AC 2010-1742: IMPROVING ENGINEERING DESIGN EDUCATION: A RELATIONAL SKILL-TASK MODEL

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IMPROVING ENGINEERING DESIGN EDUCATION: A PEDAGOGICAL SKILL-TASK MODEL

The objective of this paper is to propose a relational skill-task design educational model on how to improve the engineering design learning experience. The design engineering activity is a complex mix of skills and knowledge that has been thought over decades by directly delivering to the students the design methodologies developed by design researchers and by exposing the students to open ended projects that can develop their design skills. From this we can conclude that the three main pedagogical components of a successful educational design experience are: the design skills, the design methods and the design projects. On one hand, the individual design skills must be properly developed in the student prior to the project experience, making it an overwhelming challenge. On the other hand the design methodologies can be difficult to implement pedagogically, therefore the student struggles to learn, and even more important, to embrace such methodologies.

We present an approach to design engineering teaching through four main steps: First, define the desired knowledge and skills to be acquired by the student during the learning process. Second, organize the skills to be acquired in complexity levels. Third, generate educational objectives for each of the skills. Fourth, based on educational theories (teaching styles, learning styles, etc.), transform the design skills to didactic tasks (i.e. lectures, problems, exams, etc.) in such a way that the student will be able to develop those skills.

This model could serve initially as a diagnostic tool to characterize the current set of skills of a given course or program. The model can also be use to implement educational tasks into the classroom and labs depending on the desired student profile.

1 Introduction

Engineering design is defined as a complex cognitive activity in which the main objective is to change from a current to a desired status, through a planned and organized process that involve: multiple disciplines, social collaboration, open-ended solutions, technical knowledge and advanced skills. Our mission as educators is to cultivate design skills and abilities in our students to achieve the highest competency, but design methodologies can be difficult to implement pedagogically, therefore the student struggles to learn, and develop design skills.

The objective of this paper is to propose a model to improve the engineering design education experience by building a prescriptive relation between a desired skill to develop in the student and a specific didactical task to be performed by the teacher.
We do this by analyzing the knowledge and skills to be acquired by the student, understanding the theories behind education, searching for related art on this field and proposing a generic model. The paper is arranged in three parts, first a general background covering engineering design and education, followed by an analysis of the state of the art describing the problem, and third, our proposal to improve the educational method.

2 Background

2.1 Taxonomies

Taxonomy is a classification which helps to identify and differentiate subjects based on their characteristics. One of the most influential taxonomies within the educational field is Bloom's "Taxonomy of Educational Objectives"[2] and its cognitive domain is focused on the recognition of knowledge and the development of intellectual skills based on a constructivist model that organizes the knowledge by level of difficulty, with the purpose of providing a framework for educators to set learning objectives in their academia. Since then many improvements and criticisms have been made to this document; a resent evolution of it is Marzano's "New Taxonomy"[12] who proposes a hierarchy model in terms of control and not in terms of complexity which has been proven by psychology researches to be only a temporary state on the learner upon the familiarity of the activity, this means that the new taxonomy is able to represent the learning activity as a duality of process and state, instead of only as state as Bloom proposed. Marzano's taxonomy is a two-dimensional model as represented in Figure 1; one of the axes is the hierarchy of "thinking systems" or levels of processing and on the other axis the "domains of knowledge".

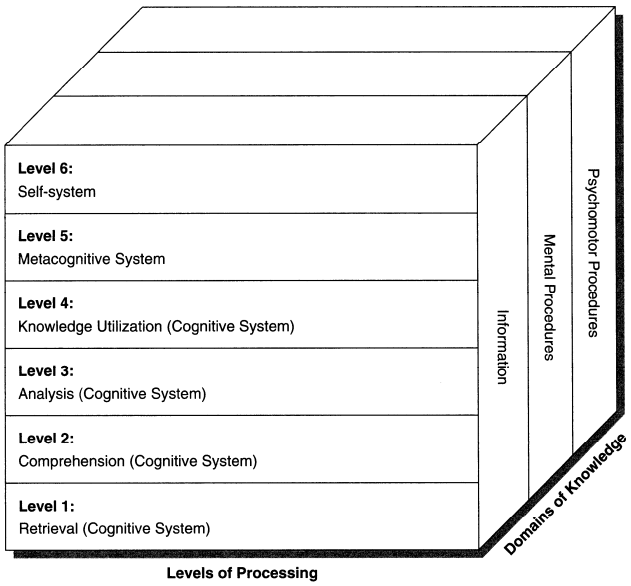

Figure 1. "The New Taxonomy Of Educational Objectives" Model (Marzano, 2007)[12]

The authors organize the knowledge in three domains: information (declarative knowledge with no procedure involved; "the what"), mental procedure (procedural knowledge; "the how-to") and psychomotor procedures (human body motion procedures). These domains are based on psychology research and each is organized with their own hierarchies and categories as see in Figure 2.

Information	1. Organizing ideas	Principles Generalizations
	2. Details	Time sequences Facts Vocabulary terms
Mental Procedures	1. Processes	Macroprocedures
	2. Skills	Tactics Algorithms Single rules
Psychomotor Procedures	1. Processes	Complex combination procedures
	2. Skills	Simple combination procedures Foundational procedures

Figure 2. Components Of The Three "Knowledge Domains" (Marzano, 2007) [12]

The thinking systems hierarchy is built according to the author's understanding of how the learning process happens in the human mind. First the learner faces a new task (new knowledge) to be acquired and makes a decision at the "self-system" level to engage or not to engage such knowledge. This level is ruled by the previous beliefs acquired by the learner in which his motivation will influence a decision depending on the perceived importance, the efficacy and the emotional response to such task. If the learner accepts to engage, he/she will set goals and strategies relative to the new task. This level is called "metacognitive system" and its main function is to control the lower level systems to

achieve the defined goals. Finally the "cognitive system" is the one that processes the knowledge through four levels: retrieval (obtaining and recognizing of information), comprehension (translation of knowledge into appropriate form for memory storage), analysis (generation of new knowledge based on reasoning activities) and knowledge utilization (synthesis of new knowledge based on reasoning activities). The cognitive and the metacognitive system are in constant interaction and iteration until the task goal is accomplished generating new knowledge in the learners mind. These thinking systems are based on psychology research and each is organized with their own hierarchies as shown in Figure 3.

Level 6: Self-System Thinking	Examining Importance Examining Efficacy Examining Emotional Response Examining Motivation
Level 5: Metacognition	Specifying Goals Process Monitoring Monitoring Clarity Monitoring Accuracy
Level 4: Knowledge Utilization	Decision Making Problem Solving Experimenting Investigating
Level 3: Analysis	Matching Classifying Analyzing Errors Generalizing Specifying
Level 2: Comprehension	Integrating Symbolizing
Level 1: Retrieval	Recognizing Recalling Executing

Figure 3. Levels Of "Thinking Systems" (Marzano, 2007) [12]

This model intends to describe and decompose the process of thought and the flow information for any learning activity within the human mind; therefore this taxonomy allows the educator to set specific objectives for each stage of the learning process of the student for any kind of knowledge or skill to be acquired.

2.2 Education: Pedagogy & Didactics

The main function of education is to improve the competency and capacity of the student through the acquisition of knowledge and the development of skills within a teaching-learning system. From a strategic point of view, education can be divided into pedagogy and didactics. The first refers to the teaching/learning theory and strategy (how to teach?) and the second refers to teaching/learning tactics and methods (with what to teach?). It is important to distinguish that teaching and learning are two different activities that relate to each other, though research and study of these two topics have historically grown in parallel paths which began to merge just a few decades ago. Therefore we need to be aware of the main theories of both topics individually.

2.2.1 Teaching Theories

Teaching theories focus on how the teacher delivers the knowledge to the learner mainly in a descriptive way. These theories are diverse, not standardized, empirical and essentially traditional based. Since there are dozens of teaching theories we will just mention some of their classifications that were collected from literature survey from several authors[1,8,10,19]:

Teaching Methods:
- Direct Teaching
- Direct Instruction
- Teacher-centered
- Student-centered

Teaching Styles:
- Lecturing
- Socratic
- Facilitation
- Experiential
- Practice based
- Problem based
- Resource based
- Mentoring

Teaching Temperaments:
- Traditionalist
- Change Agent
- Achiever
- Free Spirit

Each of these theories have their own fundamentals and applications, all of them approaching the same activity from different points of view, providing a large variety of possible combinations for teaching scenarios.

2.2.2 Learning Theories

Learning theories focus on how the learner acquires the knowledge mainly in a descriptive way. Even though these theories are diverse we could classify them in three main streams: constructive, behavioral and cognitive. The constructivism is based on the believe that learning only happens through own experienced endeavors. The behavioral approach to learning is based on measuring any kind of response for a given stimulus. And the cognitive theory comes from cognitive psychology, which objective is to model the human thinking process, including learning. To these theories we could also include "learning styles" of which there are several different models, but their purpose is to describe the acquiring knowledge preferences of the learner[1,9,10,15,17].

Learning Theories:

- Constructivism
- Behaviorism
- Cognitivism

Learning Styles Models by Author:

- Myers
- Kolb
- Dunn, Dunn & Price
- Biggs
- Reinter
- Schroeder

The main objective of these theories is to understand how the student learns either by recognizing his profile, environment, thinking process or own experience.

3 State of the Art in Engineering Design Education

Most of the available literature on engineering design education relates to descriptive experiences from engineering professors in a capstone or senior design course[16]. The least are prescriptive proposals of how to implement educational theories in engineering design activities. An example of this[6] the authors present (as pedagogy) a general model of curriculum for design engineering upon their needs of teaching: design science, technical systems, modeling and disciplinary information. They also present (as didactics) a general model of transformation system, which can be applied to the educational system to transform the competencies of the learner, using pedagogical variables that define the overall components needed for the system (Figure 4), but they acknowledge that these proposals do not consider two key issues: How the students learn?, and how to perform instructional methods for engineering design?

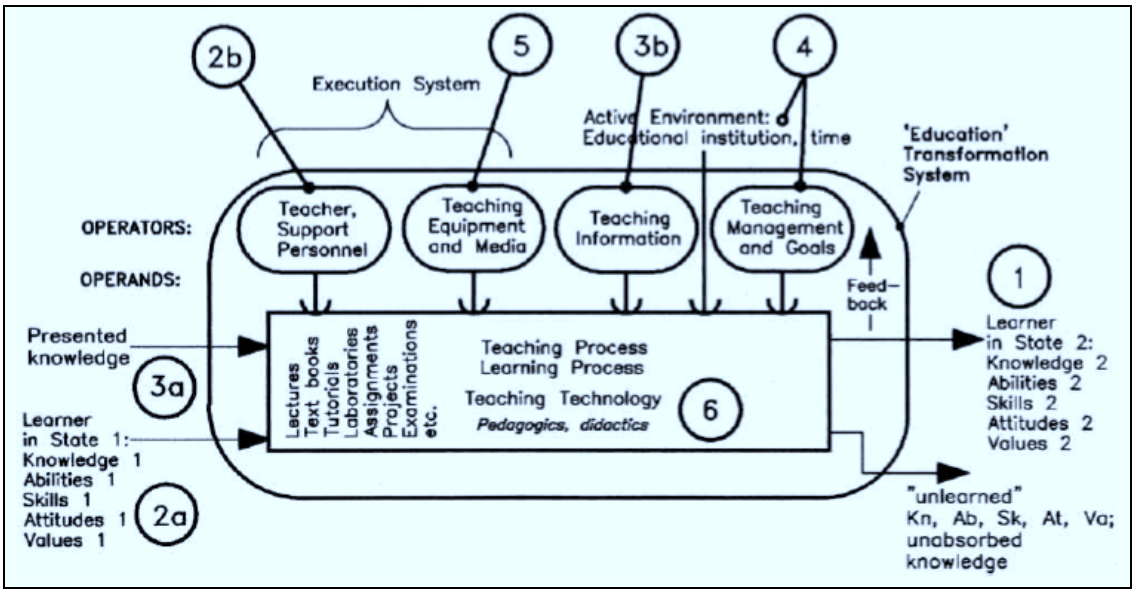

Figure 4. Educational variables and relationships to educational processes[6].

Others explored the latest didactic trend in engineering design education: problem based learning[3]. In which they correlate the complexity of the design thinking process with this well accepted teaching style due to its closeness to real design practice, but they acknowledge that this method has flaws, raising the question of: how to better develop design thinking in the students?, and they believe that the answer resides in a main skill: divergent-convergent questioning. An additional example of didactic exploration is the extensive work done with teaching and learning styles in engineering[7] which unfortunately does not go in depth of design related activities.

From this we can conclude that few pedagogical models have been developed for engineering design education, and even less didactical models have been applied in a prescriptive or systematic way, probably due to design's complex nature, making the teaching/learning system a challenging task for this activity.

4 Engineering Design Educational (Skill-Task) Model

4.1 Model Overview

Figure 5 presents the main steps of this educational model which will be review with detail in the next subsections.

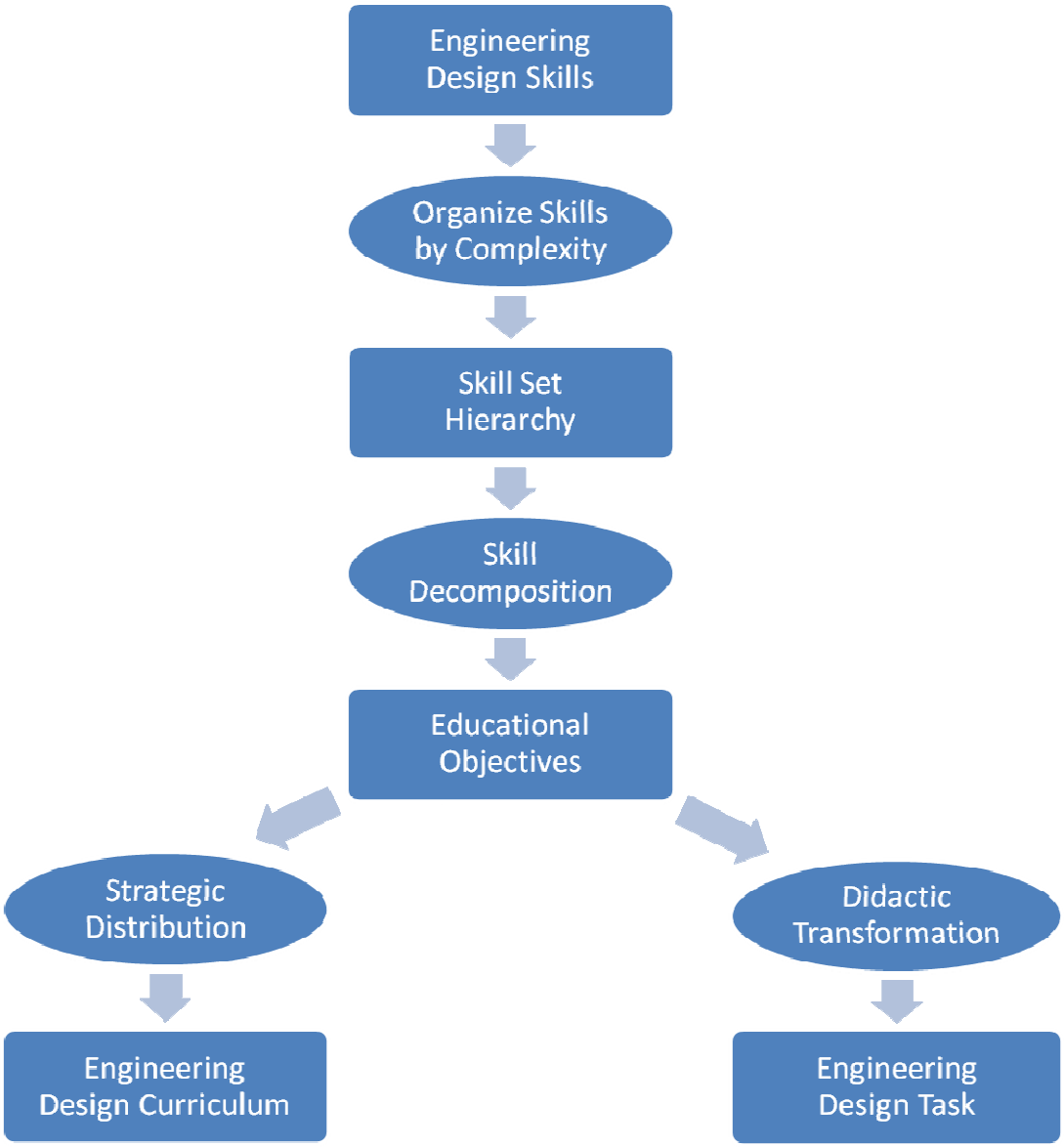

Figure 5. Educational Skill-Task Model Diagram.

4.2 Engineering Design Skills

First is important to acknowledge the vast and wide variety of skills needed to perform engineering design. Here is sample list of some of the skills related to engineering design that were collected from literature survey[3,4,5,13,14,18]:

Analytical thinking
Synthetic thinking
Critical thinking
Divergent thinking
Convergent thinking
Lateral thinking

Visual thinking
Imaginative thinking
Qualitative reasoning
Problem formulation
Problem solving
Creativity
Decision making
Learning
Organization
Prioritization
Time, project and resources control
Knowledge sharing, capitalization and management
Team work
Multidisciplinary collaboration
Intercultural collaboration
Written, oral and graphic communication
Ethics
Sketching
Conceptual modeling
Analytical modeling
Computational modeling
Prototyping
Crafting

This listing is intended to help the teacher by decomposing the engineering design activity so each skill can be developed individually or in groups that simplify the learning process for the student, acknowledging that the main design skill is probably the integration of all the previous ones in a single activity: designing. Still there is a need to classify such skills in an orderly manner; here is where the taxonomies will be used.

4.3 Organize Engineering Design Skills by Complexity

A skill taxonomy for engineering design can be created based on Marzano's domains of knowledge hierarchy and since designing is mainly an intellectual activity, the "Mental Procedures" domain, shown in Figure 2, may be the best lead in this sense. Marzano's hierarchy is based on the level of complexity of the procedural knowledge: single rule, algorithm (procedure with very specific outcomes and steps that do not vary), tactic (procedure with general rules but with no specific order) and macropocedure (operation involving many subprocedures with diversity of possible outcomes). Based on these definitions, the next engineering design taxonomy example was created:

Engineering Design Skills Set Hierarchy:

Macropocedures:
Problem solving
Team work

Multidisciplinary collaboration
Intercultural collaboration
Written, oral and graphic communication
Ethics
Analytical thinking
Synthetic thinking
Critical thinking
Divergent thinking
Convergent thinking
Lateral thinking
Visual thinking
Imaginative thinking
Qualitative reasoning
Problem formulation
Creativity
Learning

Tactics:
Organization
Time, project and resources control

Algorithms:
Decision making
Sketching
Conceptual modeling
Analytical modeling
Computational modeling
Prototyping
Crafting

Single rule design skills:
Prioritization
Knowledge sharing, capitalization and management

Since the mental procedures are constructively organized (the higher levels depend on the proper function of the lower levels) this classification will help the design educator to order the proper sequence in which the skills should be taught. But the learning process of each individual skill has several stages that need to be address one by one.

4.4 Engineering Design Skill Decomposition

Marzano's learning model describes that the knowledge that will be acquired by the learner, goes through the six levels of thinking systems: self-system, metacognitive system, knowledge utilization, analysis, comprehension and retrieval. To achieve a successful learning process the learner should experience conscious learning activities at each level. Therefore the design educator first needs to identify which operators of each

thinking systems need to be address for the intended skill and then set goals (educational objectives) to accomplish for each operator. The purpose of the educational objectives is to have a clear and well defined activity to achieve at each learning stage of the student. The "knowledge sharing" skill was chosen to exemplify the creation of such objectives using Marzano's "New Taxonomy of Educational Objectives" as presented in Figure 6.

Engineering Design Educational Objectives:

New Taxonomy Level	Operation	Objectives for "Knowledge sharing" skill
Level 6: Self-System Thinking	Examining Importance	A: The student will be able to identify how important the mental procedure of knowledge sharing is to him or her and the reasoning underlying this perception.
	Examining Motivation	B: The student will be able to identify his or her overall level of motivation to improve competence or understanding relative to the mental procedure of knowledge sharing and the reasons for this level of motivation.
Level 5: Metacognition	Specifying Goals	C: The student will be able to establish a goal relative to the mental procedure of knowledge sharing and a plan for accomplishing that goal.
	Process Monitoring	D: The student will be able to monitor progress toward the accomplishment of a specific goal relative to the mental procedure of knowledge sharing.
Level 4: Knowledge Utilization	Decision Making	E: The student will be able to make decisions about the use of the mental procedure of knowledge sharing.
	Problem Solving	F: The student will be able to solve problems about the mental procedure of knowledge sharing.
Level 3: Analysis	Classifying	G: The student will be able to identify superordinate and subordinate categories relative to the mental procedure of knowledge sharing.
	Specifying	H: The student will be able to identify logical consequences of the mental procedure of knowledge sharing.
Level 2: Comprehension	Integrating	I: The student will be able to identify the basic structure of the mental procedure of knowledge sharing and the critical as opposed to noncritical characteristics.
	Symbolizing	J: The student will be able to construct an accurate symbolic representation of the mental procedure of knowledge sharing differentiating critical and noncritical elements.
Level 1: Retrieval	Recognizing	K: The student will be able to validate correct statements about features of the mental procedure of knowledge sharing, but not necessarily understand the structure of the knowledge or differentiate critical and noncritical components.

Figure 6: Engineering Design Educational Objectives For Knowledge Sharing Skill

As one can see, the objectives may or may not use all the operations of each level of thinking system, making it a tailored method for each skill depending on the needs and criteria of the educator. These objectives will guide the design educator in the creation of the task and its assessment upon the competencies obtained by the learner.

4.5 Didactic Transformation

At the strategy level of education (pedagogy) Eder has developed models that include curricular structure of how to better teach design within engineering programs. But these models fell short at the tactics and implementation level of education (didactics). Here is where the education theory can fill the blank by applying teaching theories and learning theories to the engineering design educational system which will help us to develop the desired skill thru a specific didactical task. Teaching styles will help us to define what is the role of the teacher depending on the desired scenario (e.g. design studio, lecture classroom, workshop). Teaching temperaments will help us to choose the optimal teacher profile that fits the engineering design activity. Learning styles will help us to understand how the engineering students prefer to acquire the knowledge. Cognitive learning can help us in the improvement and development of optimal thinking models (e.g. design process, problem solving, critical thinking) of the learner.

Continuing with the exemplification, a detail task will be generated in Figure 7 for the "knowledge sharing" skill, based on the previous educational objectives (Figure 6) and suggesting possible teaching and learning theories to implement such tasks.

Engineering Design Educational Task:

New Taxonomy Level	Operation	Tasks for "Knowledge sharing" skill	Teaching Theory	Learning Theory
Level 6: Self-System Thinking	Examining Importance	A': Ask the students to work individually in an engineering design problem (pump selection for a piping system) providing each with a piece of information. Then Ask the students to share their information with other students.	Experiential	Cognitivism

Figure 7. Engineering Design Educational Task For Knowledge Sharing Skill

As one can see there could be multiple combinations to build the skill-task path giving freedom to the users to adapt the model to their circumstances, without ignoring that these educational tools are focused on three players, the teacher, the learner and their environment. On one hand, this means that this educational model could be used to acquire any kind of knowledge (design methodology) and to develop any kind of skill; but on the other hand, we need to consider that the learner profile is not a variable that the educational system can control; therefore the other two players (teacher and environment) need to be adapted to the first one. This may be the biggest challenge of the skill-task model.

5 Concluding Remarks

In this paper we presented a brief analysis of the challenges within engineering design education by understanding the gap between design and the teaching/learning system. Also we mentioned some of the available tools for education, exploring the theories of its two main activities: teach and learn. And finally propose a possible solution to this challenge, by utilizing those tools. Our future work involves detailing and testing this model for three separated applications: questioning skill, multidisciplinary collaborative skill and sustainability design methods, as starting points.

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