AC 2007-66: ARE ENGINEERS ALSO SYSTEM THINKERS? BRINGING UP HOLISTIC AND SYSTEMATIC DECISION-MAKING IN ENGINEERING THROUGH A SYSTEMS-CENTERED EDUCATIONAL FRAMEWORK

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[1]Are engineers also systems thinkers? Bringing up Holistic and Systematic Decision-Making in Engineering through a Systems-Centered Educational Framework

Abstract

Engineering is design, analysis and synthesis. Analytical and systematic skills have been emphasized as one of the most important professional abilities for the XXI century. Hence, the need for instilling in engineering students those skills has been reinforced (e.g. ABET's A-K required outcomes for accreditation). But how math and engineering courses in fact promote the acquisition of those skills is still not clear. One tool developed to assess people's understanding of basic systems concepts is the *systems thinking inventory*, STI. The STI has been used with different populations of students in different countries. The results have consistently shown that people have poor understanding of systems concepts. We also propose for as a topic for further research that the problem might reside in the educational framework commonly used in the engineering classroom and propose that more research on the system-centered approach is needed since it requires an increased emphasis on teacher's contributions as learning facilitators. We present the results of applying two of the STI tasks, to sixty-eight Industrial Engineering undergraduate students whose level range from 4th to last semester before graduation. It is hypothesized that students in the last semesters of IE training would have a better understanding of system dynamics. The results with controls of gender, high school of origin, and English language proficiency will be discussed.

Index Terms – Systems thinking evaluation, engineering education outcomes, skills assessment, industrial engineering, systems-centered framework

I. Introduction

Recently, problems with organizations, structures, and society that have a huge technological component alert us to the fact that there is a growing gap between the nature of our problems, our ability to solve these and understand their consequences in the future. It is also a truism that the world has evolved from a simple setting to a very complex socio-technical system of systems and information networks. Cascade effects of our problems are increasing faster than we can handle and it is time for us to develop new strategies and methods to resolve these issues.

Engineering education has since tried to cope with this change by addressing complexity with specialization. More and more humans, and therefore engineers, are becoming specialized in narrow areas of knowledge (e.g. services, health care, disaster relief, nanotechnology, biotechnology, transportation, airport security, optimization to name a few. This constant changing context and the accelerated development process of engineering practice highlights some discontinuities and shortages in the engineering specializations. Few cases in point can provide us with enough substance for explaining the importance of having a holistic view of engineering problems. Looking back at cases that could be deemed infamous engineering flaws, such as the Tacoma Narrows Bridge disaster in Washington in 1940, the failure of the levees built in New Orleans in 2005, the liquidation of assets of large companies such as Enron, the current fuel crisis, the failure of national security systems and intelligence in the United States to identify terrorists before September 11, the dilemma of global warming; and many others, one would easily arrive at the conclusion that all are the consequence of humans not looking at the "Big-Picture". Engineers, mathematicians, computer scientist, and managers being experts in an isolated area without "making the connections"[2].

We can attest that lower profile internal organizational failures do exist in all companies, countries and societies due to a lack of adequate problem-solving skills. Among these cognitive reactions to problem-solving, systems thinking skills and competencies are perceived as playing a major role. A number of studies have examined in the past how humans behave when having to make decisions in dynamically complex environments. The conclusion of all is that the complexity of the systems we are called upon to manage overwhelms our cognitive capabilities. Further, some show that performance deteriorates rapidly when even modest levels of dynamic complexity are introduced (see[3]**Error! Reference source not found.** for an extensive list of previous studies in this topic).

It is hard to know how much and who knew what could have happened. Is it that the engineers in charge did not see the relationship between symptoms and consequences? Or if they were able to see them, weren't they able to predict the behavior over time so that to mobilize resources on time to prevent catastrophe? Some of these disasters are still under investigation, and pointing out the failure to engineering skills alone would be an overstatement. However, as engineering educators we can ask ourselves: are we teaching our students to think systemically? Are we instilling in them the need to have a holistic perspective? Are we overspecializing?

But how math and engineering courses in fact promote the acquisition of those skills is still not clear. Several researchers have concentrated their efforts in evaluating how specific coursework (i.e. systems dynamics) affects the acquisition of system thinking skills and competencies and whether there are some natural inherent skills in some people with or without specific coursework that could be deemed systems thinking skills. There have been virtually no attempts to link these abilities to engineering skills in general and industrial and systems engineering coursework in particular. This is the purpose of this paper. To present systems thinking as an approach to problem solving that is necessary in the engineering skill-set for the twenty first century, regardless of discipline of specialization, and second, to test whether systems thinking skills are acquired or present in engineering students in the current standard curriculum with a traditional teaching framework. We present the results of applying two evaluation tasks from the Systems Thinking Inventory Tasks (STI) [2,17] to Industrial Engineering undergraduate students whose academic level ranges from 4th to last semester before graduation. It is hypothesized that students in the last semesters of IE training would have a better understanding of system dynamics due to their exposure to a specialized education related to the design of systems. The results with controls of gender, high school of origin, and English language proficiency will be discussed and a proposal for improving systems thinking in undergraduate engineering education presented.

Systems Thinking

There is no widely accepted definition or common understanding of the term "systems thinking." Systems thinking as a discipline, thinking paradigm or methodology has a rather recent recognition in the scientific field despite the fact that the systems thinking tradition has a long history. There are definitions that narrow down the concept of systems thinking e.g. "'the ability to represent and assess the dynamic complexity (behavior that arises from the interaction of a system's agents over time) both textually and graphically"[2].

Systems' thinking is perceived as a unique, powerful and useful framework of thinking and learning[1]. According to Richmond[1], "systems' thinking is "…*the art and science of making reliable inferences about behavior by developing an increasingly deep understanding of underlying structure*". Systems thinking is perceived both as a *paradigm* (vantage point and thinking skills) and a *earningethod* (process, language and methodology). The second supports the first and the two parts create a synergistic whole.

Systems Thinking in Engineering

Beginning in the mid 50s, Jay Forrester, a professor at the Massachusetts Institute of Technology, found the need for a better way to analyze social systems. He used his engineering skills and methods to simulate a social system to predict its behavior over time considering the impact of other factors. This method was called: "system dynamics", and between 1961 and 1968 Professor Forrester wrote what would become the classic works in System Dynamics[4,5,6]. Today he is widely known as the founder of the system dynamics discipline. Thanks to Jay Forrester and many other professionals in the systems thinking and dynamics field, we now have an efficient approach to understanding (and therefore solving) the consequences of real life problems. Engineering and management schools teaching students systems thinking skills are now relatively common, either as part of the regular engineering curricula or as an area of specialization. Other complex systems analytical tools have emerged in parallel to system dynamics and the theory of how complex systems behave is one of the important areas of research in systems engineering. However, not all engineering students are exposed to such a specific education. Further, many educators would argue that engineering is both, analysis and synthesis and therefore, the traditional engineering curriculum teaches in a way systems thinking. So why then does the world seem to be sinking in more catastrophic issues everyday? The answer may be in the educational framework used to teach analysis and synthesis to engineering students.

II. Short Review of Literature

There is a plethora of studies in systems thinking, some addressing the systems thinking paradigm and it's implications in various domains, other identifying the psycho-social correlation of the systems thinking as a learning discipline. Some studies more related to the purpose of this research are those presented by Sweeney & Sterman[2] on the STIs development and philosophy; Gould[7] about systems thinking in education; Mandinach & Cline's on the assessment of the system thinking project in the K-12 arena[8]. In addition, there is a broad range of studies in the field of systems thinking with a strong emphasis on psycho-pedagogical implications; such as: Toshima's[10] integrated aptitude test for systems engineers (SE), which includes intellectual abilities and personality factors; Richmond's critical systems thinking skills (dynamic thinking, closed-loop thinking, generic thinking, structural thinking, operational thinking, continuum thinking, and scientific thinking)0 ; Zulauf's study on locus of control and conceptual stages of cognitive complexity that predict success on systems thinking tasks[9]**Error! Reference source not found.**; Cross and Vick's interdependent self-construal in relation with gender related issues in systems thinking ; Fredrickson's systems thinking performance and professionals affective state etc.

The need for systems thinking in engineering education has been discussed in the literature in view of the fact that through the acquisition of this skill "people learn to better understand interdependency and change, and thereby to deal more effectively with the forces that shape the consequences of our actions."[13]**Error! Reference source not found.**. Davidz et al[14]**Error! Reference source not found.** is perhaps the work that relates the most to ours, as they are engaged in research to identify enablers, barriers and precursors to the development of systems thinking in engineering professionals. These authors emphasize the need for more information on the development of systems thinking.

Systems' thinking is used in a wide variety of in fields such as management, computing, engineering or environment and addresses complex or recurrent problems that involve an extended number of participants, issues when an intervention can affect either the natural or the competitive environment, problems whose solutions are not obvious etc.

Systems Thinking Skills

For the purpose of this study, the core categories of skills required by systems thinking; skills that will be assessed during the present investigation are as follows.

Among the most relevant *general core skills,* Sweeney & Sterman[2] **Error! Reference source not found.**mention:

- creating and interpreting graphs form data;
- telling a story from a graph and creating a graph of behavior over time form a story;
- identifying various unit of measure;
- basic understanding of probability, logic and algebra.

In addition to these, efficient systems thinking require a set of *specific skills,* such as:

- understanding how the behavior of a system arises from the interaction of its agents over time (i.e. dynamic complexity);
- discovering and representing feedback processes (both positive and negative) hypothesized to underlie observed patterns of system behavior;
- identifying stock and flow relationships;
- recognizing delays and understand their impact;
- identifying nonlinearities; recognizing and challenging the boundaries of mental (and formal) models.

The list of specific systems thinking skills is extensive and diverse, but mostly comprises the ability to see circular cause-effect relations and the ability to synthesize elements to reveal a system's structure. According to Sweeney and Sterman[2] specific systems thinking skills include "the ability to:

- Understand how the behavior of a system arises from the interaction of its agents over time (i.e. dynamic complexity);
- Discover and represent feedback processes (both positive and negative) hypothesized to underlie observed patterns of system behavior;
- Identify stock and flow relationships;
- Recognize delays and understand their impact;
- Identify nonlinearities;
- Recognize and challenge the boundaries of mental (and formal) models."

III. Methodology

The tasks

A number of evaluative testing studies [e.g.[2,15,16]] have attempted to link systems thinking/system dynamics education with important skills such as efficient communication, planning, problem solving, and organizational development skills. Above all, it has been claimed that systems thinking bring on the development of better leaders. However, there are still major questions about people's native systems thinking abilities when such a specific coursework (systems thinking) is not formally provided. While all those studies have in common the assertion that even highly educated people with strong math and science backgrounds lack natural systems thinking abilities[12]there is little evidence to support it. Furthermore, there is little evidence to support the belief that engineers are natural systems thinkers. Booth Sweeney and Sterman have developed an assessment to measure people's understanding of basic systems concepts known as the *systems thinking inventory tasks (STIT).* The overall model of the research consists on using these tasks as an instrument to measure the level to which IE students are acquiring systems thinking skills.

Two of Booth Sweeny and Sterman tasks were used: a department store task and the CO_2 zero emissions task. With this in mind, an investigation began with one research question: Are we teaching our students to think systematically?

The tasks were given to Industrial Engineering students. After they were taken, the data was filtered by type of high school, English proficiency, age and semester of study.

More basic but necessary quantitative and analytical skills such as the ability to read a graphic, interpret the data, and tell a story from the graph underlie the above listed skills and prevent the ability of a person to complete the STIT. Other important *a priori* skills include the identification of units of measure, understanding of high school probability, logic and algebra[2].

Task 1. The department store problem

The fist task consists of a graph and four questions intended to test the understanding of stocks and flows, one of the basic systems concepts. The first two questions test the level of understanding the subject has when asked to read and interpret graphs. The latter two are designed to examine the students' knowledge in regards to stocks and flows per se.

Task 2. The CO_2 zero emissions task.

The CO_2 zero emissions task has an increased level of difficulty since it measures a person's ability to not only read and understand a graph but to predict possible future tendencies given a scenario. For this reason, it is expected that students not do as well on this task as on the previous one. Subjects were asked to read a paragraph that explains how temperature behaves in relation to CO_2 emissions and afterwards, draw a graph that represents what they thought would happen with these two if there was a sudden stop in CO_2 emissions.

The Research Site

The Industrial Engineering (IE) Department at the University of Puerto Rico at Mayagüez (UPRM) educates the majority of IEs in the island. Puerto Rico is an associated state of the United States of America, a political status close to a territory. This brings unusual educational circumstances such as bilingual education (Spanish and English skills are both necessary and required to excel in college). The UPRM has a reputation of providing very challenging math, science and engineering education and attracts a population of students with unusually strong quantitative skills, expected to be above those of the general population. In fact, a high percentage of graduates are accepted at the top IE schools to pursue masters and Ph.D.s in the United States after obtaining their B.S. at the UPRM. The department as part of their mission statement states the following:

> "*Graduates from the Industrial Engineering program at the Mayagüez Campus of the University of Puerto Rico are instrumental in the planning, designing, implementing and evaluating products, services, on systems that integrate people, materials, equipment, and information for the progress and improvement of the quality of life of humankind.*"[19]

Therefore, some of the qualities of a systems thinker are supposed to be acquired during the course of IE education at the UPRM. Given all of the above, the pool of UPRM's IE students was deemed an appropriate sample to test whether quantitatively strong students naturally present (or acquire) systems thinking skills when enrolled in an accredited engineering education curriculum.

Sample

The study was conducted on a sample of 69 industrial engineering students taking classes at different levels of the curriculum, and the class and not the student was the selecting factor. For instance, two sections of a Cost Analysis and Control class where a wide variety of students is expected in terms of year of study and exposure to systems terminology (students from the 4^{th} to the 10 semester in a 10-semester program). Students in a stochastic models class, mainly in the 8th to 10th semesters, being exposed to queuing theory concepts; students in an ERP class exposed to production systems behavior, and students in the final design project during the last semester of their IE program where they are supposed to design a system using IE skills in a real life setting. All students in those classes were tested. All of them are following the Industrial Engineering specialization but differ in coursework taken, English language proficiency, as well as the nature of the high school institution from where they come from.

The following tables describe the sample in those terms.

Age

	Age	**Frequency**	**Percent**	**Valid Percent**	**Cumulative Percent**
Valid	18	1	1.4	1.5	1.5
	19	6	8.7	8.8	10.3
	20	10	14.5	14.7	25.0
	21	16	23.2	23.5	48.5
	22	11	15.9	16.2	64.7
	23	11	15.9	16.2	80.9
	24	8	11.6	11.8	92.6
	25	1	1.4	1.5	94.1
	26	1	1.4	1.5	95.6
	27	1	1.4	1.5	97.1
	32	2	2.9	2.9	100.0
	Total	68	98.6	100.0	
Missing	System	1	1.4		
Total		**69**	**100.0**		

Gender

	Gender	**Frequency**	**Percent**	**Valid Percent**	**Cumulative Percent**
Valid	Female	39	56.5	58.2	58.2
	Male	28	40.6	41.8	100.0
	Total	67	97.1	100.0	
Missing	System	2	2.9		
Total		**69**	**100.0**		

Semester of Study

	Semester	**Frequency**	**Percent**	**Valid Percent**	**Cumulative Percent**
Valid	4	8	11.6	12.7	12.7
	6	8	11.6	12.7	25.4
	8	16	23.2	25.4	50.8
	10	18	26.1	28.6	79.4
	12	13	18.8	20.6	100.0
	Total	63	91.3	100.0	
Missing	System	6	8.7		
Total		**69**	**100.0**		

Regarding respondents' English proficiency skills, students were asked for three referential points: whether their schooling was in Spanish, Bilingual or English, their own individual perception of their English language abilities and lastly, the level of English in which they were placed when entering college by standardized testing. The following tables show all three aspects:

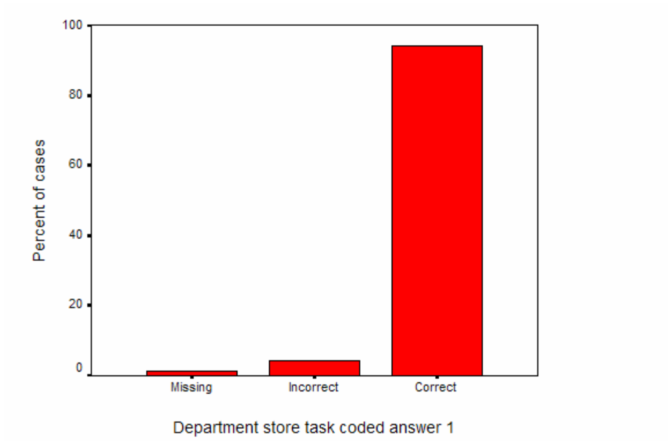
		Self-Evaluation of Student's Comprehension of English							
		Poor		**Regular**		**Good**		**Excellent**	
		Count	Col %	Count	Col %	Count	Col %	Count	Col %
Primary Language at High School	Spanish	2	100.0%	8	88.9%	23	82.1%	15	51.7%
	Bilingual			1	11.1%	4	14.3%	10	34.5%
	English					1	3.6%	4	13.8%
Entry level of English at college	Pre-Basic English	1	50.0%	6	66.7%	1	3.6%		
	Basic English	1	50.0%	3	33.3%	14	50.0%	3	10.3%
	Intermediate English					11	39.3%	12	41.4%
	Advanced English					2	7.1%	14	48.3%
		2		9		28		29	

IV. Results and Discussion

Task 1. The department store problem

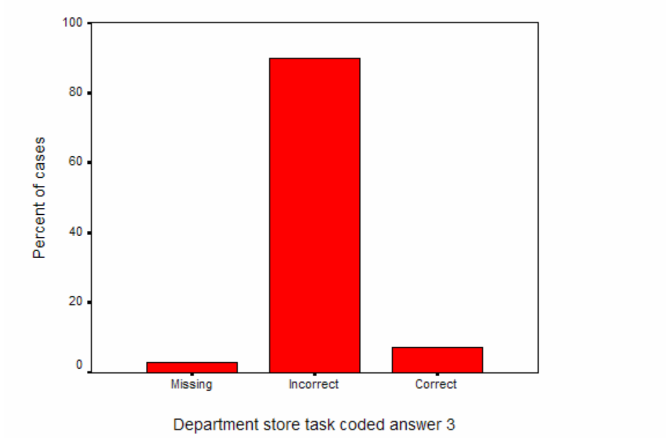
As expected, 95.52% of students tested answered the first question correctly while 91.04% asserted the second question. The third and fourth questions demonstrated totally different results: 9.26% correctly identified the moment where most people would be at the store and only two of the sixty eight students (2.9%) identified the moment where the least amount of customers were at the store. These results, similar to those reached at other institutions such as MIT (see for example the summary of results presented by Pala and Vennix **Error! Reference source not found.**) , prove that engineering students can read graphs but have difficulty in understanding stock and flow problems. There was not significant difference in any of the Chi-Square tests for any of the controls (i.e. age, gender, semester of study, exposure to queuing theory, or level of English proficiency). No group was more likely to answer correctly any of the questions of this task. The following graphics show some of the results.

TASK ONE: DEPARTMENT STORE TASK

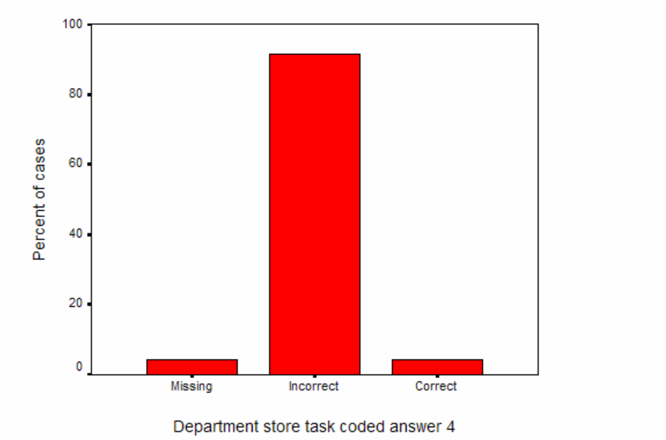


QUESTION ONE RESULTS

QUESTION TWO RESUSLTS



QUESTION THREE RESULTS

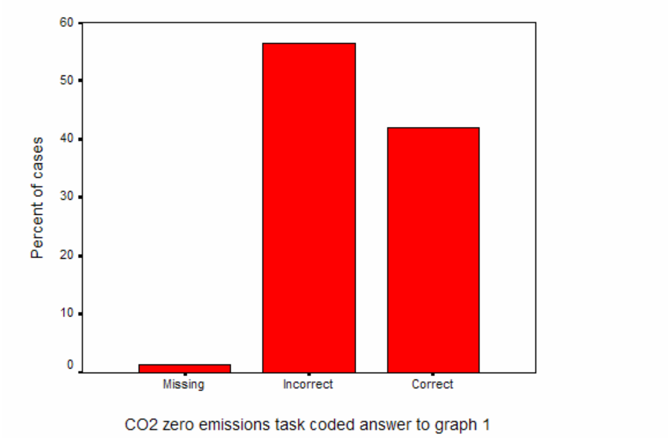


QUESTION FOUR RESULTS

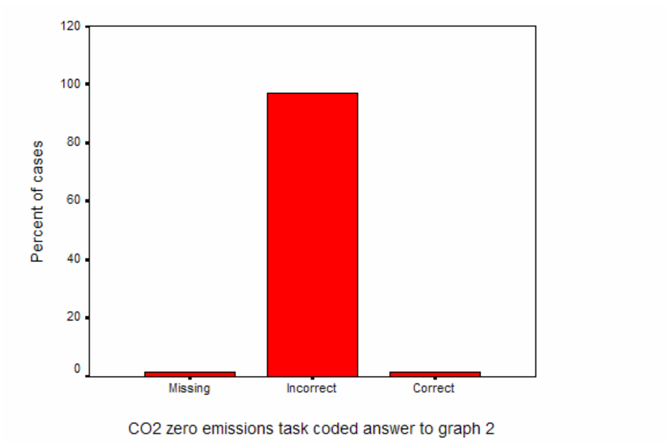
Task 2. The COs zero emissions task.

Student's answers were placed in one of ten categories. 42.65% of the students tested identified the path that CO_2 would follow if in the year 2000, CO_2 emissions had suddenly stopped being produced. However, of the 68 students tested, only one correctly identified how global mean temperature would react. Since this task had a longer text description it required a higher degree of English comprehension to be answered correctly. Again, the results did not show any significant difference at the 0.05 significance level of the results against the controls.

TASK TWO: CO_2 ZERO EMISSIONS TASK



GRAPH ONE RESULTS

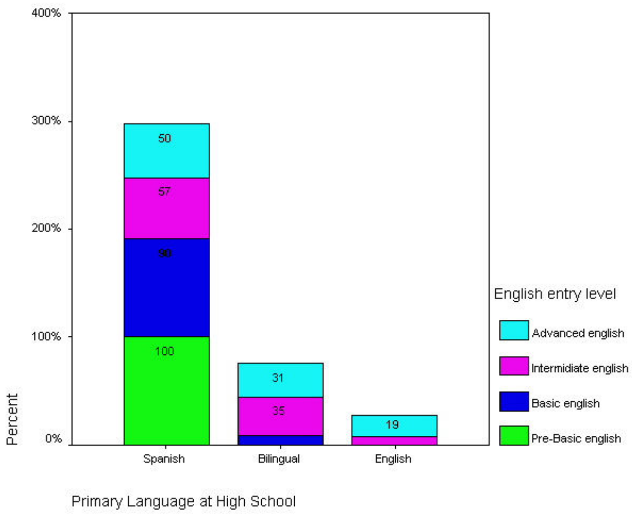


GRAPH TWO RESULTS

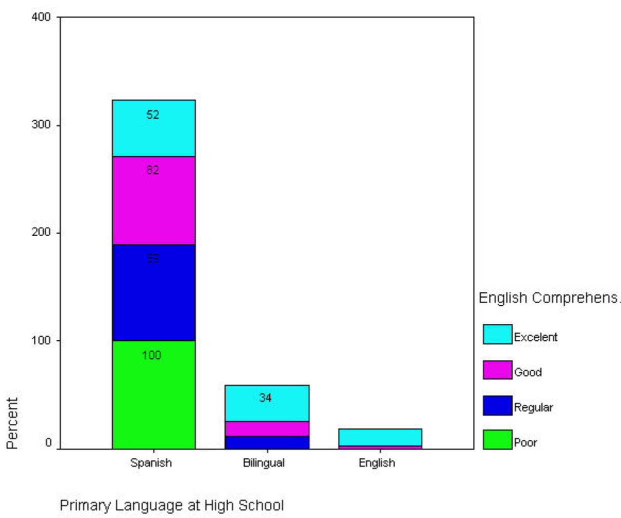
These results are surprisingly not that uncommon. They are very similar to the results obtained by researchers at MIT as well as many other universities around the world; including those that offer systems thinking courses. This test has been administered to students at the beginning of an introductory course of systems thinking and then at the end of the same course. This provides evidence that coursework of this type do help students in acquiring better systems thinking skills as was seen in the increase of correct answers in the STIT.

Results by Student's Characteristics

As stated before, the University of Puerto Rico at Mayagüez has a peculiarity, which makes it unique from any other higher education facility in the United States. Because of the political dependence of the Island on the United States, students are expected to be fully bilingual by the time they reach undergraduate studies (i.e. Spanish-English). However, this is not always true. The veracity of this assumption is highly dependant on the high school they attend as well as in their determination to conquer both Spanish and English. The sample taken was within the industrial engineering undergraduate students. Of the five hundred forty three students, sixty eight were tested; ranging from fourth semester to just before graduation. Lectures in the Industrial Engineering department are taught mostly in Spanish but all instructors' presentations, textbooks and most handouts are distributed in English. If a student lacks proficiency in the use of the English language he or she is likely to have a tough time understanding and passing the courses. The following shows the difference found when students study at either a public or a private school in Puerto Rico and how this affects the level of the English level course they will take in their first year of college.



ENTRY LEVEL ENGLISH VS.TYPE OF HIGH SCHOOL ATTENDED

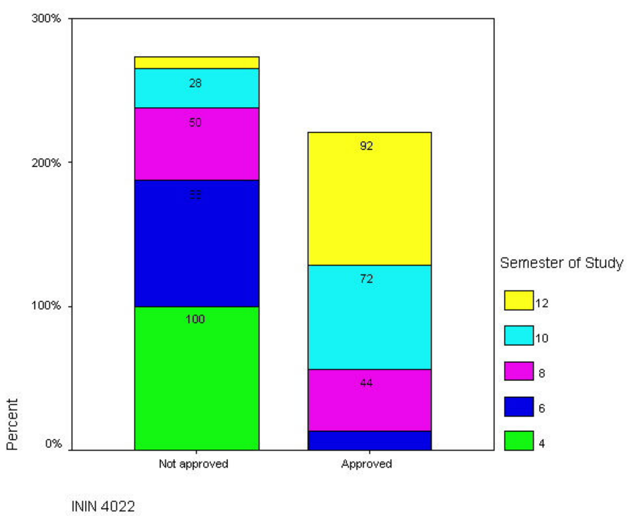


SELF-EVALUATION OF ENGLISH COMPREHENSION VS. PRIMARY LANGUAGE AT HIGH SCHOOL

Contrary to the mental model of the researchers, there was no significant difference in the level of performance in the four department store tasks and the level of students' English comprehension or English background (as measured by the primary language in High School). Most students answered correctly tasks 1 and 2, which measured their ability to interpret a graph, and incorrectly tasks 3 and 4, which measured their stocks and flows knowledge.

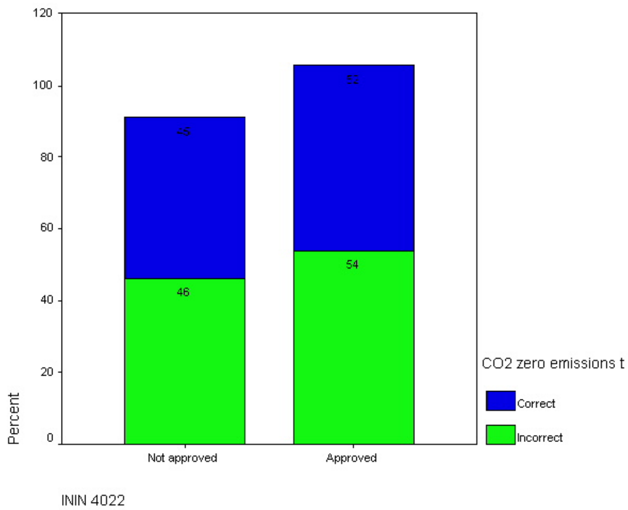
As explained before, the CO2 emissions tasks demanded the comprehension of a more complex description in order to complete the task. To our surprise, there was no significant difference related to English proficiency in the number of correct answers to any of the two tasks involved. In fact, only one person answered correctly the second CO2 task related to the average global temperature behavior after a sudden stop of CO2 emissions. This sole student reported basic English knowledge

It was hypothesized that having taken the course in Probabilistic Models in Operations Research (ININ 4022) might be of help to answer the systems thinking inventory task questions since some queuing theory concepts are related to the department store tasks 3 and 4. Here, a graph depicting the distribution of students tested that took or are currently taking this course.



SEMESTER OF STUDY VS. APPROVAL OF ININ 4022

As expected most students below the 6th semester had not yet taken the class and most students above that level had already taken it. Curiously, having queuing theory knowledge was not a predictor of correct answers and there was no significant difference in the likelihood of answering correctly any of the four questions in the department store task. The following graphic shows this situation.



ANSWER TO CO2 EMISSIONS VS. APPROVAL OF ININ 4022

V. CONCLUSIONS

One of the core aims of the present study was to raise awareness on some alternative approaches to twenty first century undergraduate engineering education such as systems thinking. Furthermore, we tried to identify whether systems thinking skills are acquired or present in engineering students in the current standard curriculum with a traditional teaching framework. In this respect, we tried to investigate if the students *in the last semesters of IE training would have a better understanding of system dynamics due to their exposure to a specialized education.* The results were correlated with controls of gender, high school background, and English language proficiency.

The IE coursework emphasizes systems concepts more than other engineering disciplines. Queuing theory, simulation, production systems, all are grounded in strong systems theory concepts. Thus, testing systems thinking concepts on IE students exposed to those classes is most appropriate.

Research findings of similar studies with different populations of graduate and undergraduate engineering and business students in different rigorous academic programs had shown that people do not naturally think systemically. While most students were able to read a graph, only 9.26% were able to identify the moment that most people were at the store and only 2.9% were able to identify the moment at which the fewest people were at the store. 42.65% of the respondents identified the path that CO_2 would follow if CO_2 emissions were to suddenly stop and only 1.5% (1 out of 68) was able to identify the average global temperature in the same conditions. These results demonstrate that highly quantitative people are able to read graphics and interpret them, but do not understand concepts of dynamic systems, such as stock and flow diagrams. Furthermore, while 42% were able to identify a delay in dropping of CO_2 in the atmosphere, almost nobody was able to identify the complexity of how temperature is affected in the environment, and recognize its behavior.

The second purpose of the study was to test whether individual characteristics of the subjects, such as their level of English mastery, the number of years in college, and their high school background, had any effect on the results. Contrary to the initial hypothesis, the results demonstrated no significant difference regarding any of those factors. This could indicate that undergraduate students at the UPRM have a reasonable level of English comprehension and that people with quantitative backgrounds are capable of understanding instructions of this nature even if their level of English is poor. In our case, there were no significant differences regarding students' ability to answer the questions. However the results may be biased by the fact that assessing the students' English proficiency does not necessary mean that it comprised also the English technical terms used specifically in systems engineering. We have to explore this issue in a follow up study.

In addition, the exploratory study provided valuable information; we can infer that mathematical training is not equivalent to systems analysis and systems thinking and that even students with coursework in certain related areas, such as queuing theory, cannot spontaneously solve these types of problems. Therefore there are many implications for engineering education research.

RECOMMENDATIONS FOR FURTHER RESEARCH

While a sample of 68 students is considered acceptable for this exploratory study, further research on a larger sample is needed in order to build up the demographic/academic and cognitive profile of those able to correctly solve the task. A special statistical technique will be used, *Classification Trees,* for developing the students' cognitive profile. This will provide valuable insights for systems thinking researchers in their efforts to differentiate between the individuals' inherent core traits and the ones that can be developed via educational interventions. Also, the impact of English mastery on the acquisition of engineering skills in students whose mother tongue is not English but receive all or part of their coursework in that language.

When presenting the results of our study we have to consider some of its limitations. In this respect we have to bear in mind that our study is an exploratory one, trying to validate a set of hypotheses that will be further used in a more extensive study, on a larger sample of subjects. Also, a comprehensive evaluation of the specific educational settings in engineering education is required and an assessment of the impact of the specific educational features on acquiring certain systems thinking skills and competencies. A special attention will be paid on assessing the viability of the systems centered educational approach as a special educational setting for undergraduate engineering education.

Finally, a more in depth study using a wide variety of systems thinking evaluation tools could be paired with the above sample characteristics. Assessing the cognitive abilities of the individual vis-à-vis the way he/she solves the tasks at hand will also be of great value for the future of engineering education.

VI. References

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