used across many industries and fields of application: automotive, semiconductor, software, defense, financial services, organizational design, production systems, and others. Recently software has been developed to aid in the application of the theory [30, 31], and three international conferences have been held [32-34].

Teaching: Suh states that "From [his] experience in teaching this subject to many engineers and students, it has become clear that axiomatic design is not an easy subject to learn, much less to master, without some effort—perhaps because of the conceptual nature of the subject. To truly understand axiomatic design, students must put theory into practice by applying the basic principles to many problems and many design tasks." [2, p. xvi]

Even though much research has been done on axiomatic design and many courses in the subject have been taught, the number of researchers who have discussed the teaching of axiomatic design has been rather limited. In the first two conferences focused on axiomatic design—[33, 34]—although "teaching and learning methods" was listed as a topic area of interest, there was only one paper presented in this category. [35] In the most recent axiomatic design conference in 2004, this situation began to improve. There were several papers related to developing courses in axiomatic design and methods that could be used to teach the subject. [25, 36-39] [25] provides a strategy for teaching axiomatic design and also presents the results of teaching this subject to students as part of Texas Tech's Transdisciplinary Master's program. Their experiences and feedback may be seen as typical of other experiences in teaching and learning axiomatic design in industry.

In the literature there have been a few other papers that mentioned teaching and training for axiomatic design: methods for technology transfer to industry [40], a capability maturity model for axiomatic design [41], growth of axiomatic design within industry and academia [27, 28], and axiomatic design education for concurrent engineering [42]

In addition to axiomatic design, other tools for transdisciplinary education and research need to be developed. For example, [25] present a strategy for teaching axiomatic design and also presents the results of teaching this subject to students as part of Texas Tech's Transdisciplinary Master's program. Their experiences and feedback may be seen as typical of other experiences in teaching and learning axiomatic design in industry.

The concepts that distinguish axiomatic design from other design theories are domains, hierarchies, zigzagging (iteretion), and the two design axioms: independence and information. For more explanation of axiomatic design, see [2] and [17].

This section will describe how axiomatic design can be used to address several of the characteristics of transdisciplinary design and process science identified earlier.

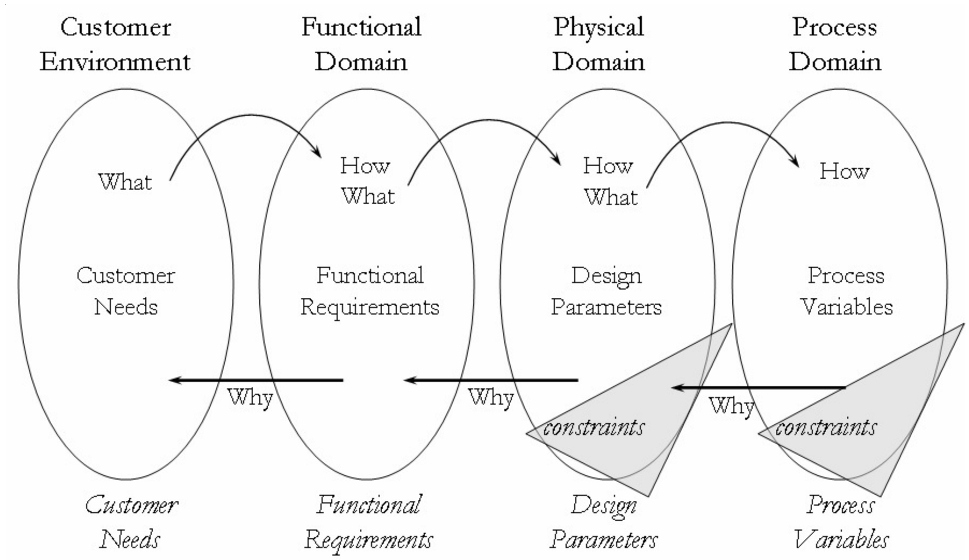

Figure 5. Design domains [43].

5.1.1 Design and process are fundamental notions for transdisciplinary approach

Axiomatic design principles provide a framework that is consistent for all disciplines and at all levels of detail. Designs in axiomatic design are modeled using *domains* and *hierarchies*. The design process is a continual interplay between *what* designers want to achieve and *how* they decide to do this, which corresponds to mapping from a domain on the left to a domain on the right.

The four domains shown in Figure 5 are termed the *customer domain*, the *functional domain*, the *physical domain*, and the *process domain*. Associated with each domain are the *design elements* it contains. In the order listed, the elements within each domain are *customer needs* (CNs), *functional requirements* (FRs), *design parameters* (DPs), and *process variables* (PVs).

Customer Needs are a collection of statements expressed in the "voice of the customer" that express the customers' perceptions of the design task. *Functional requirements* are defined as the minimum set of requirements that completely characterize the design objectives for a specific need. [17] These FRs must be specified in a "solution-neutral environment" in terms of the functions to be achieved, *not in terms of particular solutions*. *Design parameters* are defined as the set of key elements or variables of the design object that have been chosen to satisfy the

FRs. *Process variables* are the key variables that characterize the means to produce or realize the DPs.

Furthermore, in addition to these elements that are each contained within a specific domain, constraints on the design task and solution can also exist. *Constraints* are a specification of the characteristics that the design solution must possess to be acceptable to its customers and to the company that is designing it. They provide bounds on acceptable solutions.

Axiomatic design principles can be applied in the same way to problems in many fields: product design, manufacturing process design, software design, system design, business planning, and organizational design. The four domains are shown in Figure 5. The number of domains remains constant at four for all design tasks, but the nature of the design elements in each domain changes depending on the field of the problem. For example, for a business plan, the customer, functional, physical, and process domains correspond to the vision, goals, strategies, and activities of the business. For organizations, they correspond to mission, tasks, programs, and resources. [44] and [2] show how the domains in axiomatic design can be applied to design tasks in many disciplines.

Because the same structure is used to model design tasks, regardless of the discipline of application, managers and engineers from different disciplines can communicate with one another, and systems integration becomes easier because components can be integrated into a single structure that describes the whole design.

Hierarchies exist within the functional and physical domains. Functional requirements can be broken down into sub-FRs, and design parameters can be broken down into sub-DPs.

A design hierarchy is not arbitrary. Sub-FRs follow from the choices of higher-level DPs. As designers develop a new design, this means that they *zigzag* between domains. They define high-level requirements, satisfy these with high-level solutions, and then based on these, define sub-requirements and sub-solutions. Zigzagging between the functional and the physical domains is illustrated in Figure 6.

For example, in designing a transportation system for a city, if the top-level solution is the use of hydrogen-powered vehicles, then the further decomposition of the design task and solution will be very different from the situation in which a mass-transit system is selected.

In order to create innovative designs, designers need to be able to choose sets of product requirements and analyze the performance of novel arrangements of solutions.

Axiomatic design provides a unique process for design that encourages the creative search for solutions by allowing early evaluation of alternative designs. Novel combinations of design solutions—in terms of DPs—can be combined on the fly, as envisioned in Suh's paper discussing the "Thinking Design Machine". [45]—to create dynamic systems that satisfy FRs that change over time.[46] For additional

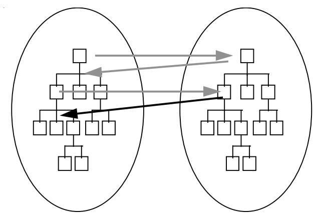

Figure 6. Decomposition by zigzagging [43].

ideas about how axiomatic design can be used to identify and reduce complexity in large, flexible (time-varying systems), see [47, 48].

5.1.3 Modern engineering systems are a challenge of integration

The major challenge in creating large systems is the integration of components. Disciplinary techniques can be used quite effectively to realize the design of individual components, but the challenge is in understanding and managing the relationships between components. In axiomatic design, these relationships are captured by means of a design matrix that quantifies the relationships between changes in design parameters and changes in the satisfaction of functional requirements. These relationships can be used then to effectively manage the development process of engineering systems and to ensure their effective operation.

An example of a large system that integrated several models for subsystems in order to reduce the necessary complexity and iteration in the design process was the design of a large naval ship. Traditionally in ship design, the design process follows a process that is known as the “ship design spiral.” In this process, the designers make decisions about various subsystems that comprise a ship, including length, beam depth draught, form, power, areas, weight, displacement, layout, etc. As the design progresses, more and more decisions are made, and as passes are made through successive subsystems, it’s hoped—but not guaranteed—that design will converge upon a final solution. In this case several sets of detailed mathematical models for subsystems in the ship were given at the onset of the project. The goal was to create a way to evaluate tradeoffs between manning and automation and the use of innovative hull forms, but the iterative nature of the design process made such tradeoffs very resource-intensive to perform. [49]

The ship design was put into an axiomatic design model, consisting of functional and physical hierarchies and design matrices of the relationships between them. As a result a decoupled solution was created and iteration in the process was almost eliminated. Because of the availability of existing mathematical models, the design could be developed to a very high level of detail—producing a hierarchy with more than 700 functional requirements and design parameters, thus demonstrating the scalability of axiomatic design and its ability to handle complexity in integrating subsystems from various disciplines. [50]

5.1.4 Engineering relationships in design should drive the development process

Axiomatic design provides a model, namely the design matrix as shown in equation 1 that shows the engineering links between parts of a design. This can be used for managing complex projects by identifying which people in an organization or network need to communicate with each other. It points to a way to help manage co-location of projects. Moreover the design matrix provides a measure of the quality of the design by checking sensitivities between elements (that is, strength of the design matrix) before doing all the detailed design and calculations. Strong interactions provide an indication that the project will experience difficulties or fail.

The design matrix (DM) shows the relationships between the FRs and DPs at one level of the design hierarchy. The elements of the design matrix are determined from the set of equations [17]:

$$\begin{aligned} \Delta FR_1 &= \frac{\partial FR_1}{\partial DP_1}\Delta DP_1 + \cdots + \frac{\partial FR_1}{\partial DP_n}\Delta DP_n \\ &\vdots \\ \Delta FR_n &= \frac{\partial FR_n}{\partial DP_1}\Delta DP_1 + \cdots + \frac{\partial FR_n}{\partial DP_n}\Delta DP_n \end{aligned} \tag{1}$$

where each

$$A_{ij} = \frac{\partial FR_i}{\partial DP_j} \tag{2}$$

In a design matrix an X can be used to represent a strong effect by a DP on an FR. That is, an X corresponds to a large $A_{i,j}$ term compared with the tolerance on FRi, and an O indicates a weak effect, relative to the tolerance associated with FRi. There are three possibilities for the nature of the design matrix. It can be a matrix populated both above and below the diagonal, a triangular matrix, or a diagonal matrix. These are illustrated in design equations 3a, 3b, and 3c, respectively. A triangular matrix, as in equation 3b, is known as a *decoupled design*. A diagonal matrix, as in equation 3a, is an *uncoupled design*. Any other matrix, as in equation 3c, is known as a *coupled design*.

$$\begin{Bmatrix} FRx.1 \\ FRx.2 \\ \vdots \\ FRx.n \end{Bmatrix} = \begin{bmatrix} X & O & \dots & O \\ O & X & & O \\ \vdots & & \ddots & \vdots \\ O & O & \cdots & X \end{bmatrix} \begin{Bmatrix} DPx.1 \\ DPx.2 \\ \vdots \\ DPx.n \end{Bmatrix} \tag{3a}$$

$$\begin{Bmatrix} FRx.1 \\ FRx.2 \\ \vdots \\ FRx.n \end{Bmatrix} = \begin{bmatrix} X & O & \dots & O \\ X & X & & O \\ \vdots & & \ddots & \vdots \\ X & O & \cdots & X \end{bmatrix} \begin{Bmatrix} DPx.1 \\ DPx.2 \\ \vdots \\ DPx.n \end{Bmatrix} \tag{3b}$$

$$\begin{Bmatrix} FRx.1 \\ FRx.2 \\ \vdots \\ FRx.n \end{Bmatrix} = \begin{bmatrix} X & O & \dots & X \\ O & X & & X \\ \vdots & & \ddots & \vdots \\ X & X & \cdots & X \end{bmatrix} \begin{Bmatrix} DPx.1 \\ DPx.2 \\ \vdots \\ DPx.n \end{Bmatrix} \tag{3c}$$

In an uncoupled design, the FRs can be satisfied independently by means of the corresponding DPs. In a decoupled design, the FRs can be satisfied if the DPs are varied in the correct sequence. A coupled design has no guaranteed point at which the FRs can be satisfied.

Explicit metrics for functionality are arranged in a hierarchy according to the design decisions. These hierarchies then capture and trace the satisfaction of high-level objectives through the layers of design decomposition. These relationships can then be used to properly assign, distribute, and schedule team tasks and responsibilities.

Steward and Tate [51] show the benefits of axiomatic design for project planning. In this case, the shortcomings of traditional software development are overcome by optimizing the assignments of project sub-components and workflow management thereby making a significant difference in the delivery time of a web-based application for charitable giving services. The key is using real engineering links derived from the design matrices between parts of the system for planning the project. These design matrix elements were preserved as links between tasks in the development process.

5.1.5 Designers need rules for process

Designers require a general model of the design process from which they can structure a specific implementation, yet researchers have recognized the challenge of creating this model. As stated by Cross [52],

> "[W]e lack a successful, simplifying paradigm of design thinking. Those simplifying paradigms which have been attempted in the past—such as viewing design simply as problem-solving, or information-processing, or decision-making, or pattern-recognition—have failed to capture the full complexity of design thinking."

Thus a science of transdisciplinary design needs a general model of the design process and design objects that is flexible to cover all instances of the design process, yet it contains enough specifics to provide useful guidance. The design process can be represented as a network of generic activities (as for example, the activities listed in [53]), with explicit relationships between them, from which the designer can structure a unique design process. Within the process, the activities are specific enough to support the designer in selecting design tools and methods for each activity, to identify clearly decision points, and to create good documentation for the process. [43, 54] show how a generic model of design process activities can be constructed based upon axiomatic design.

Axiomatic design is defined as the use of axioms to identify good design. Axiomatic design uses a zigzag process for decomposing a design into subsystems and a set of axioms for choosing among alternative design solutions. Designers are aided in their choice of solutions by two *design axioms—the independence and information axioms*. These axioms were generalized from observations of good design decisions. They establish the minimum acceptability for a design solution, and among several proposed, enable the identification of the best.

The two design axioms are stated as follows [17]:

- *The Independence Axiom (First Axiom):*
  Maintain the independence of functional requirements.
- *The Information Axiom (Second Axiom):*
  Minimize the information content [of the design].

Once a set of FRs has been formulated and possible sets of DP alternatives have been conceptualized, the two design axioms are applied to evaluate the proposed designs. The designers apply the Independence Axiom by using a design matrix (DM). If the design does not satisfy independence, then it is said to be *coupled*. Acceptable designs are either *decoupled* (a triangular matrix) or preferably *uncoupled* (a diagonal matrix). [17] In an uncoupled design, the FRs can be satisfied independently by means of the corresponding DPs. In a decoupled design, the FRs can be satisfied if the DPs are varied in the correct sequence.

5.1.6 Engineering systems include uncertainty, variation, and robustness

Robustness of engineering systems means that the system is able to perform its intended functions even in the presence of noise; for example, environmental changes, manufacturing variation, and wear. To quantify variation and give designers guidance about how to improve robustness, axiomatic design uses the concept of information content. The second axiom is stated as, minimize the information content of the design—which is equivalent to maximizing the probability of success of the design.

Information content has been defined by Suh as the log of the inverse of the probability of success of satisfying a function [17, 55]:

$$I = \log_e \frac{1}{p_t} \tag{4}$$

In generating an FR, the designers define a desired target value for the FR. They also specify an appropriate tolerance region about this target value; this region is known as the *design range,* r_d. Each available design alternative is able to provide the FR within some *system range*. The intersection of the system range and the design range is called the *common range,* r_c.

$$r_c = r_s \cap r_d \tag{5}$$

Therefore, the *probability of success*, labeled p_t, is defined as the ratio of the common range to the system range, shown in equation 6. These three areas are shown in Figure 7. The *probability of success*, labeled p_t to indicate its basis on the tolerance of the FR, therefore, is defined as the ratio of the common range to the system range, shown in equation 6, and the information content, *I*, is the natural log of this as given in equation 4.

$$p_t = \frac{r_c}{r_s} \tag{6}$$

For uncoupled designs the FRs may be considered independent variables. Therefore the total information content for a set of *n* FRs in an uncoupled design is equal to the sum of the sum of information contents for each of the *n* FRs:

$$I_{total} = \sum_{i=1}^{n} I_i = \sum_{i=1}^{n} \log_e \frac{1}{p_{ti}} \tag{7}$$

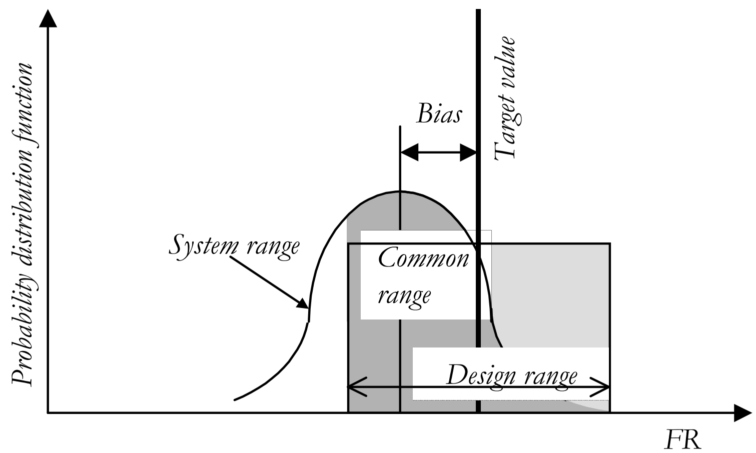

Figure 7. Information content and probability of success.

5.1.7 Engineering systems include socio-technical interfaces

Socio-technical systems are an example of large system designs that require insights from social science in defining and tackling problems. [56] Warfield [57] states "For better or worse, our society has accepted the idea of large and complex systems. If we are going to have them, it behooves us to learn how to manage them. An excellent route to doing so is to learn how to design them."

Warfield defines several types of technological systems:

- Class A systems are clearly founded in physical science such as radio, television, laser technology, telephones, airplane wings and control systems, internal combustion engines, etc.
- Class B systems could be referred to as "intellectual-technology" or products of "artificial intelligence". Examples include computer software, textbooks about computer software, computer languages, and that portion of the physical layout of human living and working environments that has been designed on the basis of some postulated image of human behavior in that environment.
- Class C systems are comprised of a mix of members from Classes A and B, whose satisfactory performance depends on appropriate integration of these two classes into synergistic units. Examples of this class include information systems, management support systems, decision support systems, expert computer systems, space missions, hospitals, nuclear power plants, banks, etc.
- Sociotechnical systems involve a mix of technology and people, and depend on a synergistic interaction of these two entities for their satisfactory performance. Any human settlement is an example of this kind of system.

Warfield further explains that Class A systems can be described and predicted in light of eternal referents or "primary standards". Class B and C systems lack such referents. The quality of the design of Class B and Class C systems must be founded in other sources. Socio-technical systems suffer the same lack of referents to an even greater degree. Transdisciplinary design and process are a means to develop standards to assess quality of systems for which primary standards are unavailable.

5.1.8 Computers and automation are necessary

Data about the design object is collected, generated, used to make decisions, and stored. The information gathered varies in certainty, quantity, and relevance for current and future use. Automation is necessary because humans alone cannot deal with the number of components and the amount of information necessary.

> [I]t is essential to bring together design and process technology if our designs are to be manufacturable and usable. The fact that the systems we are designing have a larger and larger informational component both increases their complexity and provides new possibilities for coping with the complexity. [58]

5.2 Educational effects of transdisciplinary design and process

The Fundamentals of Transdisciplinary Design and Process course—based on axiomatic design—employs a project as part of the learning process.

Table 2 shows the use of axiomatic design in the performance of various design activities across several disciplines. The use of axiomatic design in projects from the transdisciplinary master's program is also shown. Principally the projects have taken the form of use on hardware-software systems, from concept generation and selection to decoupling and project control.

Benefits of using axiomatic design—from the students in Texas Tech's Transdisciplinary Master's Program—have been identified as [25]

- AD provides a method to help focus on "the creative aspects of design" while also ensuring "functionality, performance, testability, and producibility of the system."
- Axiomatic design focuses in on an often weak area of the design process—the complete understanding of functional requirements at all design levels. Jumping to solutions often leads to "over-design" or "under-design" which leads to cost issues in the design.
- The tools provided by axiomatic design enabled them to elicit the customers' needs, organize them, and prioritize them, thereby effectively minimizing FRs and avoiding wasted time.

Table 2. Frequency of application of axiomatic design for design activities across disciplines. (Shaded squares indicate application of axiomatic design in Transdisciplinary Master's Program [25]. Stars indicate frequency of application as surveyed in [2, 33, 34, 59])

Field / Activity	products	software	systems
concept generation and selection	***	***	***
analysis of existing designs	***	*	**
decoupling	***	*	
optimization/tuning	**	*	*
decomposition and project control	*	**	***

Additional discussion of differences between the axiomatic design process and the company's current development process and challenges and questions to implementing axiomatic design can be found in [25].

6 Future direction for transdisciplinary education and research

This section outlines the future direction of transdisciplinary design as an agenda for research, education, and institutional impact.

Traditional approaches to engineering design education have been experience-based. A primary goal envisioned for transdisciplinary design is to overcome this bias by providing a scientific-basis for design practice. As Suh states, "the goal of education is to transmit systematic and generalizable knowledge, rather than experience to those initiated in the art and science." [17] The key is to teach both process and principles: "In design, we also need to do both. We need to teach both the process and the abstracted concept of what is a good design and how to develop good designs." [2]

The Master's program mentioned above is an example of the type of educational program that can be developed around a transdisciplinary basis. In this case the application area is aerospace engineering—and the disciplines being integrated include mechanical engineering, electrical engineering, computer science, systems engineering, project management, etc.—but this approach can be extended to many other fields of application.

Goals: The goals of creating a transdisciplinary approach to education are to transform engineering education. Innovative curricula and courses will be developed and disseminated at low cost though the Internet by The Academy of Transdisciplinary Learning and Advanced Studies (TheATLAS) [60]. Furthermore, the Society of Design and Process Science (www.sdpsnet.org) takes a leading role in promoting transdisciplinary education through the global academic community from the US to Japan, Brazil, Turkey, China, Europe, and beyond.

Another goal of transdisciplinary education is to make better use of educational resources by encouraging departments to work together. By offering transdisciplinary programs at the level of a college of engineering, for example, resources for a Master's or PhD program that everyone in the college can use—such as laboratories or computing facilities—can be shared among many departments and can be developed to a higher level. Money that would be wasted by duplicated efforts can be used for other purposes. Additionally transdisciplinary programs are in their infancy, and universities—even smaller ones—that adopt them can offer programs that are unique when compared with cookie-cutter programs at large institutions.

Furthermore, the authors are developing a PhD-level course in "Research Methods for Transdisciplinary Design" that will be piloted in spring 2006. The goal of the course is to raise and address some of the philosophical as well as fundamental questions raised in this paper, to teach the students to think critically about issues in transdisciplinary design, and to provide a basis for integrating research methods *from* many disciplines, including systems biology, *across* many disciplines. The goal of the Transdisciplinary PhD program is to build a research base for transdisciplinary design and process. This will create the intellectual foundation through identifying concepts and problems, demonstrating proofs of concept, creating exemplars, and developing funding sources.

Internet technology and publishing: Internet technology will continue to transform the way that materials are disseminated and received. For example, China Open Resources for Education is taking MIT's Open CourseWare, translating it into China, and assisting leading Chinese universities to implement it in their curricula. (See for example, [61] for an example of how this can be used in engineering design education.)

A series of textbooks will be published to integrate transdisciplinary, systems thinking across engineering design education. The books will be available through The Academy of Transdisciplinary Learning and Advanced Studies (TheATLAS). [60] The books will range from introductory undergraduate texts to graduate-level texts on advanced topics.

6.1 Challenges

The challenges of creating a transdisciplinary approach to engineering systems are [12]

- The academic focus is often on narrow problems, i.e., deep and soluble.
- Few deeply disciplinary faculty are interested in a broader view.
- The intellectual content can be difficult to present and see.
- Engineers tend to downplay leadership.
- Funding agencies are not configured to support holistic projects.
- Industry's needs are pressing—therefore they are unwilling to wait.
- Companies do not know how to hire people in engineering systems and believe they can only be produced by on-the-job training.

A main challenge to research in transdisciplinary design is the broad scope of topics that must be included. As Horváth says, "dealing with the order and structure of the entirety of engineering design research is an enormous challenge for everyone." [62] Some predictions about changes in engineering education over the next decade can be found in [63].

Institutional impact: It is time to think about the university as a place of ideas, not just as an organization of academic disciplines [64]. The success of disciplines is largely a function of institutionalism resulting from control over the flow of various resources. Concerning interdisciplinary centers that were started during the Cold War, "[t]he intellectual power of the founders' visions was no match for the existing department structure of universities, especially when it came to securing tenure for the would-be interdisciplinarians." Transdisciplinary researchers need to protect their broad activities so they are not cut short as they attempt to bridge or challenge existing disciplinary boundaries. [5]

Similarly most professional societies are structured around specific disciplines; although the Society for Design and Process Science was founded ten years ago with the goal to bridge the gaps and bring together researchers and practitioners from all design-related disciplines. Thus new dialog and arrangements are possible.

7 Conclusions

This paper has presented a framework and principles for a transdisciplinary approach to engineering education and research. There are many challenges faced in designing of engineering systems today, and current disciplinary approaches are inadequate to deal with the complexity involved.

Transdisciplinary approaches are needed—they draw upon commonalities and best practices across disciplines—to enable effective integration of diverse systems.

A vision for the application of transdisciplinary science to engineering education has been discussed. This paper builds upon the earlier work to elaborate on the nature of transdisciplinary design and process science. In particular, this paper argues that the notions of design and process are recognized as fundamental to transdisciplinary approaches to education; several key characteristics of transdisciplinary design and process science have been identified; and a framework for transdisciplinary engineering based on design and process has been presented.

Axiomatic design is presented as an exemplar tool for transdisciplinary engineering. In the context of an established Master's program for transdisciplinary science that has been successfully taught to an aerospace company through Texas Tech for the past ten years, axiomatic design is shown to have been fruitfully used on complex projects integrating multiple disciplines.

Finally, drawing on the successes of this program, a research and educational agenda for future of transdisciplinary design and process is advanced.

8 References

[1] A. Ertas, "The Academy of Transdisciplinary Education and Research (ACTER)," Journal of Integrated Design and Process Science, vol. 4, pp. 13-19, 2000.

[2] N. P. Suh, Axiomatic Design: Advances and Applications. New York: Oxford University Press, 2001.

[3] A. Ertas, T. Maxwell, V. P. Rainey, and M. M. Tanik, "Transformation of Higher Education: The Transdisciplinary Approach in Engineering," IEEE Transactions on Education, vol. 46, pp. 289-295, 2003.

[4] D. Sperber, "Why Rethink Interdisciplinarity?," presented at Rethinking Interdisciplinarity, 2003.

[5] S. Fuller, "Interdisciplinarity: The Loss of Heroic Vision in the Marketplace of Ideas," presented at Rethinking Interdisciplinarity, 2003.

[6] "Oxford English Dictionary," vol. 2005.

[7] T. S. Kuhn, The Structure of Scientific Revolutions. Chicago, IL: University of Chicago Press, 1970.

[8] B. Larvor, Lakatos: An Introduction. London: Routledge, 1998.

[9] L. Laudan, Beyond Positivism and Realism. Boulder, CO: Westview Press, 1996.

[10] G. D. Morgan, K. Kobus, K. K. Gerlach, C. Neighbors, C. Lerman, D. B. Abrams, and B. K. Rimer, "Facilitating Transdisciplinary Research: The

Experience of the Transdisciplinary Tobacco Use Research Centers," Nicotine and Tobacco Research, vol. 5, 2003.

[11] G. Kozmetsky, "Technology Keynote Address," presented at First World Conference on Integrated Design and Process, Austin, TX, 1995.

[12] D. Hastings, "ESD Strategic Plan (2005)." Cambridge, MA: Massachusetts Institute of Technology, Engineering Systems Division, 2005.

[13] "MIT Engineering Systems Division (ESD)."http://esd.mit.edu/.

[14] J. R. Dixon, "On Research Methodology Towards a Scientific Theory of Engineering Design," Artificial Intelligence for Engineering Design, Analysis, and Manufacturing, vol. 1, pp. 145-157, 1987.

[15] V. V. Sushkov, N. J. I. Mars, and P. M. Wognum, "Introduction to TIPS: A Theory for Creative Design," AI in Engineering, vol. 9, 1995.

[16] T. Arciszewski, "Design Theory and Methodology in Eastern Europe," Chicago, IL, 1990.

[17] N. P. Suh, The Principles of Design. New York: Oxford University Press, 1990.

[18] R. Devon, "EDSGN 497 H: Global Approaches to Engineering Design," Penn State University, 2004.

[19] R. Devon, A. McKay, P. Serrafero, S. Bilén, A. de Pennington, and J. Sánchez Sierra, "Integrated Design: What Knowledge is of Most Worth in Engineering Design Education?," presented at MUDD Workshop IV, Harvey Mudd College, Claremont, CA, 2003.

[20] D. T. Ross, "Applications and Extensions of SADT," Computer, vol. 18, pp. 25-34, 1985.

[21] A. Ertas, "Transdisciplinary Engineering Education and Research Model," Journal of Integrated Design and Process Science, vol. 4, pp. 1-11, 2000.

[22] S. Fuller, 2005. http://www.aclupa.org/downloads/Day15AMSession.pdf.

[23] H. A. Simon, "The Role of Software Engineering in Systems for Design And Process Control," Journal of Integrated Design and Process Science, vol. 5, pp. 5-11, 2001.

[24] A. Ertas, "Transdisciplinary Master of Engineering Program," in IDEATE: Institute for Design and Advanced Technology. Lubbock, TX: Texas Tech University, 2001.

[25] D. Tate and Y. Lu, "Strategies for Axiomatic Design Education," presented at Third International Conference on Axiomatic Design (ICAD2004), Seoul, Korea, 2004.

[26] N. P. Suh, A. C. Bell, and D. C. Gossard, "On an Axiomatic Approach to Manufacturing and Manufacturing Systems," Journal of Engineering for Industry, vol. 100, pp. 127-130, 1978.

[27] M. Nordlund, "An Information Framework for Engineering Design based on Axiomatic Design," in Department of Manufacturing Systems. Stockholm, Sweden: The Royal Institute of Technology (KTH), 1996.

[28] M. Nordlund, D. Tate, and N. P. Suh, "Growth of Axiomatic Design through Industrial Practice," presented at 3rd CIRP Workshop on Design and the Implementation of Intelligent Manufacturing Systems, Tokyo, Japan, 1996.

[29] D. Clausing, Total Quality Development. New York: ASME Press, 1994.

[30] N. P. Suh and S-H. Do, "Axiomatic Design of Object-oriented Software Systems," CIRP Annals, vol. 49/1, pp. 95-100, 2000.

[31] S-H. Do and N. P. Suh, "Object-Oriented Software Design with Axiomatic Design," presented at First International Conference on Axiomatic Design, Cambridge, MA, 2000.

[32] iDOT, "ICAD: International Conference on Axiomatic Design." Seoul, Korea: The Center of Innovative Design Optimization Technology (iDOT) of Hanyang University, 2004.

[33] B. El-Haik and D. Tate, "Proceedings of the Second International Conference on Axiomatic Design (ICAD2002)." Cambridge, MA: Institute for Axiomatic Design, 2002.

[34] D. Tate, "Proceedings of the First International Conference on Axiomatic Design (ICAD2000)." Cambridge, MA: Institute for Axiomatic Design, 2000.

[35] D. S. Cochran and Y-S. Kim, "Teaching Production System Design with the Axiomatic Design Methodology," presented at First International Conference on Axiomatic Design (ICAD2000), Cambridge, MA, 2000.

[36] S. Bathurst, "On Learning and Executing Axiomatic Design in the Engineering Industry," presented at Third International Conference on Axiomatic Design (ICAD2004), Seoul, Korea, 2004.

[37] S. W. Cha and K. S. Lee, "Development of Engineering Education Course for Training Creative Engineers using Axiomatic Design," presented at Third International Conference on Axiomatic Design (ICAD2004), Seoul, Korea, 2004.

[38] V. Kumar, "A Web-based Course for Practicing Engineers on Axiomatic Design Principles," presented at Third International Conference on Axiomatic Design (ICAD2004), Seoul, Korea, 2004.

[39] R. Otero, "Case Study: Axiomatic Design of the Space Shuttle Wing - Leading Edge," presented at Third International Conference on Axiomatic Design (ICAD2004), Seoul, Korea, 2004.

[40] B. Fredriksson, A. Killander, and M. Nordlund, "An Effective Model of Transferring New Methods from Academia to Industry," presented at Second CIRP International Workshop on Design Theory and Methodology, Stockholm, Sweden, 1994.

[41] J. D. Hintersteiner and R. C. Zimmerman, "Implementing Axiomatic Design in the Systems Engineering Process: An Axiomatic Design Capability Maturity Model," presented at First International Conference on Axiomatic Design (ICAD2000), Cambridge, MA, 2000.

[42] A. M. Gonçalves-Coelho, J. F. Mourão, and J. J. Pamies-Teixeira, "Axiomatic Design as a Background for Concurrent Engineering Education and Practice," Madeira Island, Portugal, 2003.

[43] D. Tate, "A Roadmap for Decomposition: Activities, Theories, and Tools for System Design," in Department of Mechanical Engineering. Cambridge, MA: MIT, 1999.

[44] D. A. Gebala and N. P. Suh, "An Application of Axiomatic Design," Research in Engineering Design, vol. 3, pp. 149-162, 1992.

[45] N. P. Suh and S. Sekimoto, "Design of Thinking Design Machine," Annals of the CIRP, vol. 39/1, pp. 145-148, 1990.

[46] D. Tate and J. Z. Cha, "The Relationship between Axiomatic Design and Grid Engineering," presented at 11th International Conference on Concurrent Engineering, Beijing, China, 2004.

[47] N. P. Suh, Complexity: Theory and Applications. New York: Oxford University Press, 2005.

[48] N. P. Suh, "Design and Operation of Large Systems," Journal of Manufacturing Systems, vol. 14, pp. 203-213, 1995.

[49] C. A. Whitcomb and J. J. Szatkowski, "Concept-level Naval Surface Combatant Design in the Axiomatic Approach to Design Framework," presented at First International Conference on Axiomatic Design (ICAD2000), Cambridge, MA, 2000.

[50] J. J. Szatkowski, "Manning and Automation of Naval Surface Combatants: A Functional Allocation Approach using Axiomatic Design Theory," in Department of Ocean Engineering and Department of Mechanical Engineering. Cambridge, MA: Massachusetts Institute of Technology, 2000.

[51] D. Steward and D. Tate, "Integration of Axiomatic Design and Project Planning," presented at First International Conference on Axiomatic Design (ICAD2000), Cambridge, MA, 2000.

[52] N. Cross, "Research in Design Thinking," in Research in Design Thinking, N. Cross, K. Dorst, and N. Roozenburg, Eds. Delft, Netherlands: Delft University Press, 1992, pp. 3-10.

[53] S. K. Sim and A. H. B. Duffy, "Towards an Ontology of Generic Engineering Design Activities," Research in Engineering Design, vol. 14, pp. 200-223, 2003.

[54] D. Tate and M. Nordlund, "A Design Process Roadmap as a General Tool for Structuring and Supporting Design Activities," SDPS Journal of Integrated Design and Process Science, vol. 2, pp. 11-19, 1998.

[55] D. R. Wilson, "An Exploratory Study of Complexity in Axiomatic Design," in Department of Mechanical Engineering. Cambridge, MA: MIT, 1980.

[56] J. N. Warfield, "A Platform for Sociotechnical System Design," Journal of Integrated Design and Process Science, vol. 1, pp. 37-53, 1997.

[57] J. N. Warfield, A Science of Generic Design, Second Edition ed. Ames: Iowa State University Press, 1994.

[58] H. A. Simon, "Integrated Design and Process Technology," Journal of Integrated Design and Process Science, vol. 1, pp. 9-16, 1997.

[59] "Proceedings of the Third International Conference on Axiomatic Design (ICAD2000)." Seoul, Korea: Center of Innovative Design Optimization Technology (iDOT) of Hanyang University, 2004.

[60] "The Academy of Transdisciplinary Learning and Advanced Studies." http://www.theatlasnet.org/.

[61] D. Tate, "Design and Creation of Web-based Educational Materials for Teaching Axiomatic Design," presented at Eighth World Conference on Integrated Design and Process Technology, Beijing, China, 2005.

[62] I. Horváth, "A Treatise on Order in Engineering Design Research," Research in Engineering Design, vol. 15, pp. 155-181, 2004.

[63] M. A. Robinson, P. R. Sparrow, C. Clegg, and K. Birdi, "Design Engineering Competencies: Future Requirements and Predicted Changes in the Following Decade," Design Studies, vol. 26, pp. 123-153, 2005.

[64] S. Upham, "The Aims of Graduate Education," presented at Workshop on Global Transdisciplinary Education, Pasadena, CA, 2001.