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Student Goal Formulation in an Introductory Engineering Design Course through Systems Thinking Scenarios

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Student's Goals Formulation Ability in an Introductory Engineering Design Course through Systems Thinking Scenarios

ABSTRACT

One key process of Systems Design is goal formulation. Such should be conducted considering short- and long-term goals from technical and contextual aspects. Engineering graduates should be able to engage in and complete such activities with high proficiency to be competitive in Professional Practice. Our study asked first-year engineering students to engage in a scenario-based task with goal formulation activities. Results from this study contribute to developing effective teaching strategies to foster Systems Thinking Skills in engineering students.

Study participants were tasked to complete a scenario-based assessment proposed by Grohs et al. (2018) that focuses on systems thinking and problem-solving as engineers by responding to a scenario that, according to the authors, elicits students' goal definition skills. The scenario prompts (Prompts 5 and 6) asked students to formulate goals/objectives for this specific issue. Data was collected electronically and analyzed following the guidance provided by the assessment tool rubric for evaluating students' ability to identify short-term and long-term goals for technical and contextual aspects. We rated their answers on the expectations of a successful plan and a draft idea,

Results show that when given design constraints (e.g., budget) and instructions (Prompt 6), more participants (approx. 43%) properly formulated their goals with consideration of short- and long-term plans from both technical and contextual aspects. However, the percentage dropped to about 28% when the information was not provided, and the participants had to make reasonable assumptions (Prompt 5). Particularly, the participants struggled to address technical and contextual aspects in their goal formulation. Roughly 67% neglected one aspect in Prompt 5, while only 33% did that in Prompt 6. Most participants (approx.95% in Prompt 5 and 76% in Prompt 6) managed to formulate long-term goals.

The findings demonstrate that most engineering students recognize that systems change and evolve with time; therefore, addressing the changing problems with short- and long-term goals is important. However, many students need scaffolding to assist their goal formulation activities, such as design constraints and guidelines. Engineering educators should consider including in their courses strategies that would train students to gather necessary information and build scaffolding on their own through goal formulation activities.

1. INTRODUCTION

In systems engineering, goal formulation is a crucial step in the early stages of the system development life cycle. It involves defining and clarifying the objectives that a system is intended to achieve. The goal formulation process helps establish a clear understanding of the system's purpose and requirements before proceeding with design and implementation. Frequently, clients encounter significant challenges when attempting to determine the performance requirements of a proposed system. This underscores the critical importance of the problem definition and goal development phase in ensuring the ultimate success of the project [1].

Conventional engineering design commonly relies on an exclusively "bottom-up" approach, assuming the status quo and proceeding incrementally towards externally defined technological goals. While this method allows for identifying short-term, narrowly focused solutions, it raises concerns regarding their broader, long-term impact. Applying this approach in isolation has proven expensive and fallible, particularly in new and unfamiliar design environments. On the contrary, a "top-down" approach takes a different perspective. Starting with the normative situation one aims to create, it moves from the general to the specific based on defined goals and objectives. Although top-down analysis corrects the errors associated with the bottom-up approach, it introduces its own set of problems when employed in isolation. The optimal procedure involves an iterative alternation between top-down and bottom-up approaches. This entails integrating a long-term top-down viewpoint into an existing short-term bottom-up planning cycle, offering a comprehensive and balanced strategy for success. While it may be evident to develop short-term technological solutions, it is equally crucial to incorporate long-term structural and functional solutions into the planning process. This holistic approach ensures a more robust and sustainable outcome for the project [2].

Based on Gibson et al.'s analysis of data from Anderson Consulting (1993) [1], the goal development represents a small part of the total lifetime cost of a system (less than 1% in a typical software system), yet "it results in a critical commitment of recourses." When the first 8% of the project budget is spent, 80% of the cost of the project/system is determined.

Competitiveness in professional practice requires engineers to participate in and accomplish goal formulation activities proficiently. In our research, we tasked first-year engineering students with scenario-based assignments involving goal formulation activities. The findings from this study play a crucial role in shaping the design of impactful teaching strategies aimed at cultivating goal development skills and enhancing overall systems thinking abilities among engineering students.

2. METHODS

2.1 Systems Thinking Assessment Tool

The problem scenario and rubric were developed to measure systems thinking competencies in contexts beyond self-reported attitudes and behaviors. The problem scenario is a hypothetical vignette that asks students to consider multiple details in an ill-structured problem context. The scenario provides information that possibly represents engineering and technical skills, economic feasibility, ethical considerations, and cultural sensitivity, which can be considered when studying potential solutions [3].

> "The Village of Yakutia has about 50,000 people. Its harsh winters and remote location make heating a living space very expensive. The rising price of fossil fuels has been reflected in the heating expenses of Yakutia residents. In fact, many residents are unable to afford heat for the entire winter (5 months). A Northeastern Federal University study shows that 38% of village residents have gone without heat for at least 30 winter days in the last 24 months. Last year, 27 Yakutia deaths were attributed to unheated homes. Most died from

> hypothermia/exposure (21), and the remainder died in fires or from carbon monoxide poisoning that resulted from improper use of alternative heat sources (e.g., burning trash in an unventilated space)."

In this study, the researchers changed the name of the hypothetical village, "Abeesee" to "Yakutia" to reflect a more realistic context. The text provided to students for the activity is, *"The region described in the scenario is real and its community members experience very harsh winters, however the specific details of the scenario are fictional for the purposes of this assignment."* We applied the assessment tool rubric to evaluate the sample of student responses using systems thinking constructs from the framework. The framework has three dimensions to be considered: the problem dimension, perspective, and time. The interaction of associated constructs within each dimension provided a way to analyze students' perspectives and competencies when considering multiple interactive constructs [3].

This study analyzes what participants answered when asked:

> **Prompt 5:** What would you expect a successful plan to accomplish?
> **Prompt 6:** Given what you know and a budget of $50,000, develop a plan that would address the Yakutia situation maximizing the impact of your $50,000. Use a numbered, step-by-step guide, recipe-style to explain your response plan. For example: Step 1: Buy the noodles. Step 2: Boil water. Step 3: Add the noodles. Step 4: Drain the noodles.

Figure 1 shows the rubrics provided by Grohs et al. [3] which we used in this study when assessing participants' answers in their original study:

Construct	Criteria and Rating Guide
Goals *Prompts 5 and 6*	**0** No response was provided, or response was unable to identify clear goals **1** The response identified ***short-term*** goal/s that address only one ***technical*** or ***contextual*** (economic, or political, or environmental, or social or time only) **2** The response identified goals that are: 1. ***long-term*** and address only one ***aspect***; or 2. ***short-term*** and address both ***technical*** and ***contextual aspects***; or 3. both ***short-*** and ***long-term*** and address only one ***aspect*** **3** The response identified goals that articulates ***both short- and long-term goals*** and address ***both technical and contextual aspects***

Figure 1 - Rubrics provided by Grohs et al. [3] *to evaluate participants' answers for prompts 5 and 6.*

3. RESULTS

3.1 Data Analysis

Twenty-one students agreed to participate in this study. Using Grohs's systems thinking assessment tool, the three raters rated each participant's answer independently (authors). After that, these scores were put together. As an example, here is the answer provided by Participant 06 to Prompt 5:

> *A successful plan would drop the percentage of residents who have gone without heat for at least 30 days from 38% to less than 15%. This would be a significant decrease, meaning far more residents have access to heating.*

The three raters provided the following scores for this answer, as shown in Table 1.

Prompt 5: Plan Expectations [with no scaffolding]						
	Rater	***Notes by rater 1***	***Rater***	***Notes by rater 2***	***Rater***	***Notes by rater 3***
Student ID #	Rater 1		Rater 2		Rater 3	
P-06	2.1	long-term goal - but only focused on reducing heat issues.	2.2	No comments	2.1	measurable, long-term. One aspect, heating

Table 1 - Rating of participants' answers for Participant 06 for Prompt 5

Regarding Prompt 6, see below for the answer provided by Participant 21 as an example:

> *1. Spend the $50,000 on winter apparel (coats, jackets, mittens) and blankets*
> *2. Create a system allowing residents below a certain income level to apply for cold-weather clothing handouts*
> *3. Form a team of Yakutia residents to sort through applications and decide the necessary handout*
> *4. Track' deaths due to cold homes' and 'hospital visits for hypothermia, frostbite, etc.' in order to see if these decrease*

This answer was scored by the raters as shown in Table 2

Prompt 6: Plan Development [with scaffolding]						
	Rater	***Notes by rater 1***	***Rater***	*Notes by rater 2*	***Rater***	***Notes by rater 3***
Student ID #	Rater 1		Rater 2		Rater 3	
P-21	3	considered both aspects - long- & short-term goals	2.3	No comments	2.3	both aspects. Although not mentioning what happens after spending all the money, the warehouses could be used in the long term, and fundraising as well.

Table 2 - Rating of participants' answers for Participant 21 for Prompt 6.

To ensure the validity of these scores, the Weighted Fleiss' Kappa method [4]–[6] was used. This method helps identify the level of agreement between raters and the "seriousness" of disagreement [5] (p.608). In this method, Weighted Kappa values (WK) greater than 0.75 represent "excellent agreement beyond chance," and values of 0.40 or lower represent "poor agreement beyond chance." For prompt 5, raters scored WK = 0.51; for prompt 6, raters scored WK = 0.53, respectively. These scores suggest fair agreement beyond chance, implying that they are valid enough to be used as evidence. In detail, for prompt 5, there was full agreement in the evaluation of 10 participants' answers and no full disagreement in the ratings provided. To determine the participant's answer level in case of a disagreement, the score in which 2 of the raters agreed was selected as the participant's answer score. For example, in prompt 6 for participant 21, two raters decided a score of 2.3, while one gave this answer a score of 3 (See Table 2). Therefore, the score selected for this participant's answer was 2.3.

3.2 Findings

Prompt 5: Fourteen participants (66%) scored in level 2 (ten (48%) in level 2.1, and four in level 2.3 (19%)), and only 6 (29%) scored 3, the highest possible score. Figure 2 illustrates the distribution of participants' responses regarding plan expectations without scaffolding.

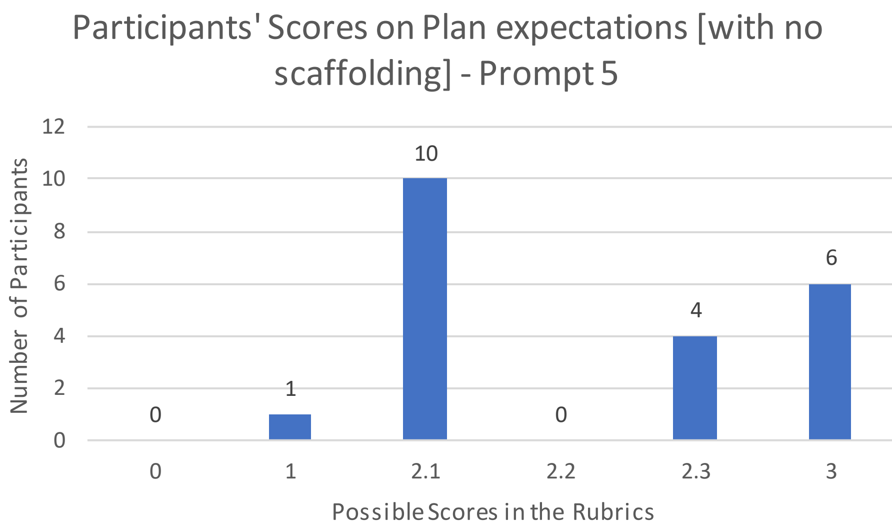

Figure 2 - Distribution of participants' answers related to Plan Expectations [with no scaffolding]

Prompt 6: Nine participants' answers (43%) were scored in the highest level, 3, while eleven were scored on the second level (six answers in level 2.1, four in level 2.2, and 1 in level 2.3). The distribution of answers can be seen in the histogram below in Figure 3.

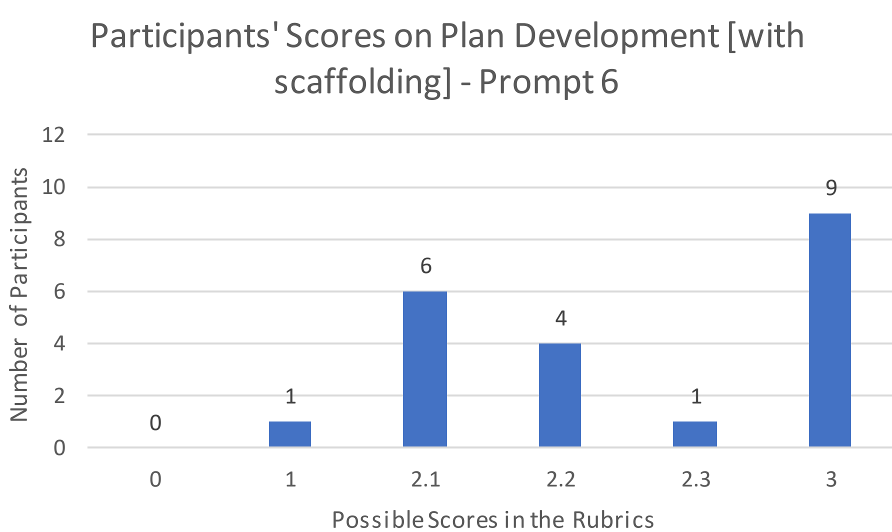

Figure 3 - Distribution of participant's answers related to Plan Development [with scaffolding]

Table 3 provides a comparative view of participants' answer scores (a total of 25).

Scores	Prompt 5	Prompt 6
1	1 (5%)	1 (5%)
2.1	10 (48%)	6 (29%)
2.2	0	4 (19%)
2.3	4 (19%)	1 (4%)
3	6 (29%)	9 (43%)

Table 3- Comparative of Participant scores for Prompt 5 (without scaffolding) and Prompt 6 (with scaffolding)

4. DISCUSSION AND IMPLICATIONS

The importance of goal definition is based on the aim of systems engineers, project managers, etc., to provide clear direction and focus for the project. Systems engineering projects are often complex, involving multiple stakeholders, processes, and technologies. Without well-defined goals (both short- and long-term) in which technical and contextual aspects are considered, projects incur inefficiencies, increased costs, and delays. Clear goals help to ensure that project teams and stakeholders understand what the project aims to achieve, which helps in aligning their efforts towards a common objective.

Results from this study show that when participants answered Prompt 5 (*What would you expect a successful plan to accomplish?*), a high percentage (48%) failed to identify both short- *AND* long-term goals of their plan. Likewise, although 19% identified long- and short-term goals, they focused only on contextual or technical aspects. On the other hand, when participants were asked to develop a plan and were given a step-by-step framework to follow and a budget constraint, as in Prompt 6, the data 52% of the participants were categorized on level 2 (29% in 2.1, 19% in 2.2, and 4% in 2.3), while 43% were scored in level 3, the highest in this rubric. Therefore, there was an increase in the participant's performance related to goal definition from prompt 5 (29%) to prompt 6 (43%). These results suggest that without a step-by-step framework, students' efforts were less focused and less likely to contribute effectively to a solution for the given scenario. Both short- and long-term thinking considerations are needed for goal definition. Using goals or targets helps prioritize tasks and milestones, which are necessary to track progress, identify issues early, and make necessary adjustments. This ongoing evaluation is critical for ensuring the project remains on track and meets its intended objectives.

Systems engineering project teams face constraints for resources, time, or technology and must find solutions that meet these challenges and are also beneficial and adopted by their stakeholders. Working under constraints or within a problem-solving environment that incorporates some constraints, limitations, or other considerations often leads to novel ideas and approaches that might not have been considered in a more open-ended scenario. This approach can be applied to students who aim to achieve the benefits of utilizing scaffolding for goal formation. Goal definition helps align varied perspectives by providing a common understanding of the project's goals.

Students' performance or responses to the systems thinking prompts highlighted a phenomenon, such as "creativity under constraints" [7], [8]. We view this phenomenon, "creativity under constraints," as a fundamental aspect of systems thinking, where the holistic view of a system is crucial for solving complex problems. In systems thinking, constraints are not limitations but are considered integral components that shape the system's behavior and outcomes. Constraints, or contextual limitations, encourage a deeper understanding of the interdependencies within a system, leading to innovative approaches that might not have been considered in an unconstrained environment.

Cognitive scaffolding is a highly effective educational strategy [9], [10], especially in the context of solving engineering problems. It involves providing a more structured framework to students as they learn new concepts and attempt complex tasks. Students often benefit from scaffolding information, which offers structured support and guidance as they formulate their problem-solving goals and develop solutions. Scaffolding can include relevant background information, step-by-step instructions, and resources that help students progressively build their understanding and skills.

Encouraging students to think about solving the problem and forming short- and long-term goals for a project, for example, serves as a scaffolded, or supportive, framework that facilitates learning and encourages students to ask the necessary questions to guide their thinking process. Recommendations for developing educational or classroom modules and scenarios focus on training students to build their own scaffolding, i.e., what to do when the step-by-step framework is not provided in the problem or scenario.

According to Gibson et al. [1], goal formulation is the most sensitive step in system analysis. They proposed a seven-step-approach:

1) Generalize the question;
2) Develop a descriptive scenario;
3) Develop a normative scenario;
4) Develop the axiological component;
5) Prepare an objective tree;
6) Validate;
7) Iterate;

Educational modules can be crafted to cultivate the ability to formulate pertinent questions that guide critical thinking by leveraging similar existing resources, such as case studies and hands-on exercises, to enhance this skill set of engineering students. Emphasis is placed on encouraging students to assess the short- and long-term goals and objectives of a given problem or project. By instilling this approach, students can be better equipped to navigate complex challenges and contribute to the success of projects through effective goal achievement. The incorporation of case studies and practical exercises not only reinforces theoretical knowledge but also fosters a practical mindset, promoting a holistic understanding of engineering problem-solving.

4.1. Limitations

One of the primary limitations of this study is the limited evaluation of technical aspects of the feasibility of student plans/ responses. The scoring rubric did not address detailed technical evaluation, which could include aspects such as system performance, engineering methodologies, or realistic resource and budget allocations.

The current study's reliance on the mostly fictional scenario as the basis for participant responses introduces limitations, such as predictive validity and participant interpretation variability. Responses in a hypothetical scenario may have limited predictive validity regarding actual behavior, i.e. the difference between what people say they would do and what they actually do in real situations. This can also be impacted by students' understanding and interpretation of the fictional scenario, which can vary widely among participants. Our setting for collecting student responses did not control for external information, such as students' own research online or using external sources to inform their answers to each prompt. The raters' assumptions in scoring the student responses were that the scenario-based activity was context-bound, meaning that the raters were aware of the context in which students applied their systems thinking knowledge but realized each participant has a different body of knowledge gained from different previous experiences or external research when answering the prompts.

5. FUTURE DIRECTIONS FOR RESEARCH

The constraints presented in the fictional prompt, and constraints that arise in real life, can compel students to think outside the box and devise efficient, effective solutions. This necessity to work within boundaries often leads to more innovative approaches. The creativity expressed by students can be seen in their responses showing the incorporation of several factors and how they relate them to goal setting. For future prompts that require students to analyze situations from a systems-thinking approach, we can develop and highlight contextual constraints as part of the prompt and create activities with the steps to help students. A scaffolded approach to help students consider how to engage with certain constraints or limitations can lead them to develop more robust, sustainable, and adaptable solutions. This process underscores the dynamic relationship between constraints, goal formulation, and creativity in systems thinking.

It would also be valuable to compare novice problem-solvers with people with higher expertise. It is plausible to think that experts when dealing with these kinds of problems, need less scaffolding to be able to think short- and long-term, and at the same time consider technical and contextual aspects.

In future research, integrating real-world elements like case studies and simulations with realistic settings could enhance the fictional scenario approach. This would align the methodologies more closely with how experts tackle problems in real-world scenarios. There are several system thinking models that can be used to understand and analyze complex systems and their behaviors, for instance, system dynamics, soft systems methodologies and others. Such approaches can prove advantageous for students as it enables them to discern how systems evolve over time, pinpoint areas where intervention can be most impactful, and craft efficient strategies for enhancing and managing systems. Concurrently, it fosters the cultivation of long-term goals. In addition to looking at the goal setting component of evaluating a system, understanding the specific functions and interactions of each component within the larger system students can develop more comprehensive and effective solutions. We also will aim to incorporate a comprehensive technical evaluation component. This would involve a more detailed, expert analysis/ scoring rubric for the feasibility of students' solutions, ensuring a more holistic understanding of the systems engineering content.

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