A Systems Approach to Design: Research and Some Results

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Abstract. A systems approach to design means designing from a holistic perspective. It is an approach focussed on understanding the functionality for which the system is designed for by keeping the focus on its need, context, and its intended lifecycle. This paper is focused on the need and current challenges of teaching engineering students a systems approach to design. The paper proposes definitions of five core concepts of a systems approach to design. Theses concepts are context, abstraction, trade-off, interdisciplinarity, and value. The paper also includes discussion on the findings of a survey of students and faculty on these fundamental concepts of system design.

Keywords: System design, Systems approach, Context, Abstraction, Trade-off, Interdisciplinarity, Total design.

Introduction

The characteristics that are expected of the engineers today are to understand the functional core of the engineering process as well as to think across disciplines (laterally) as well as in disciplinary depth (vertically). They also need to communicate ideas effectively to influence diverse groups, including non-engineers while acting both independently and as a team member. To do so an understanding of the relationship of the engineering enterprise to the social/economic/political context of engineering practice and the key role of this context in engineering decisions are required [NRC, 2003]. These characteristics and the demands of global economy require a holistic approach in addressing the engineering challenges.

A systems approach to design means designing from a holistic perspective. It is an approach focussed on understanding the functionality for which the system is designed for by keeping the focus on its need, context, and its intended lifecycle. In other words this type of holistic design with a 360 degree view and a zoom lens is called total design. Engineering education is, by necessity, mostly concerned with the acquisition of knowledge (in the humanities, management, the sciences...) and analytical techniques and skills in engineering, usually within a specific discipline or domain (e.g. mechanical, electrical, etc...). The rigorous application of such skills and knowledge to engineering elements is usually called partial design, and is often exemplified in some senior capstone design projects. But in today's world, industry is concerned with a systems approach to design or designing for the total system (total design): the integration of numerous technical and non-technical disciplines toward the development of new products, systems and services. In this regard, a misdirected engineering rigor, overtly focused on a discipline, will always give rise to sub-optimal total design.
Furthermore, and this is a major factor when considering multidisciplinary design projects, each student should be able to see how his partial contributions fit into the whole. Success in the marketplace requires total design rigor and engineering rigor of the highest order – never the one without the other. This paper is focused on the need and current challenges of teaching engineering students a systems approach to design.

The paper will also provide an overview of the research initiatives the authors have taken to overcome such challenges and to teach systems approach to engineering students. The authors of this paper have been involved in several research studies and publications in improving the design approach described above and in defining a systems approach to design. This paper will focus on defining five core concepts of a systems approach to design. These concepts or elements of system-level design help in defining the uniqueness of the field called Systems Engineering. These concepts are context, abstraction, trade-offs, interdisciplinarity, and value. The paper will share the results of a survey of students and faculty on these five concepts. A systems approach to design will not only be valuable for the systems engineering community but the entire engineering community in general.

**Need for a systems approach to design**

Increasingly, we are realizing the challenges of teaching engineering design to our students so that they will be ready to practice in a global socio-economic environment increasingly dominated by engineering systems and the design of engineering systems, and driven by innovation. Students should be exposed and, thus, should be able to apply the concepts and methodologies of *total design* in order to be able to effectively participate on multi-disciplinary teams. For example, students should learn how to define problems in response to a need or a technological opportunity, determine customer or stakeholder requirements, formulate alternative concepts and select an optimal one, etc. Engineering students often seek the “best” solution (which to them is a purely technological one and most often entirely rooted in a specific engineering discipline) with little regard for the context in which their product, system, or service may be deployed, the societal or business need it may fulfill or even its relations to all the other engineering, business or even artistic domains contributing to the successful introduction of any new product or system. This design approach restricts the ability of students to identify and resolve errors through the different life-cycle phases, therefore, resulting in most errors getting caught at the very downstream phase of systems integration – when the entire system is being assembled and tested for the first time. A further drawback of this methodology is that the students are not able to establish and trace the functionality of the system throughout the life-cycle resulting in the need for rework.

**Total Design: A Systems Approach**

Daniel Pink [2005] in his exploration of the role of the L-Directed (using the left side of the brain) and R-Directed (using the right side of the brain) thinking is moving us from the Information Age to the Conceptual Age. L-Directed thinking is characterized by sequential, literal, functional, textual, and analytic thinking. R-Directed thinking is a form of thinking and an attitude to life characterized by simultaneous, metaphorical, aesthetic, contextual, and synthetic thinking. We need both approaches to lead a fulfilling life – they work together. Similarly, we need to balance the science and art of engineering in order to design successful systems – systems that take into account not just the obvious and intended functionalities but also provide for the unintended consequences of interacting system elements. So how does one define this balanced approach of designing systems? Design is a classic whole-minded aptitude. It is a combination of utility and significance, stripped to its essence, it can be defined as the human nature to shape and make our
environment in ways without precedent in nature, to serve our needs and give meaning to our lives [Pink, 2005]. The idea of design and development is what most distinguishes engineering from science, which concerns itself principally with understanding the world as it is [Petrosky, 1996]. The first public high school in the US with a design-centered curriculum – the Charter High School for Architecture and Design started in 1999 in Newark NJ produces ‘people who can think holistically’. ‘This school will enhance their ability to solve problems, understand others, and appreciate the world around them’. An approach of this kind will lay the foundations of teaching the ‘right design’ and called as a systems approach. The term ‘right’ has to be interpreted in the context for which the design is being made. Petroski points out that no engineering problem is ever solved to everyone’s satisfaction. Engineering is the art of compromise, (through trade-offs as discussed in the later sections) and there is always room for improvement in the real world. Innovation and creativity is an important element of the right design. In the current and the future world that we are going to be designing for, there is one thing that is inevitable and irreversible and that is the complexity of systems and system functionalities and the resulting impact on unintended consequences and probable risks of failures. A systems approach helps one to understand all these challenges in a system’s context and to create a right design by addressing these challenges and establishing a complete system lifecycle.

Total Design Life Cycle

Design is an activity whose starting point or trigger is a societal need or business opportunity that may arise because of a functional or operational deficiency, a technology fusion or breakthrough, behavior analysis or an accidental discovery. The major aim of a systems approach is to develop an operational model of the system for all phases of the life-cycle, the model is then used as a basis for detail design. It is this top-down approach to design that has been missing from engineering curricula and that will be increasingly needed in the design of future systems. In fact, total design or a systems approach to design encompasses most of the approaches, methods and tools of system design and systems engineering as shown in Figure 1. The systems approach to design focusses on the design and development lifecycle of the system (Figure 2) and addressing requirements and feasibility of its operational lifecycle.

Figure 1 Systems Engineering and Total Design
Teaching System Design

System design is the most critical aspect of engineering a system as it brings the front-end processes of customer requirements and the downstream process of development and implementation together. System design is an essential task in engineering a system that lays the foundation for the tasks in the later phases of the engineering and operational process.

In an attempt to address the challenges of teaching systems approach to design, the authors redesigned and pilot tested the fundamental engineering design undergraduate courses at Stevens to include a systems approach to design [Jain et al, 2006]. Some of these modifications and enhancements included tools, techniques, and case studies which were already being used for the graduate design courses. As a result of this experience the authors realized that the fundamental concepts of system design have not been identified explicitly even though their subject matter has been taught in existing design courses in almost all engineering disciplines. At the graduate level a systems approach to design is an integral part of teaching System Engineering (SE). This systems approach is addressed through the lifecycle approach to SE. However, any attempts to define the fundamental concepts of systems design that may be generic enough to apply across domains has been non-existent. Based on their experiences from graduate-level design courses the authors selected the five design concepts and built teaching materials for the undergraduate design labs. This was not a problem as these design courses focusing on systems approach have been highly tailored for specific domains and taught to graduate students with work experience. The real life experiences of designing systems in a multidisciplinary environment resulted in exposing and reinforcing the fundamental concepts to the graduate students. This has also addressed any misconceptions of the design process and established a conceptual model for understanding systems approach to design. Hence the real challenge now lies in building that conceptual model by identifying the fundamental design concepts and addressing the misconceptions that the engineering students might have. An assessment of teaching systems design by addressing some of these concepts will further help refine these concepts.

System Design

System design is a key factor in a system’s success or failure, as well as a key cost driver. Thus, identifying means to better understand issues around system design will lead to improvements
It is through system design that the requirements are optimally distributed across the system components to define the solution. It provides a “logical construct for defining and controlling the interfaces and the integration of all the components of the system.” System design produces a fundamental structure of a system: its elements, the roles they play, and how they are related to each other and to their environment within all the given rules, regulations, and other constraints and provisions.

Understanding fundamental system design concepts is integral to the success of future engineers. Yet, these design concepts are not clearly defined. Designs are often based on ‘common sense beliefs,’ thereby leading to decisions resulting from incomplete or inaccurate information. Integrating such concepts into instruction will help students appreciate the “total” perspective of design and participate effectively on multidisciplinary teams. A necessary first step is to identify these concepts. The understanding of these concepts will enable future engineers to analyze and design systems from a holistic perspective.

**System Design concepts**  
The methodology to identify and define the fundamental concepts of system design had three stages to it. A literature review on systems design with a systems approach was performed and few key concepts that are mostly common among these literatures in describing system design were collected. An informal survey of system design experts (fellows of International Council of Systems Engineers - INCOSE) on concepts of system design and common misconceptions around system design was conducted. A list of key concepts was extracted from the survey responses. These two stages were conducted concurrently. The experiences, feedbacks, and discussions with students from the pilot effort [Jain et al, 2006] of incorporating system approach to design concepts in fundamental engineering design courses were reviewed and compared against the populated list of key concepts. Based on this five fundamental concepts of system design was identified. The five system design concepts [Jain et al, 2008] that have been explored are: context, abstraction, value, interdisciplinarity, and trade-offs. Their role in the design process is briefly discussed below:

**Context:** Understanding the design context relates to conceptualizing beyond the multidisciplinary content contribution in engineering design to include how design is practiced in a ‘context.’ Context grounds and conditions the constraints and content of a given engineering design. Constraints provide the scope of a design and they may include regulatory requirements, all forms of rules related to performance, scalability, security, stress, volume, choice of technology, etc. Content is embedded within context. However, the content is normally emphasized as the essence of engineering design, because it includes the steps and processes involved in carrying out an actual physical design. Context is the world out of which the need for the design arises in the first place, and in which the implemented design will eventually function [Moriarty, 1994]. Context determines the internal and external interface analysis for a given system. Not having a contextual understanding of the design leads to an isolation of the ‘problem’ from the ‘solution,’ resulting in sub-optimal solutions or products that do not address the needs of customers and users. It is important that engineers understand both the functionality (content) of the design, as well as where it will be used (context).

**Interdisciplinarity:** A pre-requisite of systems design is the integration of analytical strengths of two or more, often disparate, scientific disciplines to create a new, hybrid
discipline. By engaging seemingly unrelated disciplines in SE design, traditional gaps in terminology, approach, and methodology might gradually be eliminated. Instead, a true meeting of minds can take place—one that broadens the scope of investigation, yields fresh and possibly unexpected insights, and gives rise to innovative and more analytically sophisticated engineering designs [NIH, 2007].

The interdisciplinary nature of systems design allows each team member to bring his/her own discipline knowledge and perspectives to bear. The systems (holistic) design approach is based on the premise that design has to be viewed from the point of view of all relevant disciplines and stakeholders – the system in its totality. For example, aircraft design requires input from engineers in disciplines such as aero-dynamics, electrical, mechanical, materials, computer, etc. Therefore, a design team for an aircraft that does not include these and other disciplines would most likely fail to address important aspects of the missing discipline(s). Therefore, when analyzing the total functionality of a system and translating it to a design, one needs to address its design with an interdisciplinary team, which promotes a common view of the design process and a common methodology, with a minimum of misconceptions.

Systems thinking, a process of defining a phenomenon holistically—by its contents, objectives, interactions, relationships, and environment—is integral to the design process. It uses the common tools of analysis and synthesis to form new conclusions [Wigal, 2004]. In practice, it is a continuum of activities that range from the conceptual to the technical – what we earlier call the ‘L-Directed’ and ‘R-Directed’ approaches. At the conceptual end of the spectrum is an adoption of a systems perspective—seeing the whole forest and the relationships and patterns among the trees. At the other end of the continuum, activities become more concerned with implementation of the viewpoint – analyzing why and how the forest patterns exist in the observed manner.

Value: Systems exist to generate value for their stakeholders. The creation of well-defined value models provides direction that improves the quality of trade-off decisions in the design of systems, especially in systems that are deployed to many users in various settings [Microsoft, 2005]. Therefore, understanding the value proposition of the chosen design is critical for successful designs and systems developed on the basis of such designs. Designing for delivering value in the shape and form of a total system (holistic perspective) is something that is rarely addressed by design courses in today’s engineering curricula. The partial design (discipline focused) view inhibits the ability to perceive the value of the total design delivered in the final system. The intellectual content of most engineering disciplines is component-oriented and value neutral. The emphasis on stakeholder value provides a key distinction between Systems Engineering’s concern with stakeholder values and the ostensibly value-neutral orientation of other engineering disciplines. The intellectual content of realizing successful systems involves reasoning about the relative value of alternate system realizations to success critical system stakeholders, and the organization of components and people into a system that satisfies the value propositions of the success critical stakeholders.

Trade-offs: The selection of a design alternative based on trade-off analyses, an important component of evaluating design concepts. The purpose of evaluating different potential design concepts based on trade-offs such as, cost, time, performance, functionality or sometimes feasibility etc., is to select the one that is most optimally suited to the task. Design should not be driven by having a single option and implementing it. Several concepts need to be reviewed based on their pros and cons and one will be chosen to be translated into a design and subsequently into a final system. The purpose of conducting a trade-off analysis is to
understand how and to what extent the total design can address the functionality needed by the user-community. System-level design allows the possibility of assessing user requirements (needs) and the cost and benefit of addressing each of the requirements in a given systems design. Trade-off involves a prioritization of the requirements by the users-community into essential, conditional, optional, and other similar categories. Based on such classification of requirements, resources are allocated for designing and implementing systems that can deliver such requirements. Because resources are always limited in some way, proposed solutions can only be conceived of as optimal, not perfect, because trade-offs always have to be addressed and balanced.

Abstraction: The ability to abstract a design concept independent of a solution requires that systems engineers are able to think of design concepts that are not dependent on specific solutions. Keeping designs and solutions separate provides more flexibility, adaptability, and cost effectiveness, and encourages the exploration of multiple solutions. Abstraction allows designers to be able to move between different levels of decomposition without losing the guiding architectural principles. Abstraction is something traditionally left to the domains of artists and philosophers. Engineers have traditionally been expected to go directly from understanding the users’ needs to the actual development of a product to support and fulfill those needs. The risk with this approach is that a solution may be selected too early, without evaluating alternative ways in which to address the users’ needs, and thus resulting in a sub-optimal, inefficient, costly, and often, unscalable and inflexible solution. In today’s world, where technologies and solutions are often being driven by a need to implement ‘faster, cheaper, and better’ approaches, tying a design too early with a given solution can prove to be a very expensive proposition in both the short- and the long-run.

Current Research
The authors’ current research involves further identifying some common misconceptions that students have about the above discussed five concepts of system design. Furthermore, develop a tool that can measure the misconceptions students have and tailor system design courses to focus on addressing those misconceptions. An assessment of student learning of the concepts with the enhanced teaching materials will provide guidance on how students learn the concepts, what works, and what does not work. Several iterations of this methodology will help improve our understanding of how to develop design teaching materials, methods, and pedagogies that emphasize a systems approach to design.

Misconceptions are nothing but an alternate conception that the students develop to explain an undefined phenomenon or occurrence. When most engineering students are asked about the trade-offs in engineering a system it is common to get a response about only cost. This is because of the misconception that the students have that when there is a trade-off it can only occur in terms of cost. An alternate conception has occurred among students as they have seen trading in terms of cost. Hence they automatically associate trade-offs with cost. Explaining the bigger picture or a real life experience of designing a system from a holistic perspective would have taught the student that trade-offs do not always have to do with cost. But it is essential to understand that the student has this misconception and target it. Else all the advanced information on how to perform trade-offs or decision analysis during engineering a system might build upon a misconception and result in difficulties of understanding and applicability to problems. Hence identifying common misconceptions that a set of students taking the course are having is very important to improve understanding and retention of concepts discussed in the course among the students. Misconceptions vary among students based on their experiences and exposures.
In order to identify common misconceptions around these five concepts of system design, instructors of system design courses were surveyed. Also, a set of graduate students taking system design courses were asked to define and describe these fundamental concepts in their own words. A list of misconceptions was then identified from their definitions and descriptions. These were compared with the misconceptions that the instructors identified. There was significant overlap between both. A survey tool was then developed to identify misconceptions. The tool consists of terms related to each of these concepts and under each term there were a set of right conceptions and misconceptions. The students are asked to choose the statements under each term that describe or define the terms. This tool has been piloted and results have been documented [Jain et al, 2008]. Figure 3 below illustrates the level of misconception under each of the five identified concepts of system design. The bars indicate percentage of misconceptions among the students involved in the pilot test for each of the five concepts. The trade-off concept had the most number of misconceptions and value had the least misconception. The students involved in the pilot test were UG in the senior year and graduate students who had some knowledge of systems approach to design and of these concepts. Hence, the percentage of misconceptions shown might be slightly lower than if the test was to be conducted with freshmen year students. Future research work will include a more diverse student group in order further confirm our results.

![Figure 3 Percentage of misconceptions across the 5 concepts of system design and architecture](image)

**Conclusion**

The results of the proposed research have the potential to positively influence education and research in SE as a specific academic discipline, as well as the infusion of SE approaches in discipline-specific programs and courses, and the practice of systems approach in the workplace. This enables practitioners and scholars to cultivate further the habits of systems thinking and analysis.

In the long run the creation and validation of the system design concept inventory [Evans et al, 2003], a tool for understanding the misconceptions the students have, will provide an instrument for future research on student learning and concept development. By understanding common misconceptions, current and future research will lay the groundwork for improved instruction on important systems concepts. As researchers and educators use the concept inventory to probe differences among students, they may develop ways to make system design concepts and resulting engineering competencies more accessible for all students, particularly students from under-represented groups. Doing so will produce a diverse, capable field of
Systems Engineers who apply these systems approach concepts in systems design and analysis, to the benefit of business and society.

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**Biography**

Dr. Rashmi Jain is Associate Professor of Systems Engineering at Stevens Institute of Technology. Dr. Jain has over 15 years of experience of working on socio-economic and information technology (IT) systems. Over the course of her career she has been involved in leading the implementation of large and complex systems engineering and integration projects. Her teaching and research interests include systems integration, systems architecture and design, and rapid systems engineering. Dr. Jain is currently the Head of Education and Research of INCOSE. In this role she is leading the development of a reference Systems Engineering curriculum. She holds Ph.D. and M.S. degrees in Technology Management from Stevens Institute of Technology.

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