Assessing Novelty and Systems Thinking in Conceptual Models of Technological Systems

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***Abstract*—*Contribution:* The authors present a methodology for assessing both novelty and systems thinking, as expressed in the same conceptual models constructed by graduate engineering students.**

***Background:* Companies worldwide seek employees with creativity and systems thinking, since solving design problems requires both skills. Novelty and usefulness are the most commonly accepted components of creativity, while systems thinking is the holistic understanding of systems.**

***Research Question:* How can novelty and systems thinking be assessed based on conceptual models (of technological systems) constructed by graduate engineering students?**

***Methodology:* Six student teams of two to four members each ($N = 21$) constructed solution models based on Object-Process Methodology, a formal methodology and language for model-based systems engineering. The authors assessed these models for novelty and for systems thinking using two existing rubrics based on the construction of system aspects—function, structure, and behavior.**

***Findings:* The authors provide indications that both novelty and systems thinking can be assessed based on conceptual models of technological systems.**

***Index Terms*—Assessment tools, creativity, graduate education, model-based system design, novelty, object-process methodology, student assessment, systems thinking, teams.**

I. Introduction

COMPANIES worldwide seek employees who exhibit creativity and systems thinking [1]. Creativity has often been viewed as being comprised of novelty and usefulness [2]. ABET's 2019–2020 criteria for accrediting engineering programs [3] includes terms related to creativity as well as to systems thinking. Design problems in engineering and in other domains are open-ended, having multiple potential solutions and a nonprescribed path to solution. However, even though creativity is considered as crucial for solving design problems [4], [5], a review of syllabi belonging to more than 1100 accredited programs of undergraduate electrical engineering has shown that a vanishingly small percentage of them contained content explicitly related to creativity [6].

Since assessment is part of instruction, it is important to assess, and not just facilitate, creativity in undergraduate engineering. In a previous study [7], undergraduate engineering students' systems thinking was assessed based on conceptual models of technological systems. In this article, the authors focus on assessing both systems thinking and novelty—a key component of creativity—based on conceptual models of technological systems. To the best of our knowledge, no studies published to date in engineering education have investigated the assessment of novelty and of systems thinking based on the same artifact.

The objective of this exploratory study was to investigate whether novelty and systems thinking could be assessed based on conceptual models of human-made systems—technological solutions to problems—constructed by graduate engineering students, who are already engineers working in industry, for solving authentic problems through conceptual design. The research question is as follows: How can novelty and systems thinking be assessed based on conceptual models (of technological systems) constructed by graduate engineering students?

A. Creativity and Novelty

While there is no consensus regarding the standard definition of creativity, the two components most commonly mentioned when discussing creativity are novelty and usefulness. Novelty can be described as the quality of being rare within a particular group, while usefulness can be described as the utility or value of a solution [2].

Previous studies on assessing novelty, creativity, or closely related traits in engineering higher education made use of self-reporting instruments [8], [9], tests for assessing general creativity [10], or tests for assessing engineering-specific creativity [11]. However, to the best of our knowledge, no tool exists within engineering higher education for assessing creativity based on artifacts that were created by students using a formal methodology as part of an engineering design project.

B. Model-Based Systems Engineering

The International Council on Systems Engineering (INCOSE) states in its *Systems Engineering Vision 2025* paper: "The theoretical foundation of systems engineering encompasses not only mathematics, physical sciences, and

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systems science, but also human and social sciences" [12, p. 40]. In the same paper, model-based systems engineering (MBSE) is referred to as the methodology of choice for systems engineering by INCOSE.

MBSE has been defined as "··· the formalized application of modeling principles, methods, languages, and tools to the entire lifecycle of large, complex, interdisciplinary, sociotechnical systems" [13, p. 105]. As such, MBSE encompasses not only the "system proper," i.e., its mechanical, hardware, and software aspects, but also external factors, i.e., the system's environment. Moreover, as part of systems engineering, MBSE also pertains to the sociotechnical systems, of which humans are a key factor [14].

C. Conceptual Models

The term *concept* has been described as "a perceived regularity in events or objects, or records of events or objects, designated by label" [15, p. 33]. *Concept maps* are used as learning tools for representing learners' declarative knowledge structure. These maps typically consist of blocks, which represent concepts, and connecting lines, which represent relations between the concepts. Concept maps facilitate the creation of knowledge by connecting prior knowledge with new information [16], [17]. They can also be used for assessing the knowledge of students [18]. A potential benefit of using concept maps, or any other form of external conceptual representation, for assessment of learning is that multiple attributes can be assessed based on the same representation, including systems thinking [7] and the quality (clarity, correctness, and comprehensiveness) of the representation itself [19].

In systems engineering, a concept is often described as an abstract representation which maps the system function to structure or form [20]. In MBSE, a *conceptual model* is the products of the system representation process. Using conceptual models as part of MBSE allows for explicit shared representation of system architecture, helping to manage complex knowledge and resolve conflicts and ambiguities, thus facilitating the system design process. Conceptual models can be constructed using a formal language that distinguishes between various types of things and relations in a consistent and comprehensive manner [13], [21]. Assessment of learning or other attributes based on conceptual models that use formalized language has the advantage of being replicable and is therefore likely to be more consistent and reliable than concept maps or other kinds of conceptual models that are informal.

D. Systems and Systems Thinking

The notion of *system* has been discussed and investigated independently in various disciplines, including but not limited to social science [22], natural science [23], and engineering [20]. Within engineering, various definitions have been provided for the terms *system* and *systems thinking* [20], [24]–[26]; common to all of these definitions is a "hard" stance on systems thinking, i.e., the view of systems as separate entities which exist in the world [27]. Since describing these ongoing definition efforts is beyond the scope of the present study, the authors formulated working definitions which would be adequate for this study. The following working definitions, while limited to technological systems and systems thinking specific to engineering, are still comprehensive, going beyond the mere mechanics, hardware, and software of the system to include its environment, both physical and social.

A *technological system* is an entity composed of interacting parts (or elements). This entity delivers a predetermined function, or goal, via its architecture, which is a combination of its structure and behavior. The system's function is achieved via interactions of the system parts both internally and with the system's environment, and these interactions can be explained by cause and effect relationships. Some system properties vary from those of its individual parts. Systems have purpose, which is a predetermined benefit delivered to specific humans, who are the system's beneficiaries. The system's purpose is achieved via its function [20], [21], [25], [26].

In engineering, systems thinking is a higher-order thinking skill or set of skills which enable the identification, understanding, prediction, and improvement of every aspect of a technological system: purpose, function, structure, and behavior, and the way these aspects interrelate within the system. [7], [20], [21], [25]. Systems thinking has been assessed based on conceptual models of systems constructed using a formal methodology and language of MBSE [7], [28].

II. Methodology

This section details the research setting, participants, tools, and procedure.

A. Research Setting

The study took place at the Technion—Israel Institute of Technology, a top-tier research university, during a semester-long engineering graduate course on MBSE. The course was taught by two co-authors of this article. During the course, students learned how to construct system models of technological solutions to design problems of their choosing by applying an MBSE methodology. The study received the approval of the institute's ethics committee (2018–48).

B. Research Participants

Study participants comprised the majority of students enrolled in the course: 18 men and three women ($N = 21$). All the participants were employed at the time of the study. Participants shared a variety of engineering subdisciplines, including electrical engineering, mechanical engineering, and computer science, among others. Two students who were on the same team did not agree to sign an informed consent form; therefore, their data was not collected for this study. Those two students performed and submitted all the assignments as the rest of the students on the course.

C. Research Tools

Student teams constructed conceptual models in Object-Process Methodology (OPM) [29], [30]. OPM is an MBSE methodology, and the language for conceptual modeling of systems to have been granted an ISO standard: ISO

19 450 [30]. In OPM, systems are modeled using things and links: thing is analogous with concept, while link is analogous with relations between concepts. There are two kinds of things in OPM: 1) objects, which exist physically or informatically and 2) processes, which transform objects by creating or consuming them, or by changing their state. Things can be refined via zooming into them in descendant diagrams. The language has both graphical and textual modalities, named object-process diagram (OPD) and object-process language (OPL), respectively. Graphically, ellipses represent processes and rectangles—objects. Sentences in a subset of English are generated in response to the modeler's graphical edits. Links connect things to express structural or procedural relations among them: links between objects or between processes are mostly structural, while links between objects and processes are mostly procedural. An example of a structural link is whole-part: a whole object consists of two or more objects. An example of a procedural link is consumption: a process, once complete, consumes the object. OPCAT [31] is a desktop software application based on OPM, which participants used in creating their models.

The authors assessed novelty expressed in OPM models using the rubric developed by Sarkar and Chakrabarti [32] and refined by Jagtap [33], herein referred to as the design novelty assessment rubric (DNAR). The DNAR contains a flowchart for scoring the novelty of a prescriptive (proposed) or descriptive (existing) product of design. The assessment is based on the function–structure–behavior construct, which is common to systems engineering [20], [21]. As part of applying the DNAR, the authors compared each team's solution to an existing commercial product which was judged to fulfill an identical (or similar) function to the proposed solution being assessed. Keeping with the notion of novelty, the authors searched specifically for solutions that were published online during or before the relevant team's final model had been submitted. In other words, a commercial solution published after a team had submitted their solution was excluded from the novelty assessment of that solution. The reason for using commercially available solutions for comparing students' solutions, rather than using research papers or patents, was that the information provided in commercial publication is less technical and thus clearer to the nonexpert.

The authors developed detailed instructions for scoring the solution models submitted by the student teams. Scoring was based on the text provided by each model's OPL, with the model's OPDs were used for reference in case the OPL was not completely clear. The process of developing these scoring instructions was iterative, with each iteration feeding back into the scoring instructions. This approach to analysis can be described as theory-driven thematic analysis, which is deductive and "top-down," in contrast to theory-driven thematic analysis which is inductive and "bottom-up" [34], [35]. The authors selected this particular approach to thematic analysis for applying DNAR because the categories of analysis had already existed in the form of the DNAR rubric itself, as shown in the DNAR application flowchart in Fig. 1.

The authors assessed systems thinking expressed in students' conceptual models using a rubric previously developed

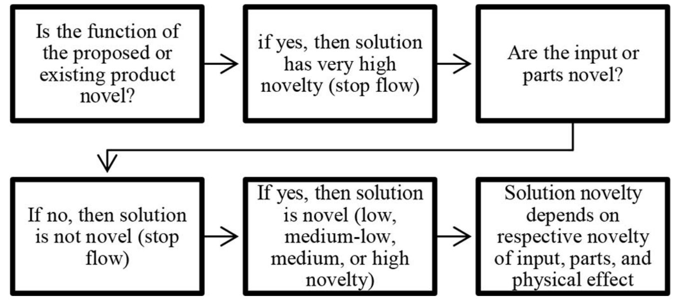


Fig. 1. Simplified flowchart for applying the design novelty assessment rubric of Sarkar and Cakrabarti [32] as refined by Jagtap [33].

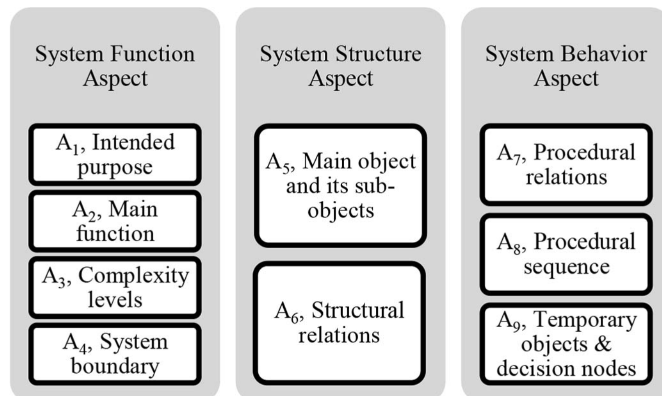


Fig. 2. System aspects and systems thinking attributes included within the STAR. Adapted from Lavi *et al.* [7]. A_i stands for systems thinking attribute $i; i = 1 \cdots 9$.

and validated for assessing conceptual models constructed using OPM [7], [28]. This rubric, named systems thinking assessment rubric (STAR), was developed by the authors of the present study along with another colleague, based on both the function–structure–behavior construct [20], and a comprehensive literature review of systems thinking assessment in science and engineering education [36]. STAR classifies nine systems thinking attributes into the three system aspects of function, structure, and behavior. Fig. 2 summarizes the system aspects and systems thinking attributes included within STAR, Table I describes each attribute. A thorough explanation of how STAR can be applied for assessing the systems thinking expressed in OPM conceptual models of technological systems is found in [7].

D. Research Procedure

Following an introduction to MBSE and OPM, students signed an informed consent form and were asked to assemble in teams of two to four members. None of the participants had learned about OPM or had used OPCAT before. Each team was asked to identify and select an authentic design problem it would like to tackle. Students were given no further guidance related to the problem selection process, and they could choose any real-life problem they wanted. Prior to designing their solution, teams were tasked with researching existing solutions for the problem they formulated and identifying deficiencies in those solutions. This contributed to driving the students to search for novel ideas. The rest of the

TABLE I
SYSTEMS THINKING ATTRIBUTES INCLUDED IN THE SYSTEMS THINKING ASSESSMENT RUBRIC

Systems thinking attribute	Description
A_1	The intended benefit of the system for its beneficiaries
A_2	The systems' main operation, main operand, and enablers
A_3	The number of levels in the system's functional hierarchy
A_4	Things which are not part of the system proper, but which affect it significantly
A_5	The parts, features, and specializations of the main operand
A_6	The relations between objects and between processes
A_7	The relations between objects and processes
A_8	Linear and non-linear sequences within the system
A_9	Objects created and consumed within system operation; flow of control within a system (system and user decisions)

TABLE II
PARTICIPANT TEAMS AND THEIR SELECTED PROBLEMS

Team	Selected Problem
A	Birds intruding commercial airport runways
B	Findings charging spots and charging electric cars is highly time consuming
C	Stock trading has high risk for non-experts
D	Truck vibrations cause health and attrition costs
E	Wafer SEM overheats during manufacturing process
F	Treatment of cardiac arrest requires outside help

semester was spent following a process of system design using the aforementioned MBSE methodology. Table II summarizes the problem each team chose to tackle.

During the course, each team created OPM system models of: 1) their identified problem; 2) two alternative solution concepts for solving the problem; 3) an expanded model of the selected solution concept; and 4) a final model of their selected solution. Once all teams' final models were submitted, the authors scored them for novelty and systems thinking, using DNAR and STAR, respectively. The first author is an expert in assessment of higher-order thinking skills; the second author is an expert in STEM education, in the assessment of higher-order thinking skills, and in visualization methods for learning; and the third author is an expert in systems engineering and MBSE, with extensive background in industry. Each author scored each one of the final models individually, followed by a joint discussion and consensual agreement on the scores for each final model.

III. RESULTS

A. Team D's Solution Model

The authors provide a scoring example for Team D. The solution which Team D conceived and designed for their

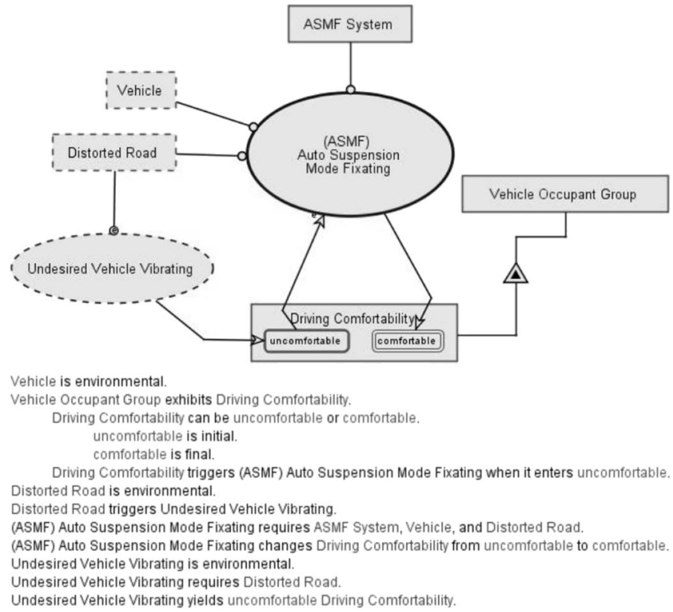


Fig. 3. Team D's solution model—top level (auto suspension mode fixating).

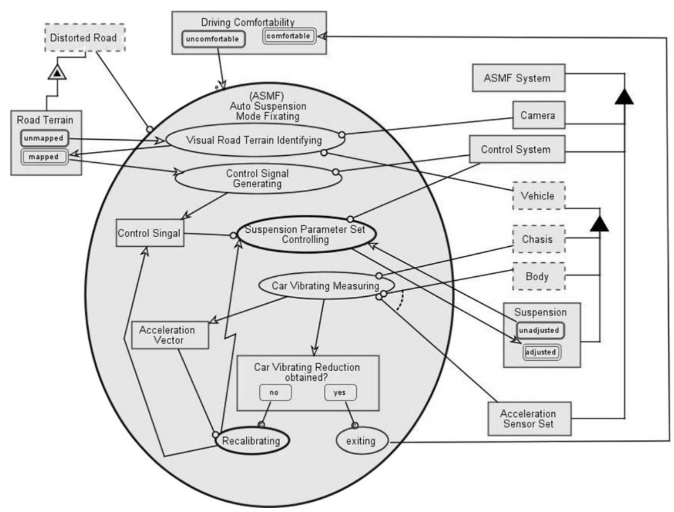


Fig. 4. Team D's solution model—first detail level (refinement of auto suspension mode fixating).

identified problem was a camera-based hardware system installed on a truck, which maps out the road ahead of the truck and adjusts its suspension to counteract expected vibrations in the suspension system to minimize shocks inflicted on the driver. Figs. 3–5 show the OPM model of Team D's solution, specifically its top level, first detail level, and second detail levels views, respectively.

Fig. 3 shows Team D model's system diagram (SD). Spelling errors were left as they were in the model. The SD includes two processes: 1) *Undesired vehicle vibrating,* which is the problem occurring process, causing a problem to the *vehicle occupant group* by creating *driving comfortability* at state *uncomfortable* and 2) the main process of the system, which Team D labeled *auto suspension mode fixating* ("auto" being short for "automated"), and concerns exerting automated control over the vehicle's suspension system. This process

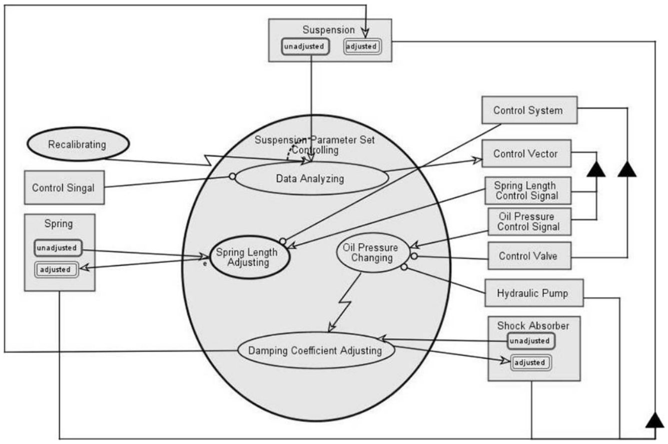


Fig. 5. Team D's solution model—second detail level (refinement of suspension parameters controlling).

transforms *driving comfortability*, changing it from *uncomfortable* to *comfortable*, thus solving *vehicle occupant group*'s problem.

B. Scoring Team D's Final Model for Novelty

Table III shows how novelty scores were derived for Team D's solution, step-by-step, using the DNAR. Team D's solution, represented by their OPM model, was compared to a benchmark solution—a commercial product published online around the same time Team D worked on its problem.

The DNAR was applied according to [33] as follows. First, the *function* of Team D's solution, as represented by their OPM model, was compared with the function of the benchmark solution. Since the function of both solutions is the same, the solution does not have very high novelty and, therefore, does not receive the maximum potential novelty score of 5. Next, the *input* and *parts* of Team D's solution were compared with those of the benchmark solution, and both were found to be the same. This means that Team D's solution is indeed novel, although not very highly so, as its function was found to be the same as that of the benchmark solution. This places Team D's solution as having high or medium novelty (score of 4 or 3). Finally, to establish the exact novelty score for Team D's solution, the *physical effect* of Team D's solution was also compared to that of the benchmark solution and found to be the same, i.e., not novel. This meant that Team D's solution model was found to have medium novelty, and therefore received a novelty score of 3 (75%).

C. Scoring Team D's Final Model for Systems Thinking

In what follows, an example for assessing systems thinking using STAR is provided based on the SD of Team D's solution model (Fig. 3). The example is for an attribute within the system function aspect—intended purpose. For this attribute of systems thinking to receive a full score of 3, the following criteria must be fulfilled: there must be at least one beneficiary and at least one benefit, and both must be correct. The main process of the system is *automated suspension mode fixating*. This process should transform an object—an attribute of the

TABLE III
COMPARING NOVELTY OF TEAM D'S SOLUTION TO THAT OF BENCHMARK SOLUTION

DNAR novelty criterion	Team D's solution – pertinent OPL sentences	Benchmark Solution[1]	Potential range of novelty scores
Step 1: Function	**Auto Suspension Mode Fixating** changes **Comfortability from uncomfortable to comfortable**.	Isolating drivers from the harshest driving conditions and providing the smoothest ride.	0–4
Step 2: Input	**Visual Road Terrain Identifying** requires **Camera**. **Car Vibrating Measuring** requires **Acceleration Sensor Set**. **Control Signal Generating** generates **Control Signal**.	measurement of in-drive car vibrations and output of signal to adjust dedicated seat.	3–4
Step 3: Parts	**Camera, Control System, Acceleration Sensor Set,** and **Control Valve.**	Dedicated seat and suspension.	3–4
Step 4: Physical effect	**Damping Coefficient Adjusting** (spring force).	Change in seat position (spring force)	3

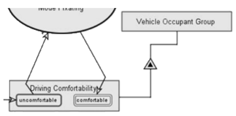
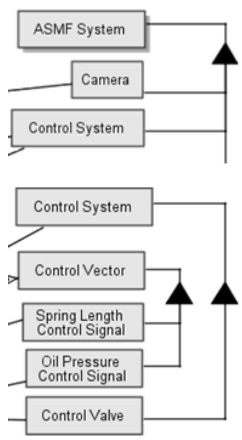
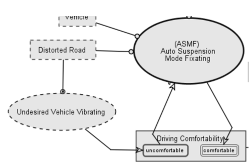
[1] Adapted from published description on the World Wide Web.

system beneficiary, also called *operand* or *transformee*. The system beneficiary is *vehicle occupant group*, while its transformed attribute is *driving comfortability*. The transformation of this attribute by the main process of the system is represented by an OPM input-output link pair—a pair of reversely directed arrows between the process and the object, with each arrow connected to a different state of driving comfortability: the input link is connected to state *uncomfortable*, while the output link–to *comfortable*. The resulting OPL sentence that expresses the intended purpose of the system is: *automated suspension mode fixating* changes *driving comfortability* from *uncomfortable* to *uncomfortable*. The attribute intended purpose thus receives a full score of 3.

Table IV shows how systems thinking was scored for the solution model of Team D, based on STAR. For sake of brevity, only one attribute of the scoring is shown within each system aspect. In the "explanation" column, the general criterion is provided in **bold**, followed by instances from the specific model in question in *italics*. The total systems thinking score was $21/27 = 78\%$. The scores for each attribute of systems thinking were as follows: System function—intended purpose: 3; Main function: 1; Complexity levels: 2; System boundary: 3. System structure—Main object and its subobjects: 2; Structural relations: 2. System behavior—procedural relations: 3; Procedural sequences: 3; Temporary objects and decision nodes: 2.

The criteria in Table IV can be mapped to the different student projects may have addressed by considering whether the students' model correctly captures the benefit of the contemplated system to the beneficiary. This is done by identifying

TABLE IV
SCORING TEAM D'S SOLUTION MODEL FOR SYSTEMS THINKING

Aspect and Attribute	Relevant Parts of OPM Model	Figs. and score	Criteria and model facts for scoring
Function – A_1, Intended purpose		Fig. 3 Score: 3	***Beneficiary***: at least one required (1) **Vehicle Occupant Group** ***Benefit***: at least one required (1) **Driving Comfortability** can be either **uncomfortable** or **comfortable**
Structure – A_5, Main object and its sub-objects		Figs. 3–5 Score: 2	***Main object***: at least one required (1) **ASMF System** **N levels sub-objects: at least three required** Two levels (-1)
Behavior – A_7, Procedural relations		Figs. 3 and 4 Score: 3	***N basic link types***: at least three required (1) instrument; (2) result; (3) consumption ***N Advanced link types***: at least three required (1) instrument event; (2) event consumption; (3) instrument condition

the value-providing object or its relevant attribute, which in our example is *driving comfortability*, and using the input-output link pair to express this benefit as the change in the value of this attribute from *uncomfortable* to *comfortable*.

D. Summary of Novelty Score and Systems Thinking Scores for All Teams

Table V shows for each team the scores for novelty and systems thinking of the final model. Team E's solution was the only one found to have a different function to that of its benchmark solution, and therefore received the maximum novelty score—very high ($5/5 = 100\%$). Team F received the highest score for systems thinking out of all six teams ($22/27 = 81\%$). Teams A and C both received the lowest possible score for novelty ($0/5 = 0\%$), while Team B received the lowest score for systems thinking out of all six teams ($17/27 = 63\%$). The sample of six models was not large enough for conducting inferential statistics.

TABLE V
ALL TEAMS—SCORES FOR NOVELTY AND SYSTEMS THINKING

Team	Total score in %	
	Novelty	Systems Thinking
A	0	70
B	25	63
C	0	78
D	75	78
E	100	74
F	75	81

IV. DISCUSSION

The findings of the present study indicate that both novelty and systems thinking can be assessed based on the conceptual models of technological systems.

A. Limitations and Future Studies

The small sample size of this study prevented the use of inferential statistics, which in turn prevented an evaluation of the DNAR's validity and reliability. Building upon the present exploratory study, future studies could evaluate the DNAR validity and reliability using a large enough sample size for providing inferential statistics on novelty scores. The ability to carry out statistical testing would also enable a potentially fruitful investigation of the relationships (if they exist) between novelty and systems thinking, as some authors have suggested [37], [38].

To the best of our knowledge, no factor analyses have been published for the DNAR, unlike STAR, for which factor analyses have been published [7], [28]. Such an analysis could help shed light on the findings of the present study. Additionally, studying larger samples of engineering students, including undergraduates and graduate students from various engineering subdisciplines, would improve the validity of the present study's findings.

The range of novelty scores obtained using the DNAR (0–100) was wider than the range of systems thinking scores obtained using STAR (63–81). A potential explanation for this discrepancy is that the teams constructed multiple OPM models, thus exercising their systems thinking, while they had just one opportunity for conceiving novel ideas. Future studies could provide students with explicit training in conceiving novel ideas by creative thinking.

Potential bias toward specific solution concepts was mitigated by having student teams work on their own self-selected problems. However, such a bias could have still been present, stemming from each student's respective engineering discipline and area of practice. Previous studies have shown that domain expertise may have an effect on the generation of novel ideas [39], [40]. A future study on the potential relationship between domain expertise and creativity could be carried out on the present study's methodology.

B. Contribution

While previous studies in engineering higher education have been published concerning the assessment of creativity or of related attributes based on student-made artifacts [8]–[11], to the best of our knowledge, the present study is the first to assess a component of creativity—in the present case, novelty—based on conceptual models created by students using a formal methodology which is replicable.

DNAR and STAR could, pending validation, potentially be used not just for summative assessment as in the present study but also for formative assessment, using the same artifact (conceptual model), thus saving time and resources for both instructors and students.

In light of clear indications for a lack of creativity-related materials in engineering curricula [6], the present study goes some way toward showing how this gap can be filled using MBSE, OPM, and OPCAT—structured methods and tools, with emphasis on problem-based assignments.

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