# Introducing Systems Modeling at the Freshman Level

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## Abstract

The Engineering program at the University of Tennessee at Chattanooga (UTC) emphasizes the elements of the design process throughout the curriculum, beginning with the freshmen year. At the sophomore level all engineering students use design concepts to design, build, and test small structural and mechanical projects. At the junior and senior level the students use the design process to solve real-life and open-ended interdisciplinary industry-based problems provided by industrial sponsors. In addition, students apply design concepts in a three credit hour discipline-based senior capstone project.

However, it is at the freshmen level where the students are introduced to the foundations of the design process. The freshmen course emphasizes (1) problem definition, (2) attribute generation, (3) function, constraint and objective identification, (4) idea generation, (5) creative thinking, and (6) simple decision-making using individual and team exercises. All this is done in the context of a real-life application—improving an entity. In this case the entity is an everyday small appliance, tool, or toy.

Systems engineering is an interdisciplinary approach to evolving and verifying an integrated set of product and process solutions that satisfy customer needs. It uses modeling techniques to analyze—separate a study or entity into individual pieces—and synthesize—look at the relationships between parts to form new conclusions. It is an integral part of the design process for any engineering discipline.

This paper describes the techniques and models of systems engineering introduced to freshman students in the Introduction to Engineering Design course at UTC.

## Introduction

*The world we have made as a result of the level of thinking we have done thus far creates problems that we can not solve at the same level (of consciousness) at which we have created them… We shall require a substantially new manner of thinking if humankind is to survive. – Albert Einstein*

Systems' thinking is rooted in systems engineering which practices an interdisciplinary approach to evolve and verify an integrated set of product and process solutions that satisfy customer needs. Systems thinking begins with analysis—separating a study or entity into individual pieces—and emphasizes synthesis—looking at the relationships between parts to form new conclusions. Systems thinking aids the user to take into account a greater number of interactions as a study evolves and to categorize interactions as to level of effect on the final solution. The spirit of systems thinking makes it an effective tool in a variety of applications and levels of complex problems.

This paper describes how systems thinking and modeling techniques are introduced to and applied by freshman engineering students at the University of Tennessee at Chattanooga. The basic theory behind systems thinking—including systems methodologies and systems definition—and the relationship systems thinking has with the problem solving process are discussed. The student course project that benefits from the systems modeling techniques is also described. Of interest is the ability of students to understand the techniques and models and to apply them to the course project. This paper also comments on what teaching strategies have worked well in introducing systems engineering concepts and which have not.

**Systems and Systems Analysis**

*For every complex problem there is always a simple solution. And it is wrong. –H.L. Mencken*

Systems analysis is fundamentally different than traditional forms of analysis. It begins with analysis—separating a study into individual pieces—but emphasizes synthesis—looking at the relationships between parts to form new conclusions. Systems analysis is most often used when confronting complex problems with a variety of variables that cannot readily be quantified and whose structures are not well defined. It uses ad hoc models to represent variables (the environment, components, and alternatives) associated with specific evaluation questions.[1]

***Defining a System***

Systems can be defined in a variety of ways using terms like interrelationships, goals, parts, and subsystems. For example, DeGreene contributes that systems are composed of "people, vehicles, computers, power plants, buildings, roads and so forth organized in terms of subtle and superimposed interrelationships."[2] Churchman adds that the interrelationships should be coordinated to accomplish a set of goals.[3] Kast and Rosenzweig and Jenkins add that a system can be broken into subsystems of lower order that also have goals.[4,5] These secondary goals influence the system goals. DeGreene integrates the above and provides the following definition:

> *A system is a set of elements or subsystems in active interaction as a bounded entity to achieve a common purpose that transcends that of the elements in isolation.*[2]

One has to be careful using this definition, however, because a single phenomenon can be defined several ways based on boundary and content definitions. To ensure consistency in defining systems, Churchman suggests that systems be determined by defining boundaries and content based on five influences:[3]

- The total system objectives and the performance measures of the whole system associated with the phenomenon
- The phenomenon's environment
- The resources of the phenomenon and encompassing system
- The components of the system associated with the phenomenon, their activities, goals, and measures of performance
- The management of the system associated with the phenomenon.

### *Systems Analysis Methodologies*

Systems literature often refers to four specific methodologies that encompass systems and systems analysis—(1) structured systems analysis and design (systems engineering), (2) 'soft' systems analysis, (3) socio-technical design, and (4) cybernetics.[6] All four are used to identify and solve systems problems for various environmental and operational conditions. For example, systems engineering concerns the whole system, providing a network (or management process) within which to tie many separate and possibly divergent disciplines by taking an iterative, interdisciplinary approach. Specifically, applying systems engineering involves three steps—requirements analysis, iterative top-down design, and bottom-up integration—that are repeated within three life-cycle phases—system definition, system development, and system deployment.[7] The result is an interdisciplinary application of science and engineering that evolves and verifies an integrated and life-cycle-balanced set of system product and process solutions that satisfy customer needs.[8]

'Soft' systems theory is problem- and process- oriented, rather than technique oriented.[9] Soft systems theory takes as its starting point not a problem but a situation in which at least one person has a *feeling* that some elements of a situation or process are problematic and hence worth exploring. The methodology moves from finding out about the situation to taking action within it, and does so not by relying on experience but by doing some careful, formally organized systems thinking about the problem situation.[10]

Socio-technical systems theory is used to define the *behavior* of organizations. Specifically, this theory defines organizations as pursuing a primary task that can best be realized if their social, technological, and economic dimensions are jointly optimized.[11] An application of this approach is DeGreene's examination of how the human, behavioral and social subsystems affect and are affected by the nonhuman (technological) subsystem and how these subsystems collectively affect and are affected by the dynamic social and natural environments in which the larger system is a part.[2]

Cybernetics, the science of control using feedback and communication, also concerns the study of organizations. However, its application is mainly the study of managing organizations.[11] The use of feedback in the analysis of organizations illustrates organizations as adaptive structures that take action in response to environmental changes to maintain a "steady state." The cybernetic approach makes the explanations of goal-seeking behavior possible.[12]

### *Systems Thinking*

Systems thinking is a generalization of systems analysis and encompasses the basic precepts of the four methodologies discussed above. There appears to be no formal accepted definition of systems thinking. However, many advocates of "systems" and "systems theory," and "systems analysis" agree that the aim of systems thinking is to spell out in detail what the whole system is, including its environment, its objectives, and how the objectives are supported by the activities of its parts.[3] Others promote that the whole system is not just the sum of the parts or subsystems; it is a system composed of *interrelated* subsystems.[4] These interactions should be studied with respect to their dynamic as well as static relationships. Thus, the subsystems of an entity should not be studied separately with the idea of putting the parts together into a whole. The starting point has to be with the total system and should consider feedback loops and dynamic interaction. Thus, systems thinking can be defined as:

> the process of defining a phenomenon holistically; by its contents, objectives and its interaction with the contents, objectives, relationships, and resources of the environment in which it operates or is applied.

This holistic view requires systems thinking to begin with analysis—separating a study into individual pieces—and to emphasize synthesis—looking at the relationships between parts to form new conclusions.

The majority systems thinking applications have occurred in the area of process analysis and improvement initiatives in industry—specifically the initiatives that improve process quality. Managers and consultants to industry have begun to recognize the value of transforming from classical department-based organizations to process-based organizations.[21] The process-based initiatives include benchmarking, concurrent engineering, continuous improvement (CI), ISO 9000, mistake-proofing, quality function deployment (QFD), six sigma, lean manufacturing, theory of constraints (TOC), Toyota Production System (TPS), and total quality management (TQM). These are systems thinking based initiatives. For example, TOC is based on a number of principles that mention systems and systems thinking—(1) systems thinking is preferable to analytical thinking, (2) an optimal system solution deteriorated over time as the system's environment changes, (3) the system optimum is not the sum of the parts, and (4) knowing what to change requires an understanding of the system's current reality and its goal, and the difference between the two.[23]

**System Models**

*The real voyage of discovery consists not in seeking new landscapes but in having new eyes. – Marcel Proust.*

Problem solving is the essential motivation for systems thinking—the more we know, the better we can define, analyze, test, and deploy. Being able to decompose a phenomenon into components and understand interrelationships is necessary to effectively and efficiently define/redefine, control, and improve the phenomenon. Specifically, systems thinking directly influences problem definition, bounding, needs and constraint analysis, partitioning, structuring, alternative analysis.

Models—abstract representations of a phenomenon—are often used to define system boundaries and content and to guide system and process definition, design, and implementation. The initial consideration of a system uses models with a low degree of restriction—for example, input-output, input, output, functional, and process models.[13] In addition, as the system definition evolves, models allow for recognition and definition of detailed parts and their relationships. Systems models begin as qualitative models though can become quantitative models as the problem solving process progresses toward design and implementation.

One model often used illustrates a process or entity as an architecture that involves operational, functional, technical, and physical descriptions (see Figure 1). The operational description introduces the entity and concisely defines how it meets its stated goal. The functional description is a decomposition of the main function of the entity into its subfunctions, taking care to define the required inputs and outputs of each subfunction and the behavior of each function. The technical description defines the arrangement, interaction, and interdependence of the elements of the entity so that a set of requirements is met. The physical architecture clarifies the physical resources that support and constitute the entity, as well as their relationships [10].

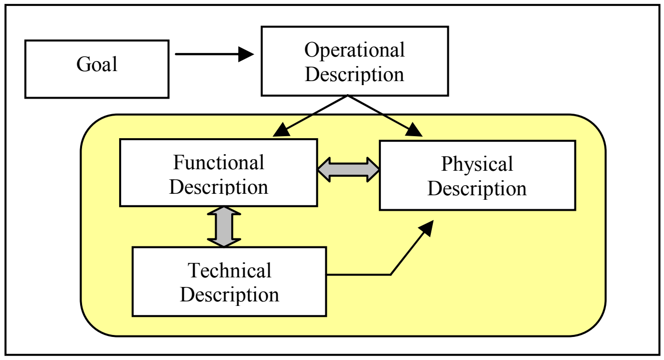


Figure 1.0: Process Approach to Systems Modeling [16]

**Introducing Systems Models**

At UTC we introduce the use of low level systems modeling at the freshman level in the "Introduction to Engineering Design" (IED) course that all engineering students take. The freshman design course uses short lectures and hands-on design exercises to emphasize the body of the design process—problem definition, conceptual design, alternative selection, and preliminary design (see the shaded portions of Figure 2).

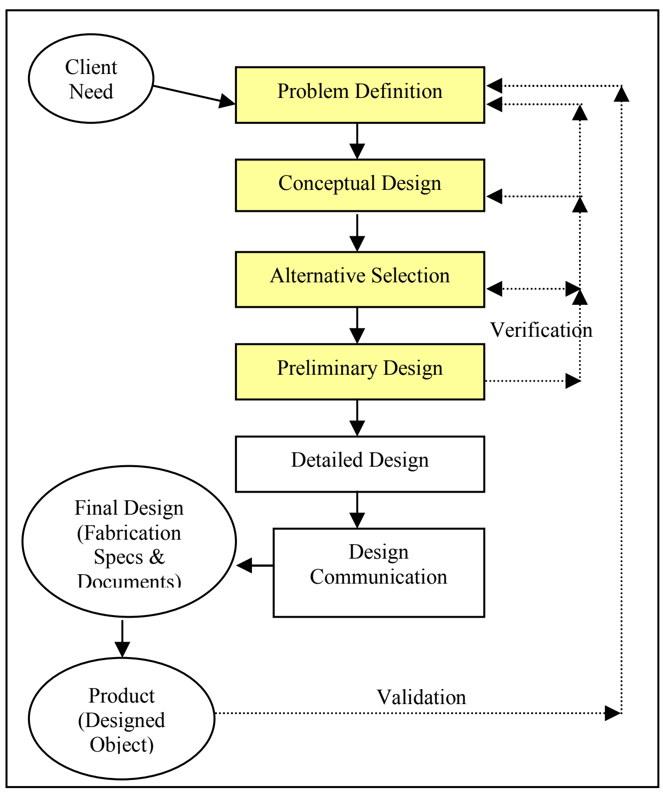


Figure 2.0: The Design Process (UTC Emphasis)

Concurrent with the design methodology is a graphics design laboratory on graphical sketching and CAD. A major outcome of the course is a small team design project, with application of basic engineering science, engineering graphics, and written and oral presentation.

***The Course Project***

The goal of the project in IED is to design a better device for a specific customer. The device of emphasis is a small tool, appliance, or toy costing less than $25.00 retail. The project begins the second design session meeting and is completed the last week of class when the students demonstrate their prototype. The project has two parts—the individual component and the team component. The individual component emphasizes identification of the problem and understanding of the device. The team component emphasizes idea generation, decision-making, and design test. The project process is shown in Figure 3.0.

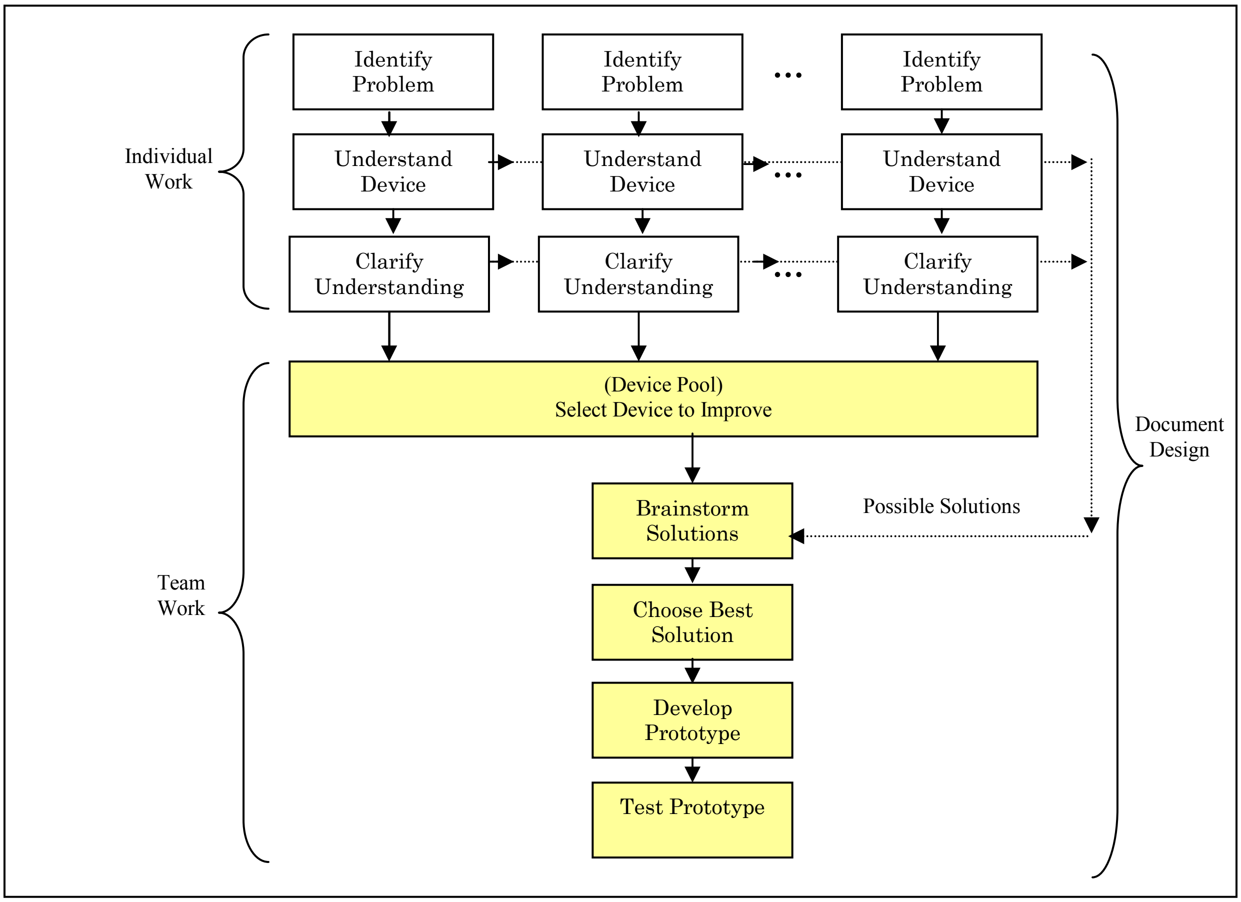


Figure 3.0: The IED Project Process

Tables I and II summarize the class discussions and assignments that introduce and integrate the concepts of design and systems thinking with the project activity.

Table I: IED Topics and Assignments

| Topic | Lecture Emphasis | Assignment |
|---|---|---|
| Introduction to Engineering | Defining the engineering design process and the entities involved. | |
| Problem Formulation | Defining client/customer needs | Select a small tool or appliance in need of improvement; determine client and client needs; create a goal statement, design objectives and constraints; present in a report |
| Developing Design Criteria | Identifying and distinguishing between attributes, functions, objectives, constraints, and implementations of a device. | List device attributes; clarify objectives; define functions; create objective tree; create 3 levels of functional block diagrams; present in reports |
| Technical Writing | Formatting for readability; eliminating vagueness, sexist language, wordiness; ensuring parallel construction | Create a report on device research and findings |
| Ethics and Professional Context | Recognizing ethical situations | Complete survey on "Professionalism Indicators" |
| Oral Presentations | Types of oral presentations; planning and organizing; creating and using slides; delivery | Present research and findings on device |
| Group Dynamics | The triad of teaming components; responsibilities of the team leader and team members; ethics in the team environment; components of a successful team. | Take Personality Style Survey; participate in team building exercises |
| Project Management | Recording results of team meetings; setting reasonable goals; scheduling activities; creating a Gantt chart; using Microsoft Project | Create personal MS Project Gantt charts for semester; create team MS Project Gantt chart; record minutes for all team meetings |

Table II: IED Topics and Assignments – Creating Results

| Topic | Lecture Emphasis | Assignment |
|---|---|---|
| Concept Generation and Creativity | Defining concept generation and creativity; Model of the creative process; Blocks to creativity; techniques for aiding idea generation | Decide which device to improve; brainstorm 10 possible solutions; create a morphological chart of solution components |
| Decision-Making | Identifying the need for decision-making tools; introduce pair-wise comparison, evaluation scales and metrics, comparison evaluation using scales and weights | Select 3 to 5 solutions you believe best; compare using comparison techniques; select best; substantiate reason |
| Prototype Testing | Understanding the need for test procedures; creating usable test procedures; documenting procedures | Determine how to complete a puzzle; write instructions for another team to put puzzle together; write test procedures for new functions of your device. |
| Documenting Design | Creating a usable package | Create team report |

### *The Systems Thinking Emphasis*

At the beginning of the semester each student selects and purchases a small tool, appliance, or toy he or she or someone they know has observed as operationally or functionally deficient. Initially the students learn all they can about this device including it history and its users and clients to identify the problem. They look at the device's physical, functional, and operational features and define device attributes. They can learn about the device on the product website or through other applicable resources, or by tearing down the device and researching each component.

To aid the students in this assignment students are introduced to and practice using simplified objective trees, input/output functional block diagrams, and function node trees to clarify and document their understanding of the devices' functional and objective relationships. Objectives trees, functional block diagrams, and function node trees are systems thinking tools designed to help the students focus on understanding the device from an environment focus. Figure 4.0 shows a student generated objective tree for improving the basic drafting compass. This tree was initially generated by a single student during the first half of the semester then revised and improved by the student team during the second half of the semester.

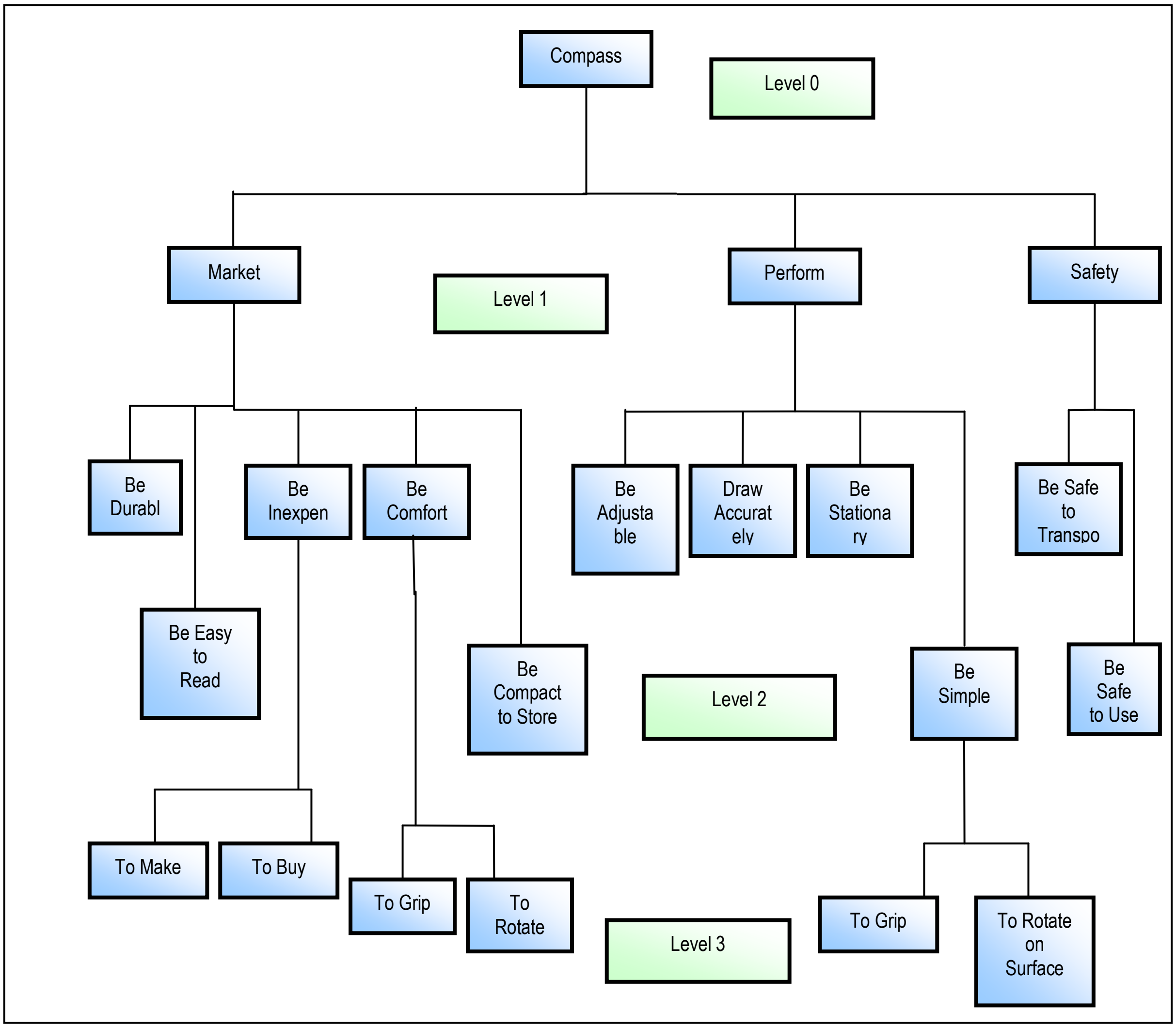


Figure 4.0: Sample Objective Tree

Similarly, the individual student generated input/output functional block diagrams to define the functional relationships of the drafting compass. The team directed to improve the drafting compass then revised and improved the diagrams. This exercise ensures that the functional architecture considers all necessary inputs, outputs, controls and supporting mechanism in functional relationship definition of the device. Controls are shown entering the top of the blocks, mechanism are shown entering the bottom of the blocks, inputs enter the left side of the blocks, and outputs exit the right side of the blocks. The context diagram and two lower level diagrams for the drafting compass are shown in Figures 5.0, 6.0, and 7.0.

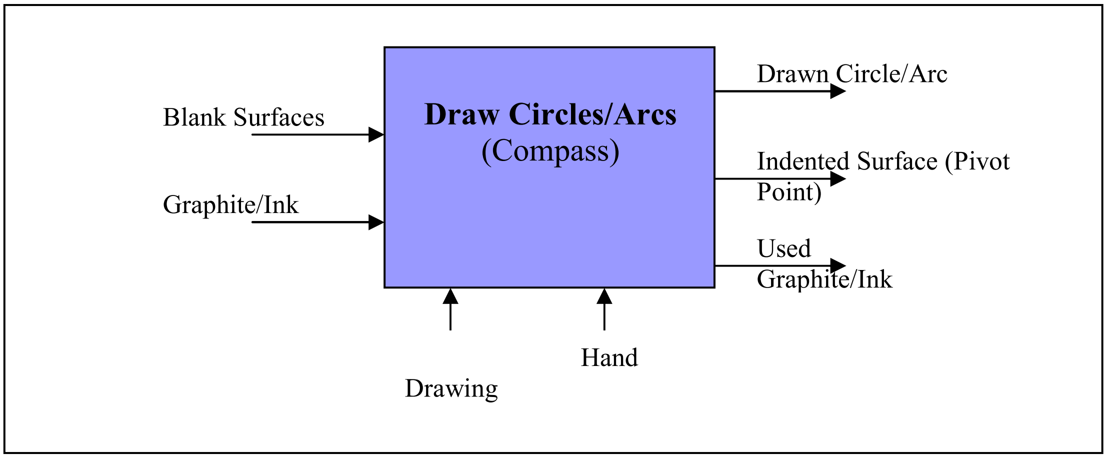

Figure 5.0: Sample Context Diagram

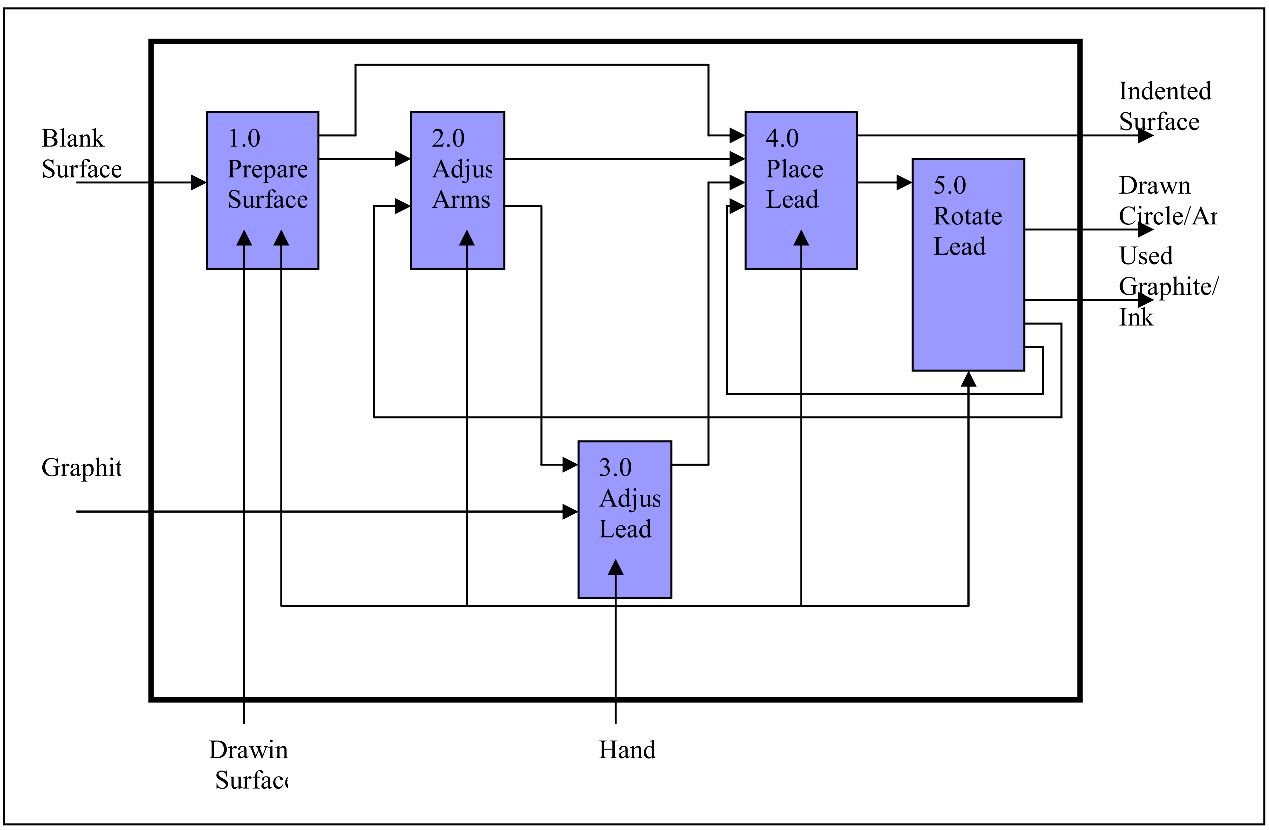


Figure 6.0: Sample Level 0 Input/Output Diagram

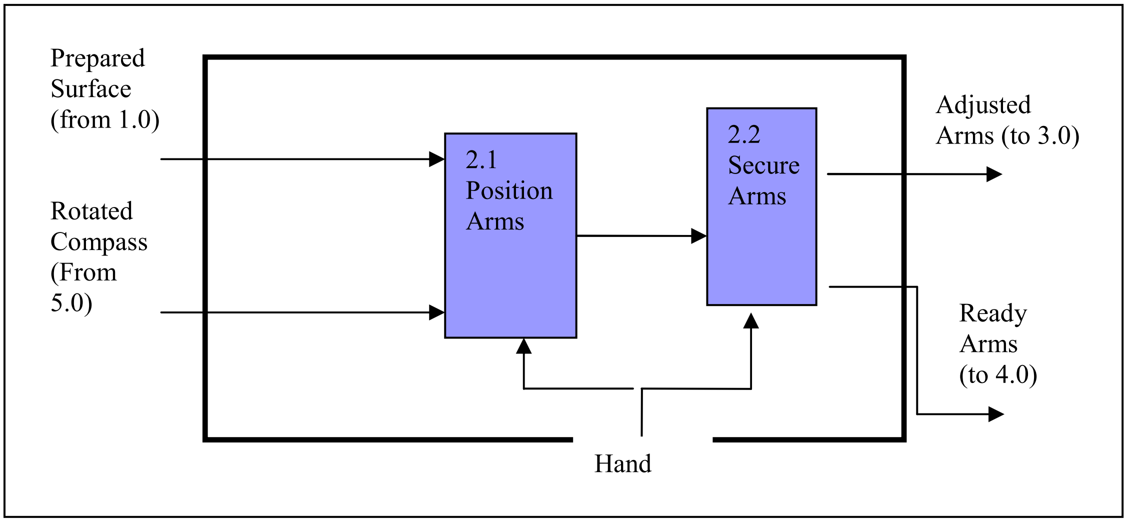


Figure 7.0: Sample Level 1 Input/Output Diagram

**Discussion**

As is for any type of work expected of students, the results and the feedback from the students experiencing the IED project and the emphasis on design and systems thinking vary. The students have some difficulty defining their devices with respect to functions. The systems practice of using input/output functional diagrams takes a level of thinking they are not used to. They have some difficulty defining the main function but even more difficulty determining subfunctions and their relationships. The students do have much less difficulty defining the operation of their device as a process of steps (linear thinking). However, as the students practice expressing functions as verb-noun phrases, they begin to recognize they are thinking linearly (as a process) and adjust to functional thinking from the view point of the device. The students show more thorough understanding of the device and its functional operation at the end of the semester than at the beginning, as expected. The final exam confirms they understand a device based on its functional relationships in addition to its process steps.

The students perform well at defining the customer, client, and designer objectives for their device. This appears to be a result of an emphasis on defining objectives as "being" statements with a specific phrase structure (to (action word) + (object) + (qualifying phrase)). Harder to define, however, are constraints that emerge from the objectives. Even though constraints are described as limiting factors to the design space and boundaries to the system environment, the students have difficulty stating the constraints so they can be measured.

The students react interestingly to the creative element in the project and the nonlinear thinking often involved in systems thinking and modeling. They enjoy creating a prototype of the solution to improve their device. However, they want to start the prototype work before working through the creative process. The students tend to want to go from a shortened "statement of problem and data gathering" stage to the "solution description" stage. The course structure and assignments, however, force the students to stay in the first stage and provide an opportunity to experience stage 2—idea generation—only after providing time for holistic thinking and incubation.

Some students and teams experiment with nonlinear thinking techniques such as mindmapping and brainstorming. The course does not force the students to use these techniques though the instructor requests students to record how they generate ideas and experience "group think." The course final does ask students to define a device using mindmapping to illustrate their understanding of mindmapping and how it can be applied. Most students attempt the exercise. While some students continue to illustrate linear thinking, more students are beginning to show spatial and visual representation and a tendency toward new connections (see Figure 8.0).

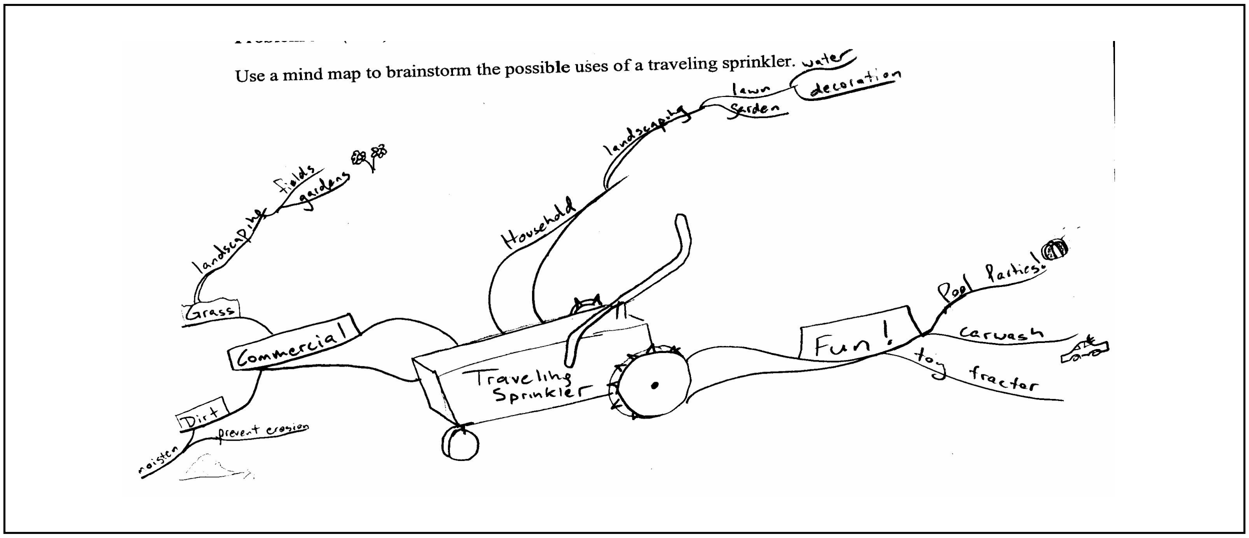


Figure 8.0: Student Generated Mindmap

## Conclusion

The freshman design course at UTC takes the freshman student away from the traditional student and instructor expectations of the typical analytic engineering course. The emphasis on systems thinking in the context of the design process is new to the students. The emphasis of the instructor to grade on thinking processes instead of results is also foreign to the engineering students. Some students are resistant to the experience, but many others openly enjoy the opportunity to create unique solutions.

As the course has evolved, it has produced better results from the student as the instructor has begun to relate each class topic to its role in the design process or systems thinking. The "why" for each activity or exercise needs to be emphasized since the three concepts being introduced are rather abstract.

Evaluation of the effects of the course on the student products during the sophomore, junior, and senior years is presently occurring. There seems to be some changes to how students are thinking about defining a problem and evaluating alternatives appearing in a requisite sophomore course. In the junior year students are showing an ability to identify project objectives more thoroughly and relationally. Assessment of the IED curriculum will continue over the next 2 years as the students progress through the design sequence.

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