AC 2011-897: IDENTIFYING AND DEFINING RELATIONSHIPS: TECHNIQUES FOR IMPROVING STUDENT SYSTEMIC THINKING

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Identifying and Defining Relationships: Techniques for Improving Student Systemic Thinking

Abstract

ABET, Inc. is looking for graduating undergraduate engineering students who are systems thinkers. However, genuine systems thinking is contrary to the traditional practice of using linear thinking to help solve design problems often used by students and many practitioners. Linear thinking has a tendency to compartmentalize solution options and minimize recognition of relationships between solutions and their elements. Systems thinking, however, has the ability to define the whole system, including its environment, objectives, and parts (subsystems), both static and dynamic, by their relationships.

The work discussed here describes two means of introducing freshman engineering students to thinking systemically or holistically when understanding and defining problems. Specifically, the modeling techniques of Rich Pictures and an instructor generated modified IDEF0 model are discussed. These techniques have roles in many applications. In this case they are discussed in regards to their application to the design process.

Introduction

The Engineering program at the University of Tennessee at Chattanooga (UTC) defines the design process as a systematic decision-making process that aids the engineer in generating and evaluating characteristics of an entity (physical or process) whose structure, function, and operation achieve specified objectives and constraints. The program describes the process as the application of the solid foundation of the basic sciences, mathematics, and engineering sciences to the abstractness, complexity, and solving of real world problems.

The elements of the design process are emphasized throughout the program's curriculum, beginning with the freshmen year. At the freshman year the Introduction to Engineering Design (IED) course uses project-based learning to address (1) problem definition, (2) attribute generation, (3) function, constraint and objective identification, (4) idea generation, and (5) simple decision-making as they apply to the design process. Of particular emphasis is the definition of functions, objectives and constraints that provide boundaries, guidelines, and clarification to project definition and design. The freshmen are introduced to project definition research involving customers and users to help them recognize project needs and requirements. The needs and requirements are transferred into project objectives, functions, and constraints using structured nomenclature and modeling techniques.

Traditionally students and practitioners use linear thinking to help them solve design problems. However linear thinking has a tendency to compartmentalize solution options and minimize recognition of relationships between solutions and their elements. In effect, most students and practitioners do not take a systemic view of a situation for problem solving.

The work discussed here describes two means of introducing freshman engineering students to think systemically or holistically about problem solving. Specifically, freshman students are introduced to the modeling techniques of Rich Pictures and Integrated Definition (IDEF0) model (used by the Systems Engineering community).

Rich Pictures

Rich Pictures, as defined by Checkland[1], pictorially and informally capture the structures, viewpoints, responsibilities, and processes of a situation. In addition, these pictures can illustrate relationships between the structures, processes, and responsibilities. Thus, these pictures aid users to think systemically about a situation.

Vanasupaa, Rogers, and Chen, at the 38th ASEE/IEEE Frontiers in Education Conference[2], discussed the findings of a pilot study on the outcome of the use of Rich Pictures by materials engineering students. Initial findings indicate that using Rich Pictures can broaden students' abilities to participate in systemic thinking.

IDEF Modeling

Integration Definition (IDEF0) function modeling was designed to provide better analysis and communication tools for improving manufacturing productivity. The IDEF family of models is based on the concepts of Structured Analysis and Design Technique (SADT) developed by Douglas T. Ross at SoftTech, Inc.[3] IDEF0 (Integration DEFinition language 0) focuses on the functional or process model of a system. IDEF0 is used to produce a structured representation of functions, activities, or processes within a system of interest.

Background

Freshman Design

The goal of UTC's Engineering design curriculum is to graduate students who understand and can apply the steps of the design process to various interdisciplinary and discipline-based applications. The first step toward meeting this goal is to introduce the steps of the design process in the 3 credit hour freshman level course Introduction to Engineering Design (IED).

The freshman IED 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. Concurrent with the design methodology is graphics design practice on sketching and solids modeling necessary for communicating the design.

Systems Thinking

Engineers seek solutions for simple to very complex problems. They must understand the problems, needs, and relationships to develop the possible solutions. Visuals as well as state-of-the-art hardware and software enhance an engineer's ability to effectively develop solutions.

Systems thinking is one means to aid problem understanding. 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 affect on the final solution. The spirit of systems thinking makes it an effective tool in a variety of applications and levels of complex problems.

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.[4] Others promote that the whole system is not just the sum of the parts or subsystems; it is a system composed of *interrelated* subsystems.[5] 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.

Systems Modeling

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.[6] In addition, as the system definition evolves, models allow for recognition and definition of detailed parts and their relationships.

Rich Pictures and Systemic Thinking

Rich Pictures are most commonly associated with Peter Checkland's Soft Systems Methodology (SSM) as a means to express a problem situation in a holistic sense. Rich Pictures are ad hoc sketches that serve as vehicles to help users explain a situation or problem context to the viewers. Rich Pictures have little to no formal rules to follow, though it is strongly suggested that the developer use simple sketches, lines, arrows, and symbols to convey ideas. The basic practice is for the problem solver, using a large sheet of paper and colored pencils or pens, to illustrate the structures, processes, concerns/issues of a problem situation as well as their interconnections.[7,8] Structures, processes, and concerns are best illustrated by sketches. Interconnections are often represented using lines, arrows, and circles. The use of words is often minimized.

The primary benefit of using Rich Pictures is that they encourage situational holistic or systemic thinking rather than reductionist thinking.[1] This allows the problem solver to consider a larger realm of issues as well as a larger number of solutions. Specific to engineering problem solving, this systemic thinking has a higher probability of producing a successful initial solution.

IDEF0 Modeling

A proven methodology used to model systems is based on a standard established by the Integrated Computer Aided Manufacturing (ICAM) program of the United States Air Force. As illustrated in Figure 1.0, the main components of IDEF0 models are functions (represented as boxes in the model), and inputs, constraints outputs, and mechanisms (ICOMs). The functions are actions or transformations, and are described as verb-noun phrases. ICOMs, are represented as labeled arrows. Input arrows represent data or objects being transformed by the function and terminate on the left side of the function box. Output arrows represent data or objects produced by the function and initiate at the right side of the function box. Control arrows represent conditions or guidance required to produce the desired output. They terminate at the top of the function box. Mechanism arrows represent the supporting means (physical resources) used to perform the function and terminate at the bottom of the function box.

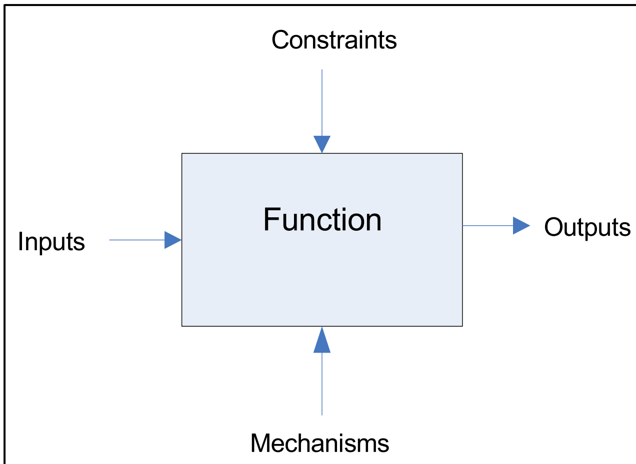

Figure 1.0: IDEF0 Function Structure[12]

The power of the IDEF0 model is its ability to illustrate functions and subfunctions as layers of hierarchical diagrams that introduce levels of increasing functional detail and thus system understanding. The hierarchical diagrams (see Figure 2.0) consist of an external system diagram, a context diagram, a top-level function diagram (level 0), and often between three and six sub-function decomposition diagrams. The context diagram contains the top-level or primary function (the parent) and the ICOMs that enter from, and exit to, the environment external to the modeled system. The level 0

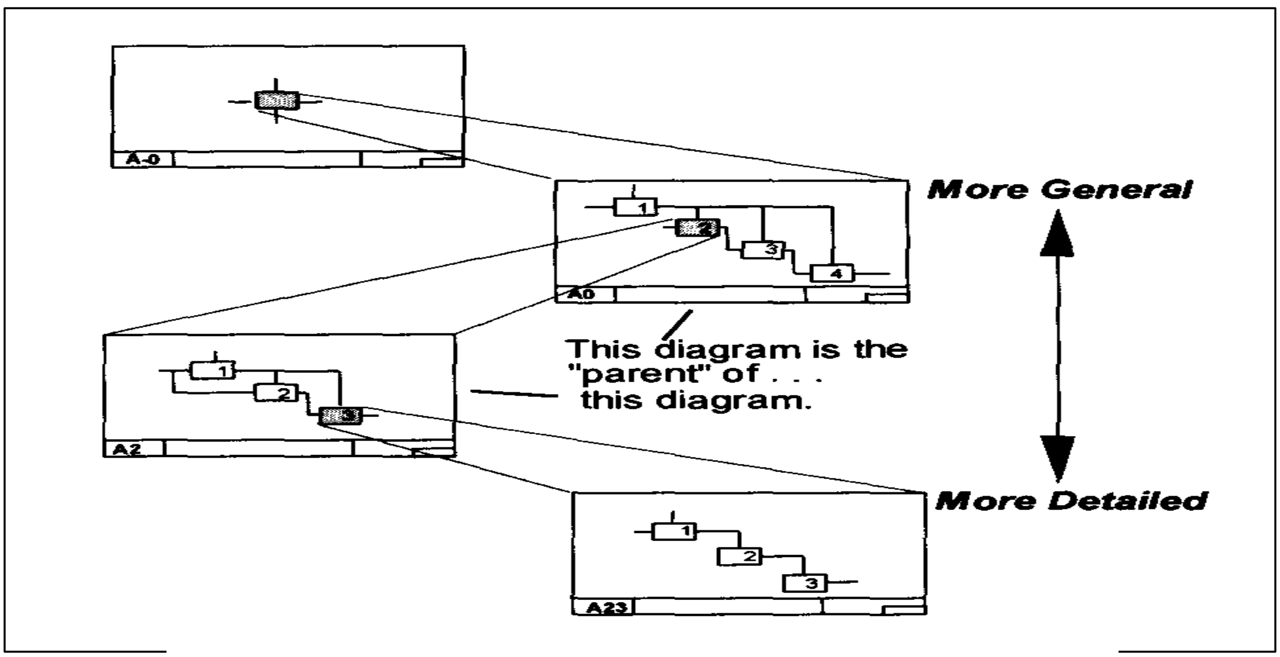

Figure 2.0: IDEF0 Decomposition[11]

diagram illustrates the high-level relationship between the major system sub-functions (the children) as well as the associated ICOMs defined in the context diagram. The hierarchy of diagrams continues as higher level subfunctions are decomposed into their more specific associated lower level subfunctions. [9]

The modeling method defined above is rather complicated for freshmen engineering students. Thus, the proven IDEF0 functional decomposition model is simplified for introduction to the freshmen. Specifically, since the identification of functions and their relationship to each other and the environment are the course emphasis, the identification of mechanisms and controls is deleted. In addition, for freshmen, the initial IDEF0 diagram is the context diagram, not the external system diagram. The freshmen are simply asked to identify the main or primary function and its associated inputs and outputs. Then they are asked to identify the subfunctions of the main function and their relationships. It is emphasized that inputs always enter the left side of a function box and outputs exit from the right side. For the freshman inputs are defined as "things" that the function transforms into new "things". Things are considered nouns.

Methodology for Introducing Systems Thinking to Freshmen

Rich Pictures

Freshmen are introduced to Rich Pictures during the course's team project. Following the initiation of the team projects, student project teams are introduced to the concepts of creative thinking and brainstorming as a team. To monitor their ability to creatively brainstorm, student project teams are asked to record their understanding of a problem situation using the white board and various colors of white board markers. Teams are given approximately 15 minutes to complete this task. The instructor observes student interaction. A sample result is shown in Figure 3.0 for brainstorming issues related to parking at the University.

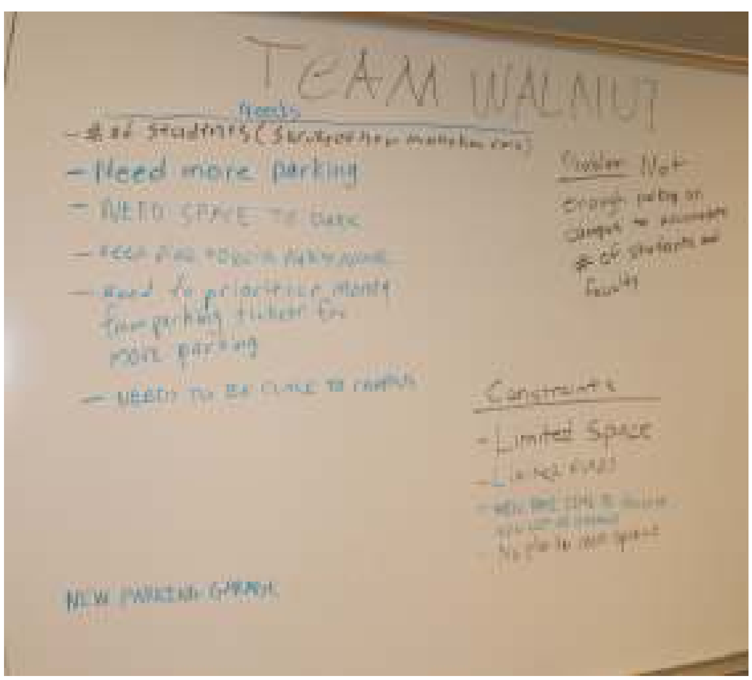

Figure 3.0: Brainstorming parking issues at the University (Team A)

Following this activity the students are introduced to the SSM technique of Rich Pictures. Students are shown a few examples of Rich Pictures as well as a slide show on how to draw Rich Pictures. The student project teams are then asked to record their understanding of the problem (again using the white board and the white board markers). Teams are given approximately 15 minutes to complete this task. The instructor observes student interaction. A sample of student work for this exercise from the same team that developed the work shown in Figure 3.0 is shown in Figure 4.0.

The two sets of sketches are compared to determine difference in coverage and illustration of relationships. The experience is discussed with the students and their reactions are shared.

Students are then instructed to create a Rich Picture addressing the issues of their selected team project. They have a week to complete this task. They must digitally record it and post it on their team site on the course BlackBoard location.

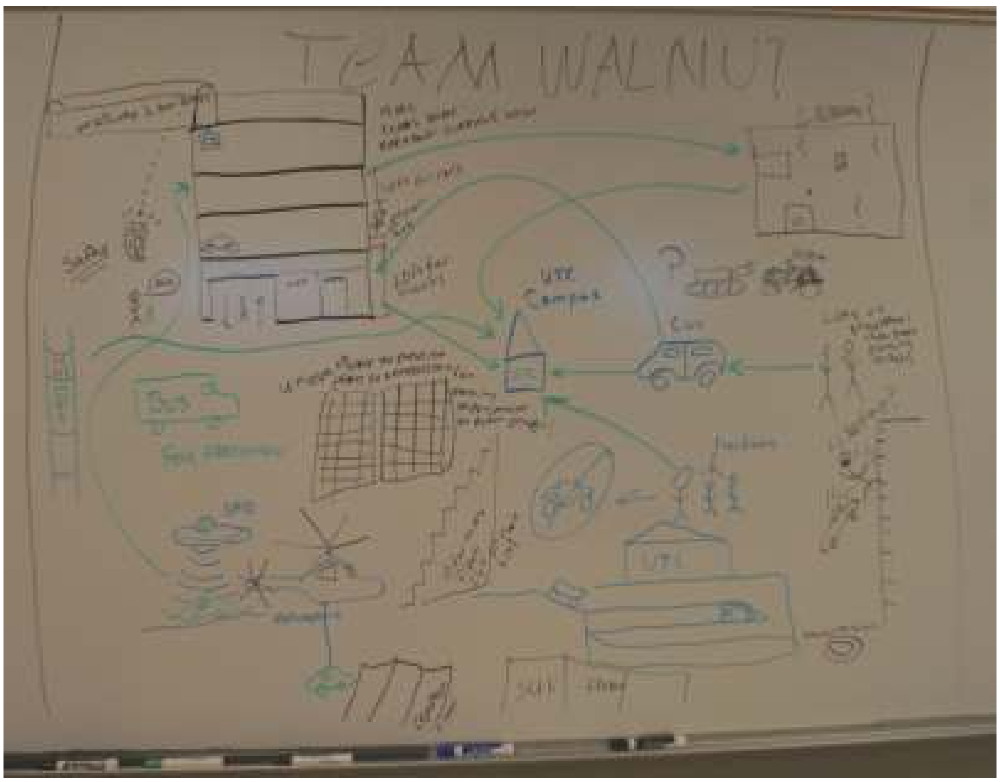

Figure 4.0: Brainstorming parking issues at the University using Rich Pictures (Team A)

IDEF0 Modeling

Students are introduced to function modeling during a course project in which all students participate. This project addresses a need of the College and the goal is to develop a device that addresses that need. During the needs identification phase of the design process, the class, led by the instructor, works together to develop a list of functions the device should do to meet the customers' needs.

From this list the students develop, with instructor prompting, the IDEF0 Context Diagram based on the identified primary function. They first clearly identify the primary function by ensuring it is structured as a specific verb-noun phrase. They then identify the outputs they want the function to achieve. For example, if the primary function is to "encourage recycling," the expected outputs may be "cans", "paper", and "plastic." (See Figure 5.0). The students then identify the inputs that are transformed by the primary function into the identified outputs. Sometimes, identifying inputs results in identifying additional outputs. For example, the students identify that used material is the input to the Encourage Recycling function. They then identify that not all used material is labeled as "cans," "paper," or "plastic." Thus, as shown in Figure 5.0, they label the remaining material as an output titled "garbage."

Figure 5.0: Identifying Inputs and Outputs

Then the next hierarchical diagram of the IDEF0 family of diagrams (Level 0) is developed. What is important is that the students identify 3 to 6 "subfunctions" that, at a high level, define the functional decomposition of the primary function. Then the destination and origins of inputs and outputs with respect to the subfunctions are identified to show functional transformations and relationships. To help students complete the diagrams, students are told that miracles (function boxes with outputs and no input(s)) and black holes (functions with inputs and no output(s)) can not occur. A sample Level 0 diagram for the "encourage recycling" function is shown in Figure 6.0.

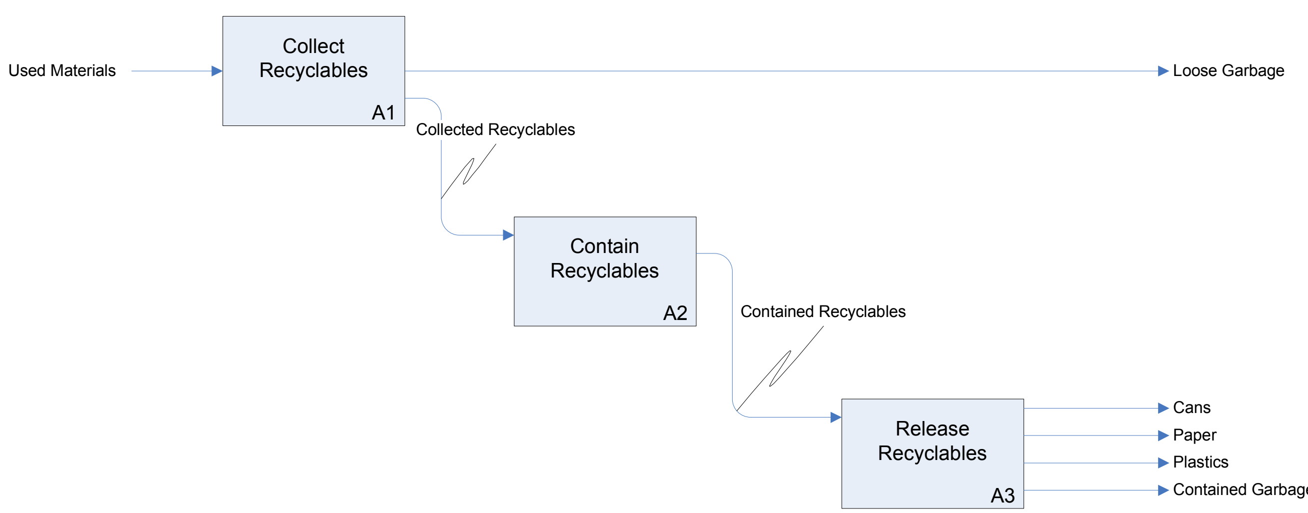

Figure 6.0: Level 0 Diagram for Encourage Recycling

What one should notice in Figure 6.0 is that the output "Garbage" has been clarified as having two types – loose and contained. Since both types of garbage are shown as outputs on the Level 0 diagram they must also be shown as outputs on the Context Diagram. Thus, the Context Diagram should be updated as shown in Figure 7.0.

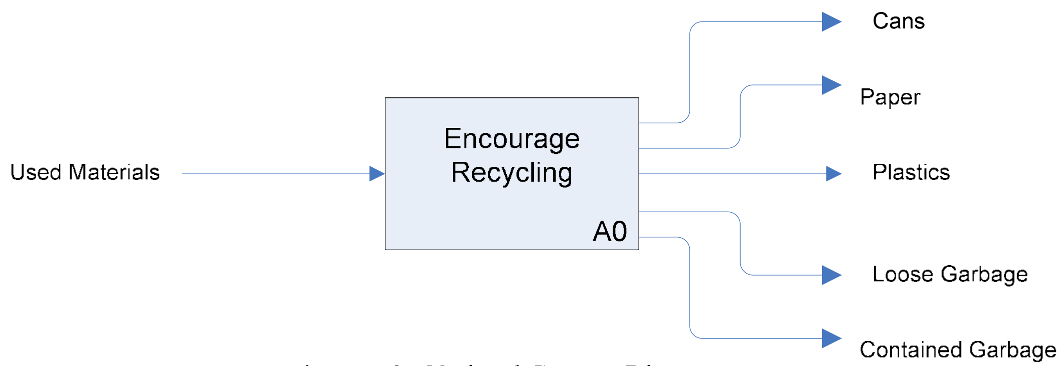

Figure 7.0: Updated Context Diagram

Once the Level 0 diagram is identified, the students, in like manner, decompose each Level 0 subfunction into a Level 1 diagram to illustrate its subfunctions and relationships. If new inputs and outputs are identified, the student should update the previous drawings to illustrate the impact on the upper level functions. Doing this helps the students iteratively define and understand the functions, their transformations, and their required inputs and resultant outputs.

A sample Level 1 diagram for the “Collect Recyclables” function is shown in Figure 8.0. The updated Level 0 diagram follows in Figure 9.0. The Context Diagram should also be updated to now include the input “Possible Recycler” which is transformed by the Advertise Recycling subfunction.

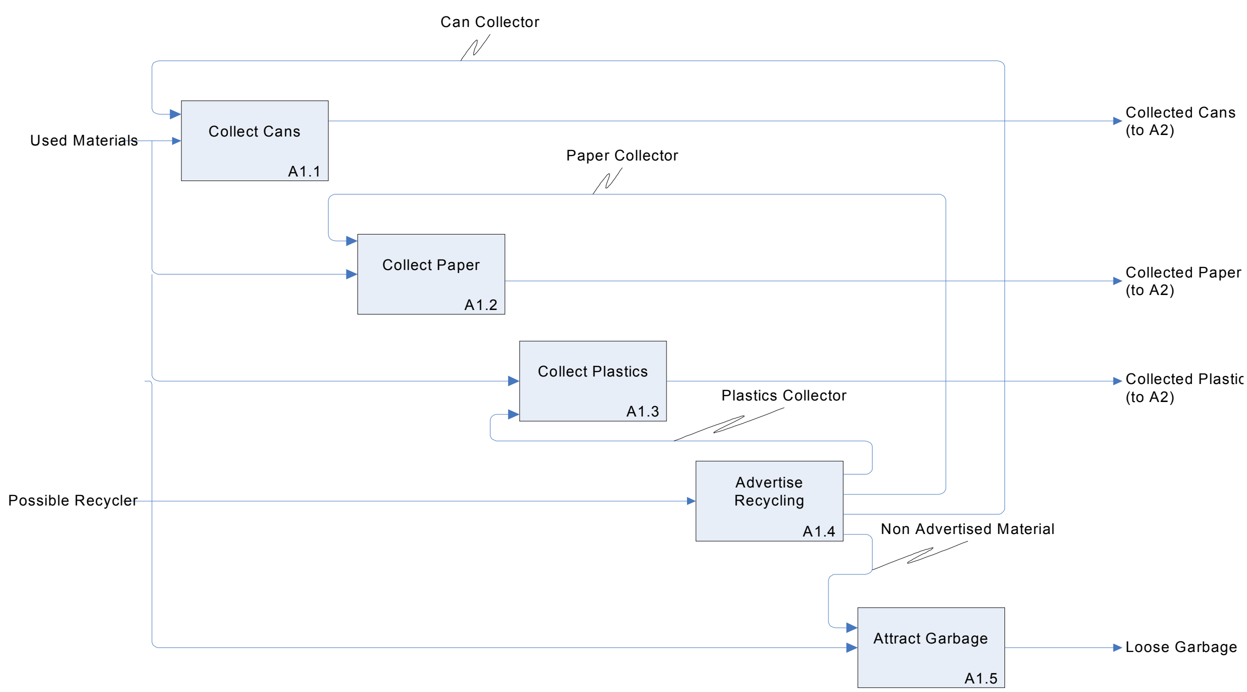

Figure 8.0: Level 1 Diagram for Collect Recyclables

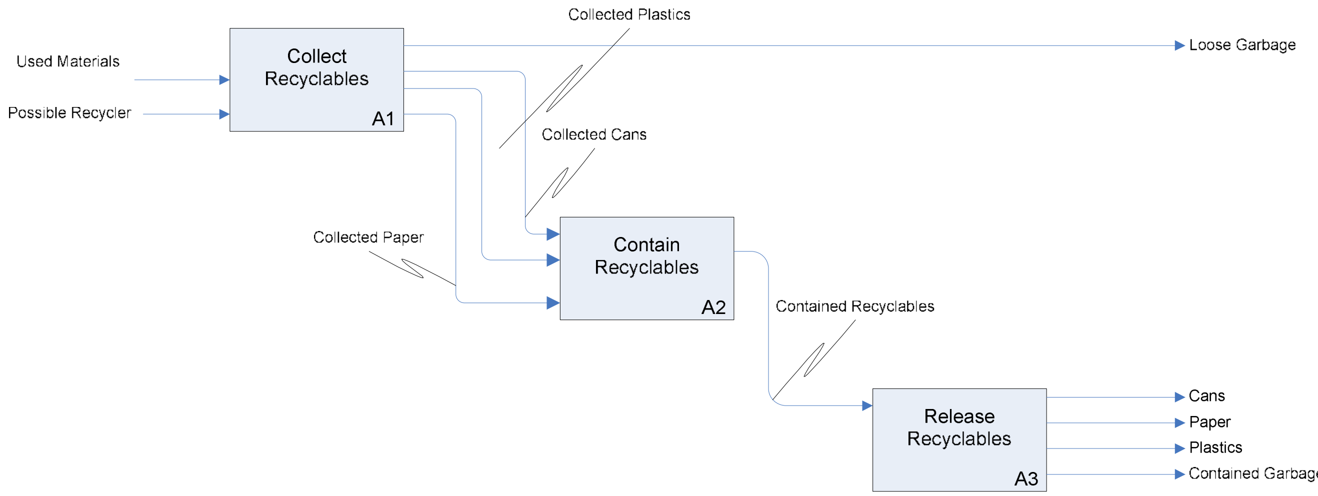

Figure 9.0: Updated Level 0 Diagram following A1 Subfunction Identification.

It may appear that the diagrams shown above make students think about a device or process as individual compartments. However, the goal of the diagrams is not to compartmentalize functions but to identify the *relationships* between the functions. Identification of relationships helps the user (students here) to recognize that how one solves one issue (such as how to collect recyclables) has an impact on how one may solve another issues (such as how to contain recyclables). Thus, the parts of a problem (subfunctions) need to be considered in relationship to another (as a system) to create a solution.

The Student Modeling Experience

Rich Pictures

Of the teams that participate in the Rich Pictures exercise most teams produce a list (sometimes bulleted) of words for addressing the initial issue. Some teams used a variety of marker colors to create their lists but this is due to personal pen choice. Some teams use larger print and explanation points to show emphasis. Generally one team out of the ten to twelve teams participating in the activity does use pictures to illustrate their ideas prior to being introduced to the Rich Pictures technique. Asked why they do this, the common response is that they recognize that people recall pictures more often than words (as discussed in a previous class lecture).

When addressing the issues of the second problem all teams produce Rich Pictures. It appears to the instructor, and is confirmed by the teams, that the teams enjoy developing the Rich Pictures much more than the lists. Specifically, there is much more interaction between the team members. The teams state that they can more easily build ideas from what another sketches. This creates a richer and more complete illustration of issues.

Figure 10.0 is a Rich Picture a student team developed to address the issues of their team project – adapting a toilet seat for a child with dwarfism. The issue of the child's lack of height with respect to the toilet is clearly illustrated. Thus the environment of the "system" is addressed. The Rich Picture also illustrates possible solutions but one can also observe that the illustrators are considering the customer (the child and parents) and their needs – specifically safety and space conservation – and how these needs may interact. This relationship would not be as apparent in a list of needs and possible solutions.

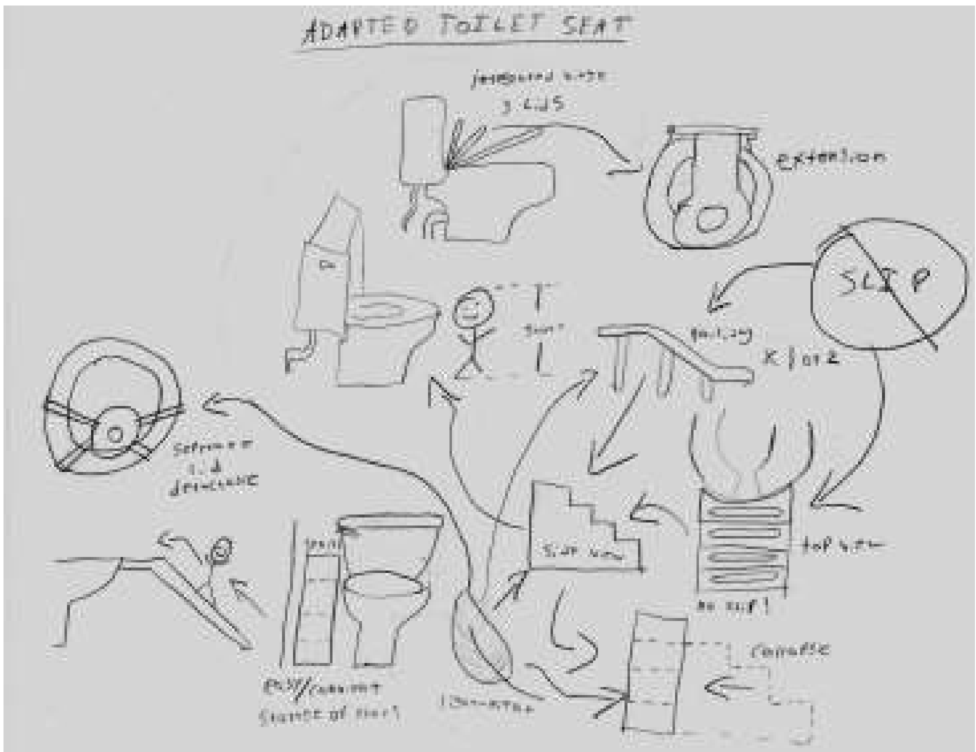

Figure 10.0: Student Rich Picture for Adapted Toilet Seat Project

IDEF0 Modeling

Students use the experience of function modeling developed during the class project to help them understand and identify the device functions for their team project. The models produced by the students indicate that they identify and structure functions (as verb-noun phrases) rather easily.

The task of developing the IDEF0 diagrams, however, is more difficult for the students. The concept of breaking functions into meaningful and applicable subfunctions requires a process of thinking that many have not yet practiced. During the in-class IDEF0 model development only a few students participate in the model building. However, the questions generated during the development are inquisitive and revealing. The students identify the iterative development and benefit of the IDEF0 hierarchy of diagrams. They recognize that identifying a new input or output in a level 0, 1, or 2 diagram requires that it be added to the appropriate upper level functions in the previous diagrams. They also recognize that through this iteration the functions and their roles and relationships are more thoroughly defined. However, the ability to group functions in categories that encompass subfunctions and illustrate the relationships between the subfunctions comes with practice.

Half of the project teams (four to five) are able to successfully iteratively develop their project IDEF0 diagrams. These teams can analyze the main function to define the subfunctions and then synthesize to determine the relationships between the subfunctions.

For example, Figure 11.0 illustrates that the primary function of the Vertical Moving Whiteboard (VMW) is to provide productive instruction. The VMW is designed for a primary classroom where there is minimal wall space for mounting a white board at the children's height. The VMW must be mounted above wall flushed lockers but lowered for use for instruction at the children's height. The context diagram illustrates that students, materials, and teachers are converted by the "provide productive instruction" function to the outputs of "productive circle time" and "productive class time."

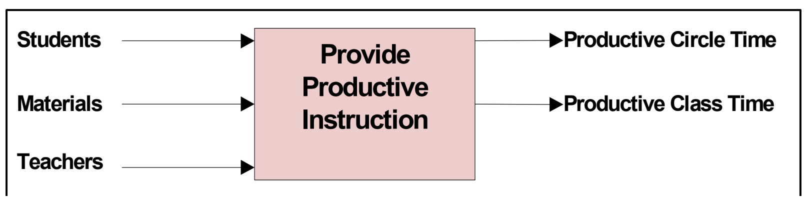

Figure 11.0: Vertically Moving White Board Context Diagram

The students determined that there are four main subfunctions that support the VMW primary function. These are "moves vertically," "holds materials," "provides bulletin space," and "provides writing space," Figure 12.0 illustrates that there are relationships between these subfunctions. For example, "holds materials" converts materials to outputs that are used as inputs by the "provides bulletin space" and "provides writing surface" functions to create the main outputs. About half of the project teams are able to recognize that these relationships exist.

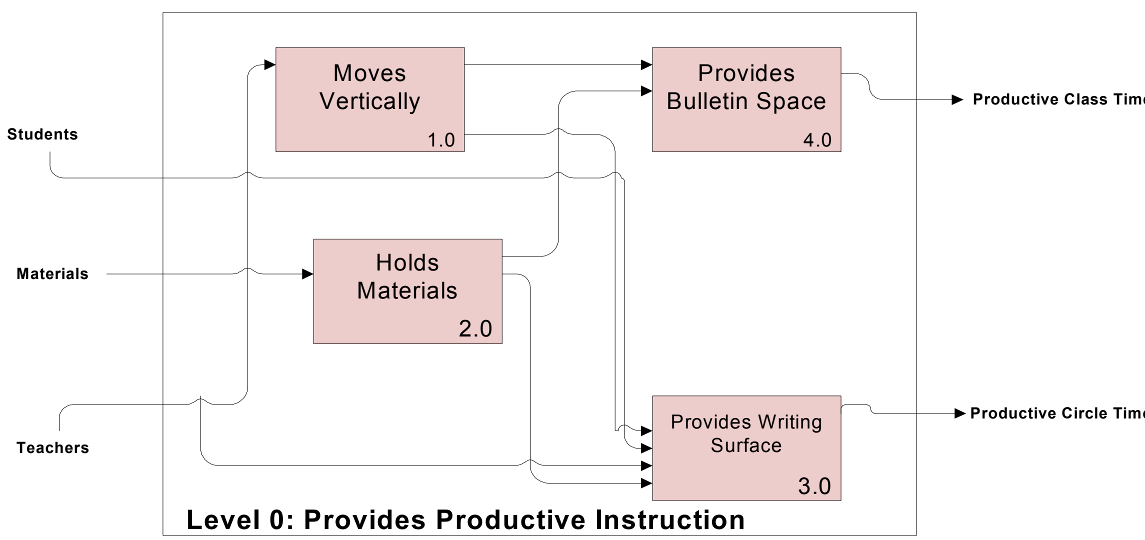

Figure 12.0: Vertically Moving White Board Level 0 Diagram

The students further decomposed the "moves vertically" function into three subfunctions (see Figure 13.0). The Level 1.0 diagram balances with the level 0 diagram in that there is one input to the "moves vertically" function and two outputs. The students successfully illustrate that the two outputs are internal and not external to the system by indicating they go to other subfunctions.

Again, about half of the project teams successfully distinguish between internal and external output flows and successfully balance their hierarchical diagrams.

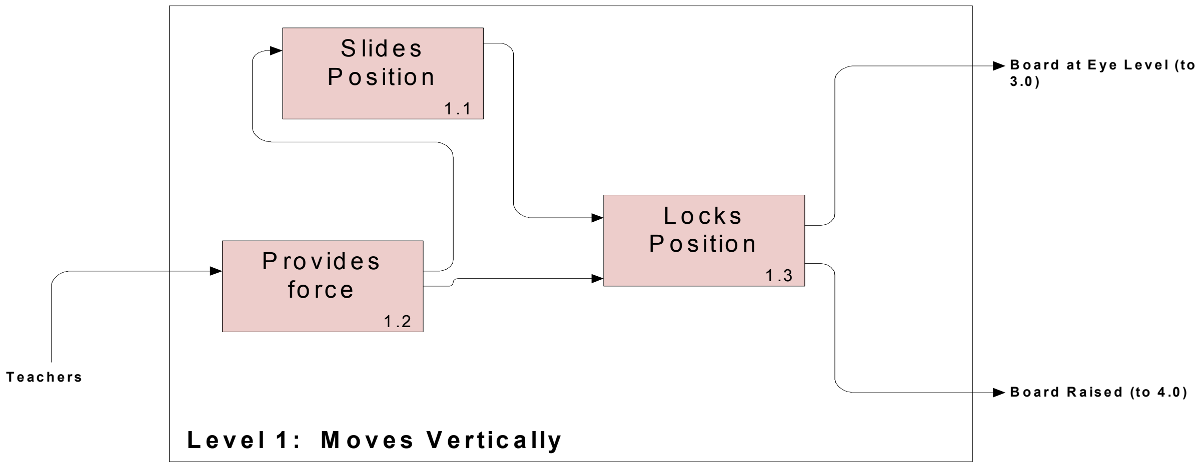

Figure 13.0: Vertically Moving White Board Level 1 Diagram (Moves Vertically)

Discussion

When students are surveyed at the end of the course, many students state that Rich Pictures is the one technique that benefited them the most during their development of design solutions. They recognize the benefits of the visualizations to expand their thought process from typical linear thinking to more holistic thinking. They specifically mention the benefit of the technique to include the thoughts of all team members and to illustrate relationships between contributions.

The provided student generated IDEF0 diagrams illustrate the level of decomposition detail expected of freshmen students. At this level the students identify sufficient subfunctions and relationships to help them understand the functional requirements of a device. For example, as seen in Figure 14.0, the level 1.0 diagram helped the students recognize that the VMW must not only slide into position, but also lock into position. In addition, they recognized that to complete these two functions, some type of force is required.

When students use simple lists of functions they tend not to recognize this level of detail or to identify functional relationships. The IDEF0 modeling forces students to think about functional relationships and thus to take a systemic view of a situation. Thus, the IDEF0 diagrams provide a vital role for developing students' systems thinking skills. However, developing these skills does not come quickly or easily to the students. There is much interaction with the instructor to confirm the iterative growth of the diagrams. Students have a tendency to develop broad based functions and not to recognize the specific supporting functions. Feedback is needed from the instructor to ensure depth of detail.

During IDEF0 model development students are quick to note that there are many different versions of decomposition diagrams for the same device or project. They specifically recognize that team members identify different functions and relationships depending on their personal view of the project. This leads to their understanding the benefits of using a team or multiple viewpoints to develop the IDEF0 diagrams – having different viewpoints involved in problem solving expands the systems view.

During the fall semester two sections of the course were taught by one instructor (instructor A) and one section was taught by the instructor more familiar with the systemic models (instructor B). Interestingly, the projects developed by the students in all three sections were equally strong. However, those students in the sections of instructor A required much more hand holding and direction to get their projects completed. They also did not document as well their understanding of the functional and customer needs. In the end, they did not present as thorough a substantiation for their design as did the student teams in instructor B's section.

Conclusion

Does using Rich Pictures and IDEF0 modeling improve the designs created by freshmen students? The author would like to give an emphatic "yes", but this is difficult to prove. However, the author witnesses that the practice of modeling requires students to consider how the device exists in its environment and to discuss what a device must do to meet customer needs prior to developing the design. It also identifies how one function may interface with another function so that device function activities are not considered as isolated events. This increases the opportunities for success of device design solutions. It also improves the students' abilities to substantiate their designs.

It was found that the ability of the students to grasp both the Rich Pictures and the IDEF0 modeling technique was highly related to the experience of the instructor with the technique and with systemic thinking. Thus, a change was made to the spring semester to have the instructor with the most experience with these models lead the lecture sessions related to these techniques.

Accreditation agencies and industry emphasize the need for engineering graduates to have the ability to understand the relationships within and between devices and processes. In other words, they want graduates to analyze in a systems sense. Introducing students to Rich Pictures and IDEF0 diagramming and providing them opportunities to practice modeling is one means to help students develop this systems thinking. As shown by the activities in UTC's IED course, emphasizing these practices at the freshmen year can be done and can be successful.

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