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MEASURING THE VALUE OF SYSTEMS THINKING FOR DESIGN-CENTRIC ENGINEERING EDUCATION

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Abstract

Systems thinking, design thinking and strategic thinking have been identified as important competencies for future engineers. Many institutions have introduced these subjects into their engineering courses. However, there is need for a deeper appreciation of the underlying assumptions behind these strands of thinking and ways to measure their impact. This paper draws on a four-year experience in implementing systems thinking in a design-centric engineering program in India. It presents the approach adopted and a complexity-based measure to track development in systems thinking competence.

Keywords: systems engineering (SE), design thinking, complexity, competency model

1. Introduction

It is well recognized that engineers of today and tomorrow require a broad set of competencies to address the challenges of innovation and sustainability in a world of increased complexity. As a result, many engineering institutions across the world have been tweaking their curriculum to incorporate subjects such as systems engineering, product design and entrepreneurship.

However, integrating these subjects into the engineering curriculum poses two key issues. First, the ambiguity with respect to the underlying strands of thinking - systems thinking, design thinking and strategic thinking. Are they similar, different or synergistic? Second, measuring the impact of these strands of thinking on the student's problem-solving capability.

The first issue is actively being debated by scholars such as Greene et al. (2017), Buchanan (2019), and Junior et al. (2019). Having participated in strategy and innovation initiatives in the industry for over two decades, the author's view is that systems and strategic thinking promote strong abstraction and pattern seeking behaviour, while design thinking promotes deep contextual awareness and action orientation. The outcome of both is the ability to grasp/sense the underlying and emerging patterns that cut across technical, economic and social dimensions. This paper adopts this view and focuses on the second issue - measuring that ability. It presents a generic complexity-based model to measure this ability by synthesizing the key aspects of systems and design thinking competence. The model was developed as part of an initiative to introduce a product and design-centric engineering curriculum in a young, public-funded technology institution in India.

The paper is organized as follows: Section 2 provides an overview of the context in which this action research was carried out. Section 3 discusses the complexity-based approach to measure the systems and design thinking competence. Section 4 presents the results and Section 5 presents the conclusion.

2. Systems thinking for product and design-centric engineering

The site in reference is an institute of national importance in India. It was setup in 2007 with a specific mandate to promote a new breed of engineers who can leverage Information Technology and design to develop knowledge-intensive products/processes for the manufacturing sector. Seven years after its inception, the institute launched a design-centric engineering curriculum for all the three undergraduate courses - mechanical, electronics and computer engineering. It involved allocation of about 30 credits (17% of the total credits) for subjects aimed at promoting product design and entrepreneurial orientation among engineering students, right from the first semester. The remaining 83% of credits were allocated to engineering (42%), basic and engineering sciences (24%), internship & project work (13%) and free electives (4%). The list of product design and entrepreneurship subjects, their sequencing across semesters, and expected learning outcomes are shown in Figure 1.

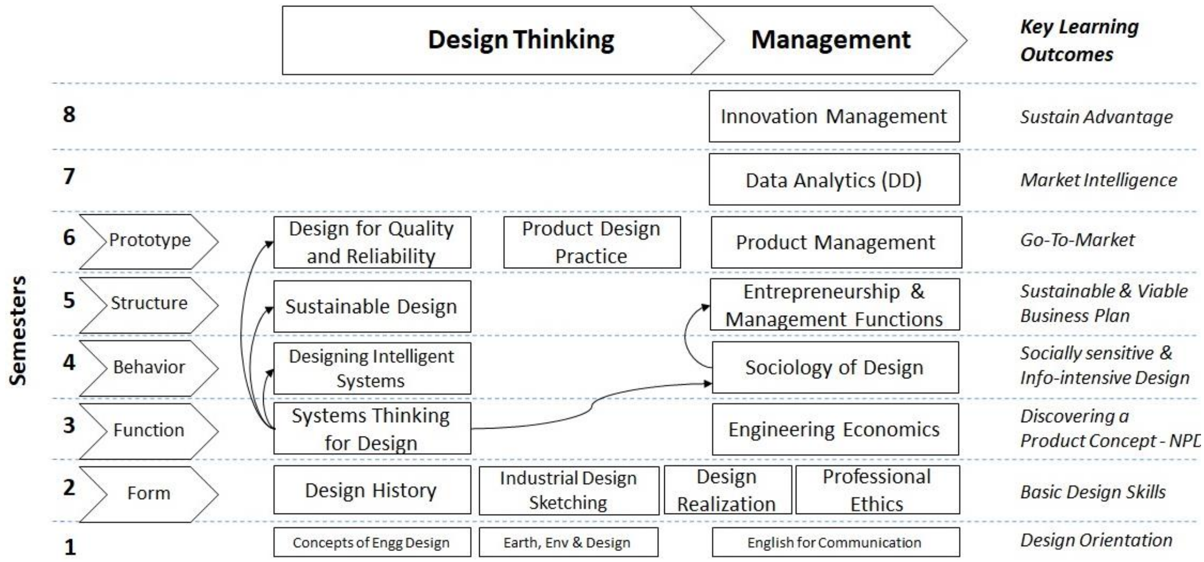

Figure 1. Product design and entrepreneurship subjects in the design-centric engineering curriculum adopted by the institute in 2014

One of the subjects introduced as part of this curriculum was "Systems Thinking for Design". It was positioned as a compulsory two-credit subject in the third semester. The positioning of the subject in the third semester triggered several questions.

a) Is it appropriate to teach systems thinking at an early stage in an undergraduate course when it is viewed as a meta-cognitive skill?
b) How would it relate to the design and entrepreneurial concepts taught in preceding and succeeding semesters? How would it relate to the technical subjects taught in different engineering streams that emphasize analysis over synthesis?
c) Can students, with a mindset of qualifying rule-based competitive exams and with very little preparation for design, cope with a higher-order thinking skill? Can a two-credit subject encourage focus and effort from students whose time and attention may be divided among several other engineering subjects that have higher credits?
d) Can systems thinking be effectively delivered for large class sizes of 120-160, and for a total strength of 450-600 students per faculty in a semester?

There is some support for introducing systems thinking at an early stage in an engineering program. Studies conducted with final year Electrical Engineering students working on their capstone project (in the US) have shown that students who are equipped with systems thinking do far better in their capstone projects compared to those who are not exposed to these concepts (Flores et al., 2012). This is surprising since the word 'system' is frequently used in many Electrical & Electronics courses. Scholars have also argued for an integrated and long-term approach to develop system thinking competencies (Hiller et al.,

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2012). Taking a cue from the above and two decades of experience in applying systems thinking in practice, the author adopted a five-pronged strategy.

First, clarifying the positioning of the systems thinking vis-a-vis the other subjects preceding and succeeding it, and in relation to the overall purpose of the new curriculum. A careful observation of all the design subjects in the first two semesters suggested that they are related to appreciation of form and redesigning the form of existing products (as shown in Figure 1). The subsequent semesters (4-6) dealt with design for different behaviours and structure (intelligence, sustainability and reliability). As a result, systems thinking was positioned to address the fuzzy front-end of new product development. i.e., to identify the new product concept and define the functional requirements in a holistic manner. Literature shows that systems thinking has a key role to play in the fuzzy front-end (Jetter, 2003; Erden et al., 2008; Tomko et al., 2017). The content was tweaked to place strong emphasis on discovering the problem situation, diagnosing the real issues, designing the high-level product concept, and defining the functions (inter-disciplinary). In other words, systems thinking was targeted at the translation from need identification to Requirement (R)-Function (F)-Expected Behaviour (Be) in the FBS model (Cascini et al., 2013).

Second, introducing a set of complex systems principles that would help students make sense of a problem situation in a holistic manner and tease out the requirements (without any disciplinary bias). In addition, the focus was on explaining the distinctions between principles of systems, cybernetics and complex adaptive systems so that it could support discussions in subsequent subjects such as Designing Intelligent Systems, Sociology of Design, and Entrepreneurship & Management Functions (shown in the form of linkages in Figure 1). This vertical integration among subjects was also done to promote development of systems thinking competence over time, and help students experience the entire journey from concept to prototype.

Third, adopting a problem-based-learning / learning-by-doing approach. This has been recognized as an important element of developing students' engagement with systems thinking practice (Camelia and Ferris, 2017). It involved encouraging students to start by reflecting on their everyday experience, identifying a topic/domain of interest, interacting with fellow students to find similarities and partnerships, jointly research about the problem, identify the real issues, and define the purpose of the product, its high level requirements, and the functions through constant iteration between why and how. Problem-based learning also meant that evaluation had to focus on the quality of participation.

Fourth, promoting collaborative practices and teamwork to help develop systems thinking competence through social interaction. In addition, external mentors were introduced at various stages through invited talks during the semester, during hackathons and during industry open house events so that students get exposure to external perspectives. Students were also encouraged to use digital tools such as Google Docs to support collaborative content creation. In other words, systems thinking competence itself was treated as an emergent property that could emerge out of interactions around a specific problem of interest. Team-based approach also proved useful for engaging a large class.

Finally, measuring the everyday activities of students (individual and team) so that the development of systems thinking competence could be tracked clearly. Instead of taking attendance, small exercises were given in every session and these were evaluated from the systems thinking competence perspective. The competency model and the evaluation approach are discussed next.

3. Measuring the systems thinking competence

3.1. Proposed model for systems thinking competency assessment

One of the key challenges with systems thinking is the lack of clear models and metrics to measure the competency. For instance, Frank (2012) has argued that there is a dearth of literature on effective means for testing the systems thinking skills of undergraduate students. He compared different models of successful systems engineers and proposed sixteen cognitive competencies to assess systems thinking. Huang et al. (2015) proposed a 30-item 6-point Likert scale to measure attributes like thinking holistically, interdisciplinary knowledge, optimization and communication and interpersonal skills. Castelle and Jaradat (2016) have proposed a framework to measure individuals' systems thinking competency. The instrument consists of seven scales to measure fourteen major preferences reflecting an individual's systems thinking capacity in dealing with

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complex system problems. However, these methods rely on survey instruments and capture the qualitative perceptions of individuals at a point of time. They do not measure the progress in terms of systems thinking maturity.

Recent literature points to more precise methods to assess systems thinking competencies. For instance, Tomko et al. (2017) have measured students' ability to abstract function. Grohs et al., 2018 proposed another framework to evaluate systems thinking competence. Lavi and Dori (2019) argued that students' systems thinking can be assessed through conceptual models created using a model-based-systems engineering methodology. Buckle (2018) argued that systems thinking competence is reflected in the orientation toward causality, logic, explicit and implicit structures, subjectivity, and self-reflection. Argued that contextual awareness, a core engineering competency emphasized in the Accreditation Board for Engineering and Technology criteria, is largely overlooked in existing definitions of systems thinking. One key gap that is noticed in literature is the absence of studies that combine problem-based learning with competency measures drawn from the micro-level activities of individuals / group that can help track competency over time.

This paper presents an approach that combines problem-based learning and a generic complexity-based model for tracking development of systems thinking competence over time. It uses a set of five key activities to measure the competencies - identification of key elements, classification of elements, identification of relationships, seeing patterns and synthesis with or without metaphors and the level of creativity in synthesis. These five activities mirror the five factors used to measure complexity of a system, i.e., number of elements (n), the number of relationships (k) and the three patterns of relationships among the elements - hierarchy, feedback loops and clusters (example, Sinha and Suh, 2018). In other words, the ability of a student to model/grasp the underlying or emerging complexity of a system can be evaluated by focusing on these activities. Table 1 shows a mapping of these activities to the key competencies identified in different cognitive models of systems thinking.

Table 1. Mapping of system thinking competencies to key activities in the proposed model

Systems Thinking Competencies as per CEST Model (Frank, 2012)	**Cognitive psychology related concepts (Greene and Papalambros, 2016)**	**Equivalent activities in the proposed complexity-based model**
Understand systems without getting stuck on details	Abstraction; subsumption	Identify Elements
Able to take into consideration non-engineering factors	Conceptual combination	Identify Elements
Understand a new system/concept immediately upon presentation	Categorization; conceptual learning; inductive learning	Classify Elements
Able to define boundaries	Functional decomposition	Classify Elements
Understand interconnections	Induction; information integration	Link Elements
Understand the system from multiple perspectives	Perspective taking	See Patterns
Understand the whole system and see the big picture	Sensemaking; mental model formation; generalization	See Patterns
Ask good (the right) questions	Critical thinking	See Patterns
Understand the implications of proposed change	Hypothetical thinking	See Patterns
Understand limits to growth	Information integration	See Patterns
Able to "see" the future	Prospection	See Patterns
Understand system synergy (emergent properties)	Deductive inference	Synthesis
Are innovators, originators, promoters, initiators, curious	Inquisitive thinking	Synthesis
Able to optimize	Logical decision-making	Synthesis
Understand analogies and parallelism between systems	Analogical thinking	Synthesis
Think creatively	Creativity	Synthesis

In addition, the five key activities were also mapped to the core competencies of design thinking that are closely related to systems thinking. Conley (2010) had identified seven core competencies of

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design: the ability to recognize a broad range of potential in a given problem statement; the ability to work at varying levels of abstraction; the ability to model and visualize solutions before all the information is available; an approach to problem solving that involves the creation and evaluation of multiple alternatives; the ability to add or maintain value as elements are integrated into a whole; the ability to identify and respond to relationships between a solution and its context and the ability to use form to embody ideas and communicate their value. These predominantly relate to seeing patterns and synthesis as shown in Table 2. Leclerc and Horan (2018) had matched psychological traits/types to Conley's seven design attributes: leadership, creativity, adaptability, organization, receptivity, exploration, discrimination and communication. Junior et al. (2019) identified key systems skills relevant to design: multilevel perspective, complexity handling, adaptability, multiple stakeholders, and multidisciplinary teamwork. These are also shown in Table 2. Most design competencies map to the two higher level competencies, i.e., ability to see patterns and synthesis. Therefore, it is proposed that student performance in the five activities could point to systems and design competence.

Table 2. Mapping of core competencies of design to the key activities in the proposed model

Core Design Competencies (Conley, 2010; Leclerc and Horan, 2018, Junior et al., 2019)	**Equivalent activities in the proposed complexity-based model**
the ability to recognize a broad range of potential in a given problem;	See Patterns
the ability to model and visualize solutions before all the information is available; (complexity handling)	Identify Elements; Link; See Patterns
the ability to work at varying levels of abstraction; (multi-level perspective)	See Patterns
the ability to add or maintain value as elements are integrated into a whole; (multi-disciplinary teamwork)	See Patterns
the ability to identify and respond to relationships between a solution and its context (adaptability)	Synthesis
the ability to use form to embody ideas and communicate their value	Synthesis
an approach to problem solving that involves the creation and evaluation of multiple alternatives;	Synthesis

3.2. Approach for measurement of systems thinking competence

The approach to measure everyday activities of students individually and in groups was done in the following manner. A baseline is set in the first session where students are asked to capture the pattern that they saw in the first-year subjects. It has been observed that most of the students end up writing down descriptions of the first-year courses. Very few students exhibit traits like grouping/classifying subjects or linking the subjects or using some metaphors to convey the pattern of relationships.

In the second session, the students are asked to identify a topic of interest through a process of reflective writing, i.e., asking themselves about their core values, their passion and why engineering. Here again, most students struggle to reflect, and respond to each question in isolation. Very few manage to communicate the connections among the three responses. This is not just a problem with language, but the difficulty in relating things. In the third session, they are asked to interact with fellow students to identify potential collaborators and decide on a real-world problem.

In the subsequent sessions (4-10), the students are introduced to systems principles and three methods to apply these principles to define the problem, elicit the requirements, develop a solution strategy and arrive at a concept design. The assignments are evaluated in terms of how well the students perform in the five activities – identifying key elements, classifying elements, linking elements, seeing patterns and synthesizing / use of metaphors. The final scores include both team and individual performance.

4. Results

The study has been done for four years (2015-2019) with approximately 240 students in each year (increased to 330 in 2019). The results are presented at four levels: (a) overall performance of students in

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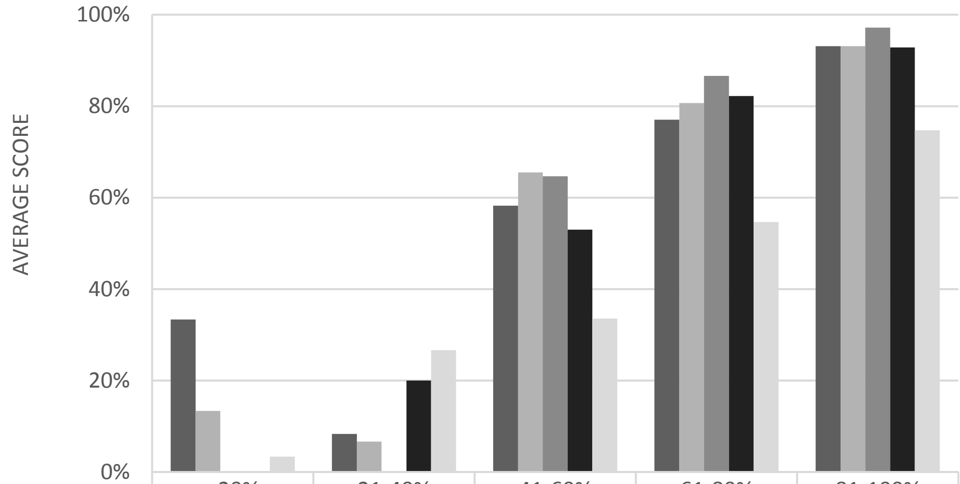
terms of the critical competencies; (b) early predictors of performance; (c) impact of team characteristics on acquisition of systems thinking competencies; and (d) impact on performance in subsequent semesters.

4.1. Performance in systems thinking competencies

Figure 2 shows the average score of students in each of the five competencies across five performance bands (0-20% to 81-100%), ordered from low to high. The average score in each of the five competencies increases as we move from the low performing to high performing students. The difference between the highest performing students (81-100%) and the mid-level (41-60%) is highest in two higher level systems thinking competencies – seeing patterns (40%) and synthesis (41%).



	<20%	21-40%	41-60%	61-80%	81-100%
Identify Elements	33%	8%	58%	77%	93%
Classify Elements	13%	7%	66%	81%	93%
Link Elements	0%	0%	65%	87%	97%
See Patterns	0%	20%	53%	82%	93%
Synthesize/Use Metaphors	3%	27%	34%	55%	75%

Figure 2. Average systems thinking competency scores (Low to High, n=913)

4.2. Early predictors of performance

Another important observation is that performance in one of the initial assignments (the depth and clarity in the self-reflection) emerged as a strong predictor of student performance in the subject (Figure 3). The same test can be used to identify students who might need more attention. Figure 3 also shows that each of the assignments has a strong correlation with overall performance. One area where no correlation was seen was the multiple-choice questions given in the end semester. The element of chance in such a test may be the reason for no correlation.

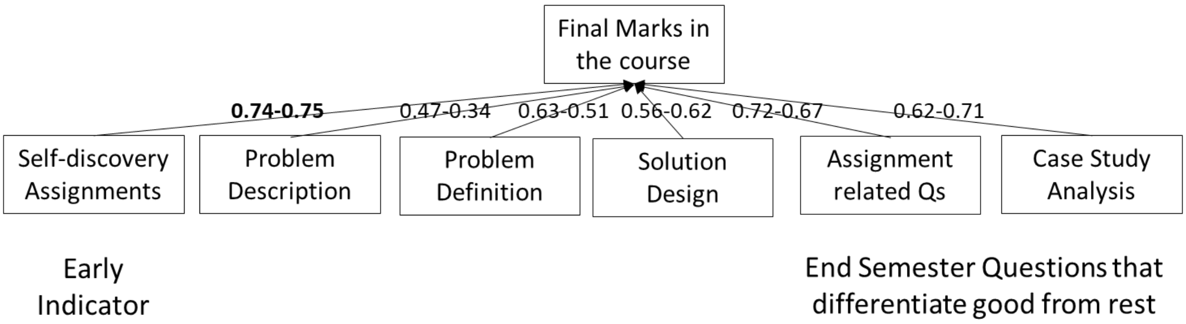


Figure 3. Early predictors of overall performance

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4.3. Impact of team characteristics

The results also revealed that team diversity in terms of the disciplines and regional background of students impacted student performance. The diversity had a positive impact in problem discovery and scoping, while the homogeneity of the team had a positive impact on the convergence of the solution. In general, it has been observed that teams with greater diversity in terms of regions (languages) and engineering disciplines and having a higher proportion of girls tend to perform better.
An analysis of the team characteristics and their overall performance revealed four clusters.

1. Cluster 1 included students that performed well both as a team and individually. This was about 25% of the total number of groups.
2. Cluster 2 included students who performed better as a team but not as individuals. About 10% of the groups belonged to this category.
3. Cluster 3 included students who performed well individually when compared to their team. About 25% groups feel in this category.
4. Cluster 4 included students who underperformed both individually and as a team. About 40% of groups fell in this category.

4.4. Performance in subsequent semesters

The performance of students in the design courses in the following semester suggested a growing influence of systems thinking. For instance, in Table 3 one can notice that in 2014 the % of students who either retained or improved their grades in design subjects between the third semester (systems thinking for design) and the fourth semester (intelligent systems and sociology of design) was between 39-43%. This increased to 63-69% in 2015 batch and to 74-80% in the 2016 batch.

Table 3. Performance in design subjects in subsequent semesters

Batch	% of students whose grades remained same or improved from Systems Thinking to Intelligent Systems	% of students whose grades remained same or improved from Systems Thinking to Sociology of Design
2014	39%	43%
2015	63%	69%
2016	74%	80%

Overall it was observed that students who participated well, truly appreciated the value of systems thinking in exploring the complexity of a problem situation, understanding the real issues, identifying a compelling product concept. They also developed the collective energy to take it forward in the subsequent semesters. This clearly showed that systems thinking could trigger curiosity among students to create new knowledge from their own experience and exploration. A few others who were unable to see a correlation between their effort and the outcome in one semester, felt the difference after a couple of more courses or while doing internships in the industry. About 30-40% of students seemed to struggle with the process. Problem-based learning did create a challenge with respect to new product development because in this case students need to work more with information than physical artefacts. Getting undergraduate students to work with information is a challenge because most of them are used to consuming knowledge (cause-effect theories) and not used to research / explore a problem situation. This points to the need for a strong foundation course in the first year to prepare students for design to foster curiosity and ownership for self-directed learning. We also noticed that increased ambiguity and uncertainty led to breakdown of some teams. This suggests the need to introduce ethnography and sociology of design before systems thinking.

5. Conclusion

This paper discussed an approach to develop systems thinking competence among undergraduate engineers in a relatively young, public-funded institute in India. Several challenges in introducing systems thinking in a product focused and design-centric engineering curriculum have been discussed

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along with the implementation strategy to address them. The paper also presented a generic complexity-based model for measuring systems and design thinking competence over time.

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