Engineering Thinking: Characterization by Experts and its Appearance in Graduate Design Projects

Authors:

Nissim Sabag, The Academic College for Engineering ORT Braude, Karmiel POB 78, Israel, Phone: 97249901942, Fax: 97249580289, nsabag@Braude.ac.il
Elena Trotskovsky, The Academic College for Engineering ORT Braude, Karmiel POB 78, Israel, Phone: 97249901709, Fax: 97249580289, elenatro@Braude.ac.il

Abstract — *Engineering thinking is a crucial part of the engineering profession. Lack of knowledge in this field encouraged us to inquire into the engineering thinking process. This article describes the research which deals with the characterization of engineering thinking. In order to clarify various aspects of the engineering cognitive process and to understand its nature, we interviewed approximately 30 experts from the disciplines of electrical and electronic, mechanical and software engineering. All our experts were well experienced senior engineers from the industry and lecturers from the academia. Based on these collected data, we characterized the engineering design thinking.*
Most graduates of our academic institute are involved in design and development of new products in Hi-Tech industries, i.e. engineering design. This kind of activity necessitates engineering thinking. We developed an internship module which is an obligatory requirement of the B.Sc. curriculum for the electrical and electronics engineering degree. 15 students were interviewed while performing their first engineering design project in industry, as part of their internship program.
The analysis of the students' interviews, their monthly and final reports, and the final presentations of their projects shows that those engineering thinking characteristics that were described by the experts, were expressed by students as well. Some of the characteristics are: concrete thinking, compromise on accuracy and adapting the term tolerance, creative thinking, algorithm routine thinking, and integrative thinking.

Index Terms — *Characterization of thinking process, cognitive activities, engineering design, engineering thinking*

INTRODUCTION

One well-known convention is that the design is a dominant activity of the engineer [1]. It is very common that young engineering graduates are involved in design and development of new artifacts, machines or electronic circuits, i.e. engineering design. We use the name engineering design thinking to describe this kind of intellectual activity, which demands a specific type of thinking. According to [2], "design thinking reflects the complex processes of inquiry and learning that designers perform in a systems context, making decisions as they proceed, often working collaboratively on teams in a social process, and "speaking" several languages with each other (and to themselves)." It is important for educators in all areas of engineering to understand the nature of engineering design thinking, its uniqueness, components and their interrelationships. It is advisable to develop engineering thinking among undergraduates already in the course of their B.Sc. studies. This may reduce the gap between knowledge and skills acquired by novice graduates and market demands, and help them to soften the transition from academia to real work.

Educational researchers have become increasingly interested, lately, in various aspects of engineering design thinking [3-9]. Most of these studies belong to the disciplines of mechanical and industrial engineering. Nevertheless, there is a lack of design thinking research in the field of electrical and electronic engineering.

Fortunately, the internship program in the Department of EEE of the Academic College for Engineering ORT Braude provided us with the opportunity to research the cognitive processes of students in electronic engineering design. This internship activity is an obligatory requirement of the B.Sc. curriculum for the electrical and electronics engineering degree. The internship program forces the student to perform at least 1000 hours of engineering design project in an industry or research institute within the fields of electricity and electronics. In order to characterize engineering design thinking, we investigated the views of experts – well experienced engineers from industry and senior lecturers from academia (usually with industry background as well). We also examined the thinking process of electric and electronic undergraduate students in the area of their internship while developing engineering design thinking, and attempted to locate their intellectual activities in the experts' characterizations. This paper seeks to contribute to the educational research knowledge concerning cognitive processes and activities in electronic engineering design.

METHOD

In the first part of our longitudinal study [10] we mainly used quantitative research tools. The comprehensive survey questionnaire for our graduates and their employers was completed. Results showed that there is a need for a deeper understanding of the cognitive processes of students in the course of their first engineering project design. Therefore, in the second part of the study we moved to a qualitative research methodology.

We assumed that interpretive research [11] would be appropriate to our goal. This kind of study allows for clarification analyses and a deeper understanding of researched cognitive processes. We used open interviews as the main research tool. More than twenty in-depth interviews with experts and fifteen interviews with students were conducted. The majority of experts were electronic engineers. Six of our experts had 40 years experience, 11 of them had 30 years and another 3 had 25 years of professional experience. Most of the specialists had both industry and academic experience, and 13 experts had a Ph.D. degree.

All interviewed undergraduates were EEE students. Their projects dealt with different areas such as digital electronics, analog electronics, RF, software, and integration. Some of them performed their projects in large firms and others in medium or small companies. The central question in the experts' interview was "How do engineers think in each stage of the design process?" In order to help them to characterize engineering thinking, we suggested that they compare it to scientific research thinking which is well established. The main question of the students' interview was "How did you think in each stage of your design work?" Additional data was collected by analyses of monthly and final students' reports and observations of students' final work presentations.

An analytic induction strategy [12] was applied for data analysis on this part of study. The verification procedure had two stages. First, interviews with the experts were continued until the collected data did not contribute further to the gathered database. Second, inductive analysis of the collected information was performed until a stable structure of engineering design thinking categories was obtained. After verification of the characterization, a series of student interviews yielded additional data about students' activities. Then we matched the students' data to the experts' characterizations.

RESULTS

In order to characterize engineering design thinking, we constructed a system of categories concerned with different aspects of engineering cognitive activities. Figure 1 presents five main categories of thinking, which have been identified in our study. As can be seen, in the characterization of engineering thinking, pure cognitive factors appear as well as additional aspects, such as links to environment and motivation, which can affect the cognitive process.

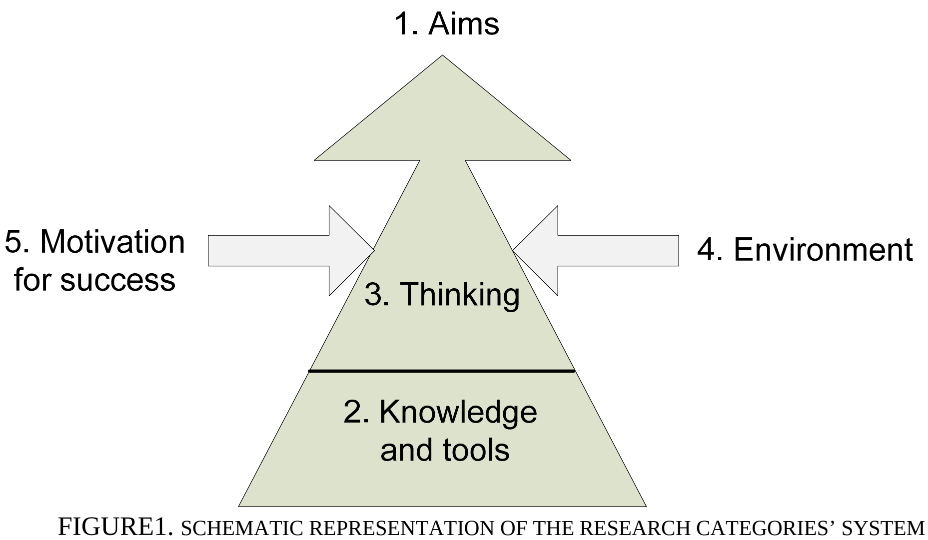

FIGURE1. SCHEMATIC REPRESENTATION OF THE RESEARCH CATEGORIES' SYSTEM

The first category indicates the aims (1) to which thinking is directed. The second is knowledge and tools (2) upon which thinking is based. The third and central category is the thinking (3) itself or cognitive processes. Two additional categories are the environment (4) and the motivation for success (5) (external and internal factors) which affect the cognitive processes.

Several sub-categories were found for all categories. Table 1 shows the categories revealed in the research including sub-categories. Some of them are consistent with Waks's dimensions of science-technology interrelationships [13]. Yet, emphasizing the thinking aspects distinguishes between the sub-categories of this study and Waks's multi-dimensional approach [13].

Category	Num.	Engineering Design sub category
1. Aims	1.1	Knowledge application: directed to a new product
	1.2	Engineering research: knowledge broadening for knowledge applications
	1.3	Engineering for research: knowledge application for knowledge
2. Knowledge and tools	2.1	Creation of a knowledge base
	2.2	Collecting and learning relevant knowledge
	2.3	Mainly use of application models and laws
	2.4	Using heuristics
3. Thinking	3.1	Synthesis, aspiring to understand how
	3.2	Concrete thinking
	3.3	Systems thinking
	3.4	Advance toward the desirable
	3.5	Creative thinking and algorithmic routine thinking alternately
4. Environment	4.1	Working mode: team work mainly
	4.2	Firm working conditions
	4.3	Economic facet is very significant
5. Motivation for success	5.1	Motivation: real need to succeed and individual responsibility
	5.2	Appreciation: reputation in firm, patent

TABLE 1.SYSTEM OF CATEGORIES CHARACTERIZES THE ENGINEERING DESIGN THINKING

Now let's discuss the results of the final stage of our study –analysis of students’ cognitive activities on the basis of this characterization. We will refer to a small portion of the collected data and illustrate how a number of thinking characteristics described in table 1, paragraph 3 (category of thinking) appeared in students’ interviews and reports.

Concrete thinking

In engineering design, the engineer deals with a system realization. Within a thinking process, he translates the customer demands into system specifications which should be designed, in accordance with the users' comfort. He chooses practical components with specific parameters to the system, connects them and determines their working modes. After the system construction, he conducts a series of experiments to verify the system's functioning. It is evident that all these actions might be ascribed to concrete cognitive activities. Here are some citations from experts' interviews related to concrete thinking:

- An engineer must rely on existing entities…using what already exists in development: materials, parts, components and known data [expert 5].
- When you come to build systems…you bring practical considerations to see if this thing can be built …can we build it this way or that way. What other considerations should be taken to account…ha…not only mathematical. You should say…can it be implemented?… are the values reasonable? If I give it to production, can it be produced? Are there the needed tools and abilities? [expert 9]

As we can see, the experts testified that engineering thinking is based on concrete and well known parameters of materials and components. The engineer's cognitive operations can be referred to as concrete operations.
Different aspects of concrete engineering thinking were expressed in students' work. For example, students described the specifications of the system that they developed:

- When I am specifying a product I specify its features. Then I must close any corner. For example, the issue of manual operation: the user wants to open the valve, he opens it and goes. So, what now? Will the valve stay open forever? Will this valve close at midnight? Or, maybe, it will stop after a specified time? Another example refers to odd and even watering days in the U.S. If you are allowed to irrigate on an even day you get a big penalty. Now, what if a person starts his irrigation system on Monday at 11:00 P.M. and sets the system for 2 hours? Will the system stop at 12:00 P.M. or not? You must close this corner. [student 4]
- Mathematics… it is more about hardware. You, mostly, do not need to rely on mathematics. It is simple to see the things. To see how things come together. To see the whole picture, what problems can be expected, what do you want to check and what is most important? [student 8]
- It means, of course, that you have to test it *(the system)* in extreme situations: when it is loaded, when you do not have ideal conditions, with long supply lines, when some supply lines are close to each other, and you have

situations that work well in the laboratory, but this is not real. This system can be 500 meters long from one side to the other. It is not like connecting a 10 meter cable and saying: fine, it is working! [student 8]

It arises from both the experts' and students' interviews that the design process contains a lot of concrete aspects, such as understanding and using existing elements, checking and rechecking the system's appropriateness to its specifications.

Compromise on accuracy and adapting the term tolerance

According to Waks [13]: "the technologist or engineer cannot expect pure pre-calculated accuracy in the operation of a designed set-up or process, because its ingredients and external conditions take values spread over externally imposed ranges (e.g. ±10% of resistors values in electronic instrument)."

The experts in this study emphasized the importance of the terms tolerance and approximation in engineering design. Here are some examples from their interviews:

- i. Engineering is blamed for "cutting corners". Engineering approximations are measured by sensitivity to end performance and justified by experience. ii. Scientific approximations are justified by the model sought [expert 8]
- In engineering thinking, we move from an existing set of tools and seek a solution within the limits of accuracy. Yes, in the limits of accuracy or inaccuracy, I am saying it in purpose, I mean sufficient from the specifications point of view...I want to emphasize that the base is imprecision. Hamm…An engineer's solution is never like a thin line. It always has some thickness. On the other hand, there are always tolerances and approximations, so engineering design mean compromising. The one who knows how to compromise and estimate variables more efficiently, is the one who gets a cheaper product [expert 4].

The students mainly referred to components tolerance and their influence on the developed system's parameters:

- The resistor has 5% tolerance, so 5% it is. If you want to build a 300 kHz oscillator you might get 329 kHz. You must take it into consideration…especially when it comes to capacitors. They have a standard tolerance of 10% and the temperature can make it to 20% or even 30%. So, it must be taken into consideration. To know that such things happen. [student 8]
- When I say a 51.94 ohms resistor, so what is the problem, it is only a number? Especially when we deal with a capacitor which has a standard tolerance of 10% and becomes worse with the temperature. You never see it during studying because it is all (studying) theoretical. [student 8]
- There are a lot of resistors. So, for self test purposes I defined 2.5 ohms instead of 1 ohm. It is the resistor's resistance plus the wire's resistance. There about 1.5 meters of wire, this has approximately 1.3 to 1.4 ohms. I determined it as a fact. So if the resistor shorts out I will see only 1.5 ohms and if it cuts out I will see a cut off. [student 7]

The interviews above demonstrate that accuracy replaced by the term tolerance, which is more appropriate in engineering design.

Creative thinking and algorithm routine thinking

De Bono [17] claims that lateral thinking is in use both in science and engineering and he also says: "…the design process involves much lateral thinking". Waks argues [18] that lateral thinking: "…pave the way for new ideas to evolve", meaning, lateral thinking is a form of creative thinking. According to Voland [19], the creative thinking in design engineering involves the ability to synthesize, meaning to combine things and ideas in new meaningful combinations.

The importance of creative thinking is expressed by some experts as cited below:

- Need leads to thinking…special needs…yield deviation from norms. This is creative thinking that there is no compromising. [expert 4]
- It is like with artists, where does it come from? How does he create a picture or a piece of music? There is something unknown, unclear, some secret. He himself does not know how it comes out. I think that here is something in common between an artist and scientist. The engineer has it as well. [expert 15]
- His ability (the scientist) to jump from one subject to another and to look at the same problem from different points of view should be more developed. [expert 6]

Here we bring examples of creative thinking among students. Whenever the student showed a nonstandard or original solution to his project problem, we classified it as creative thinking:

- One of the serious reasons that I created a coded controller is for "High Z". I want it to tell me who's on the BUS now, so others will not be able to reach it. This was one of the central problems. I could solve it without a controller. The controller is only to see who's on the BUS…to avoid collisions. It just monitors the BUS and does not allow anyone to get the BUS till it's free. [student 5]

- The controller manages a dialog with you. That means, it asks yes or no questions and directs you according to this. The controller that I am developing now, it cost me my health; you don't need any manual to work with it. It will just ask you yes or no questions. After you answer yes, it will tell you: "use the + and – keys to enter the watering time for valve one then press yes". After you press it will tell you: you did such and such. [student 4]

Creative thinking is required mainly in the first steps of engineering design, when alternatives for the problem solution are raised. In the advanced stages of development, the engineer uses algorithmic, or vertical, thinking mostly [17]. Waks [18] indicates that: "Vertical thinking is a sequential process in which every step has to be correct and justified before moving to subsequent stage – it is hierarchical ordered process." The vertical or algorithm routine thinking is activated by a sequential logic thinking process aimed to achieve concrete desired results. The next citations support this argument:

- The first stage is really the creative, in which, one really tries to make breakthroughs…in a certain stage the creativity ends this is the time to complete the product…some people deal with how to do things all their lives, others work more systematically. That's it, we already said that both things are important, if everybody were creative all the time we wouldn't achieve anything. [expert 11]
- The level of creative thinking that you want from the engineer should be balanced; it must be in proportion since you always seek for balance between efficiency and innovation…in every organization you will find a few…two, three or maximum five percent of nonconformist people; they are always think out of the box…this depends on the organization…as much as the organization requires high class innovation it needs more of this kind. It's a combination of experience and mentality. [expert 8]

In spite of the importance of creative thinking, experts emphasized that turning an idea into a working product involves routine algorithmic thinking too, as cited here:

- Thinking process is… logic and knowledge that a man acquired…they build the thinking process. I don't think there is much difference between engineering and science. [expert 5]

An example of algorithmic routine thinking from a student's interview appears here:

- I should choose a transistor, so, he (who?) directed me to transistors in use for VCO applications. I searched for data sheets from where I took out what I needed, according to the Noise Figure more or less. I found the most suitable quiescent point, then I found what resistors to connect to it in order to get the desired quiescent point that I want. Ha,…before I had the quiescent point there was the story of the feedback to create the VCO's oscillations. So, for the compensation (circuit) based on two capacitors and an inductor, I used the existing experience some presentations and examples to decide what the best is. [student 3]

It is evident from the citations above that engineering thinking invites both creative and routine algorithmic thinking.

Integrative thinking

One of the most experienced experts, an engineer with more than 30 years seniority, said that the electronics industry today is the industry of composition [expert 14]. That means, many new systems use components such as SRU (small range unit) or entire blocks that were developed for different goals by other manufacturers. The accessibility to information on the internet brings to use products, as well as ideas and solutions for specific engineering problems. In order to use this kind of approach, the engineer should develop integrative thinking. Here are citations from some experts' interviews:

- A large part of the abilities today is evolution and the fact that you gather a lot of things from different sources, and connect them together to do something new. The thinking now is how to integrate things that I know and things that I need, and is this the most appropriate for me? Before, I had to break my head…how will I build it, in order to implement it? Today I go and see what they did, if it helps me I will take it from there. The thought now is how do I integrate things that I know and things that I need and will it be the most suitable for me? [expert 9]
- Electronic engineering today… is playing LEGO if you know how to develop the LEGO. Take for example the issue of development today ha…assuming they know the technology; they know the input and the output. They say: ok. I have the LEGO…all the logic design is LEGO…in digital electronics it's usually this way and digital electronics is about 70% - 80% of the whole electronics, in my opinion, it may not be exact. Actually you use…you learn to use integrated circuits in the field of RF, that's the only difference. Take E. for example…yes E. It is for many years a successful company. It had two or three things of their own, self developed, all the other products were, what we jokingly call, confectioned products. They took a system…from R… attached it …let say to a sound system…they joined it to an electro-optic system and fitted it to a product. Actually the project manager had to characterize the product according to is connections with the defense market, ok? What they did actually they stuck things together,

ok, took from here and from there integrated it and made it an E.'s system. It's a pure LEGO even in principal…every institute here works this way, not only digital electronics but electro-optics, RF, and other sophisticated systems as well. [expert 14]

The students also brought examples of using existing components and SRUs in the design of electronic systems. The next citation refers to the compatibility between the existing parts and the system being developed.

- I had two main lines. One is to design an assisting hardware for testing. Meaning, I had some purchased data acquisition to make the samples and so. From there…it's not good enough; it works with its voltage levels. It sometimes has problems of loading so it needs some buffering. [student 8]

The next citation refers to the economical aspects of using existing solutions when designing a new system:

- Once we went towards a SRU (buying a ready one) we decided to add some more options, such as PLLs. This was supposed to save us a lot of money. Today, we purchase it from National Instruments and say: let's save this money. The cost of developing such a SRU is 20,000$. So, since we already invested this money, it is better to use it (efficiently both now and in future projects). [student 5]

The citations above revealed the great importance of integrative thinking these days, which enables using existing solutions in new areas. Forming ideas by using a ready component in a new system or using a device that was designed for one use in new areas is the fruit of both creative and algorithmic routine thinking. This is the process of integrative thinking.

Conclusions

In our efforts to understand the nature of engineering design thinking, we tried to characterize it. The way we approached this task included a set of interviews with experts from the field of electric and electronic engineering. In order to help them to characterize, we suggested that they compare engineering thinking to scientific research thinking. In the second step of this research, we identified those characteristics in students' work while designing their first engineering project. Here we focused only on a few of the characteristics. As shown above, engineering thinking is concrete. It takes into consideration the customer's needs, financial aspects, what already exists in the field and sufficient tolerances. Engineering thinking is composed of both creative and algorithmic routine thinking. In our opinion, educators should aim in both their curriculum and teaching efforts towards enhancing these abilities among their students. The appropriate area for these activities might be the hi-tech industry environment where real design engineering is performed.

REFERENCES

[1] Simon, H.A., *The Science of the Artificial*, 3rd ed., Cambridge, MA: MIT Press, 1996.

[2] Dym, C. L, Agogino, A. M, Eris, O., Frey, D. D., and Leifer, L. J., Engineering Design Thinking, Teaching, and Learning, *J. Eng. Educ.*, **94** (1), 2005, pp.103-120.

[3] Shah, J.J., Smith, S.M., Vargas-Hernandes, N., Gerkens, D.R., and Wulan, M., Empirical Studies of Design Ideation: Alignment of Design Experiments with Lab Experiments, *Proc. of DETC 2003: ASME 2003 International Conf. on Design Theory and Methodology*, Chicago, IL, 2003.

[4] Bailey, R., Comparative Study of Undergraduate and Practicing Engineer Knowledge of the Roles of Problem Definition and Idea Generation in Design, *Int. J. Eng. Educ.*, **24**(2), 2008, pp.226-233.

[5] Davidz, H.L. and Nightingale, D.J., Enabling Systems Thinking To Accelerate the Development of Senior Systems Engineers, *System Engineering*, **11**(1), 2008, pp.1-14.

[6] Smith, R. P. and Tjandra, P., Experimental Observation of Iteration in Engineering Design. *Research in Engineering Design*, **10**(2), 1998, pp. 107-117.

[7] Adams, R. S. and Atman, C. J., Cognitive Processes in Iterative Design Behavior, *Proc. Frontiers in Education Conf.*, **11**ab, 1999, pp. 13-18.

[8] Hey, J., Pelt, A.V., Agogino, A., and Beckman, S., Self- reflection: Lessons Learned in a New Product Development Class, *J. of Mechanical Design*, **129**(7), 2007, pp.668-676.

[9] Atman, C. J, Adams, R. S., Cardella, M. E., Turns, J., Mosborg, S., and Saleem, J., Engineering Design Processes: A Comparison of Students and Expert Practitioners, *J. Eng. Educ.*, **96**(4), 2007.

[10] Sabag, N., Trotskovsky, E., Schechner, P. Internship as an Obligatory Requirement for the Degree of B.Sc. in Electronic and Electrical Engineering. *ITRE 4th International Conference on Information Technologies.* Tel-Aviv, Israel, 2006.

[11] Denzin, N. K. and Lincoln, Y. S., *Handbook of Qualitative Research (2nd ed.)*, Thousand Oaks, London: Sage Publications, 2000.

[12] Patton, M. Q., *Qualitative Research and Evaluation Methods* (3rd ed.), Thousand Oaks, CA: Sage Publications, 2002.

[13] Waks, S., Science – Technology Dimensions in Physics Education: Prospects and Impact, *Physics Education*, **29**, 1994, pp.64-72.

[14] Tadmor, Z., Redefining Engineering Disciplines for the Twenty-First Century, *The Bridge – The Journal of US National Academy of Engineering*, **36**(2), 2006. Accessed February 9, 2009.

[15] O'Connor, J. and McDermott I., *The Art of Systems Thinking: Essential Skills for Creativity and Problem Solving*, San Francisco, CA: Thorsons, 1997.

[16] Frank, M., Engineering Systems Thinking and Systems Thinking, *Systems Engineering*, **3**(3), 2000, pp.163-168.

[17] De Bono, E., *Lateral Thinking for Management*, New York, NY: Penguin Books,1971.

[18] Waks, S., Lateral Thinking and Technology Education, *J. of Science Educ. and Technology*, 6(4), 1997, pp. 245-255.

[19] Voland, G. (1999). *Engineering by Design*. US: Addison Wesley Longman.