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Exploring how students attend to the nature and dynamics of complexity in their design problems

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Abstract

Authentic design problems necessarily reflect the complexity of real-world dynamic, open systems that have numerous components and nonobvious connections across different systems or components. As engineering design teams define, scope, and research their problem the team will develop a shared understanding of the problem and any complex system(s) underlying it. This conceptualization may then continue to evolve throughout their design process and deeply impact the direction of their project. Therefore, the degree and depth to which the team attends or conceptualizes the complexity of the underlying problem will likely affect the effectiveness, adaptability, and longevity of any resulting design solution. In this work we propose to examine how capstone engineering design teams attend to complexity within their design problems through a modified method for complex system mapping. We draw on complexity theory, and specifically the framework of Paul Cilliers to define complex systems as systems with many elements, dynamic and dense interconnections, nonlinear and shortrange interactions, feedback loops, open to environmental inputs, operating far from equilibrium, possessing a unique history and trajectory, and where elements have limited "awareness" of other elements or lack a global view.

This work adapted an approach used in policy planning and evaluation research called Participatory Systems Mapping (PSM). Within policy evaluation, PSM is used to bring together a group of stakeholders to identify a policy target (e.g., reducing city pollution) and then collectively map out a full view of the complex system(s) impacting this target and the relationships or connections between systems and/or their components. PSM is adapted into Design Problem Systems Mapping (DPSM) by contextualizing the original protocol into engineering design concepts and language. Data is collected from two capstone engineering design teams who have completed at least one semester of their project. Sessions were audio recorded and students' final systems map, and other design documents were collected. Design teams maps were analyzed through content analysis using Cilliers framework deductively, to answer the following question:

How do students attend to complexity within their design problem?

Results report on how the two design teams attend to different dimensions of complexity in their problem as viewed through the Cilliers framework. Findings suggest differences between the teams which may be affected by assumptions and framing of the problem itself. Connections are made for what this may mean for supporting students to attend to complexity within their problems and how instructional decisions can affect this.

Introduction

The ways in which design teams come to understand, scope, and frame their problems has a tremendous impact on their subsequent design process and the nature of the solutions(s) they arrive at [1]–[3]. Contemporary times and associated problems and challenges have become increasing complex, ill-defined, and open-ended [4], [5] driven in part by rapid and expansive technology advancement [6], greater interconnections between social, economic, technological and associated domains [7] and heightened expectations for engineers to respond to these changes [8]. While concepts and theories from the transdisciplinary field of complexity science [5], [9], [10] have begun to make their way into engineering, they are often limited in how complexity is addressed or conceptualized [4], [11]. For example, Summers and Shah [12] proposed a framework to assess the complexity of design problems, which focuses on the size, coupling and solvability of problems. While these are important dimensions of complexity their framework ignores many other dimensions of complexity or complex systems such as nonlinearity in interactions and path dependency of the system [10], [13]. Regardless of how researchers conceptualize the complexity of real-world problems, design teams will face these exact problems. Design teams will need to learn to understand and deal with the complexities in the problems they face for not doing so risks creating solutions that are inappropriate or ill-fitting, harmful or some cases even catastrophic in impact and/or which may be ignored or quickly dis-adopted by users.

This raises a key question – when design teams begin to research and understand their problem in what ways and to what degree are the problems complex attributes salient to the team? To begin working toward an answer to this broad direction, we adapt an approach from policy evaluation research called participatory systems mapping or PSM [14], which has been used with policy stakeholders to better understand how problems are situated within complex systems and how interventions may be made into those systems. PSM results in a collaboratively generated system map centered around a problem of interest. We call this adapted approach Design Problem System Mapping and apply it to two senior engineering design teams who completed at least one semester of capstone design. Our driving research question is:

(1) How do students attend to complexity within their design problem?

In interpreting design teams maps, we leverage the complexity framework from Cilliers [10], which outlines ten dimensions that distinguish complex systems from other types of systems. In the next section we review how complexity theory has been addressed in engineering education research broadly and for engineering design in specific. We then present Cilliers [10] complexity framework. Next, we address methods. First, we describe PSM, how it was adapted and a step-by-step overview of mapping sessions. We then discuss our data analysis approach and participants. Results follow. For each team, we present their final system map and the results of analyzing their map through Cilliers [10] framework. Finally, results are discussed, and conclusions presented.

Literature Review

Research and theory from complexity science have seen increased traction within engineering education research [4], [11]. While there is growing interest in how complexity science and theory may enhance engineering education, how complexity is conceived varies substantially across research findings. Some works make general or broad reference to complexity and often have limited grounding in relevant complexity science literature [15]–[20]. Others work are grounded explicitly in relevant theory from complexity theorists such as Edgar Morin [4], [11] and Paul Cilliers [21], [22] which results in more robust conceptualizations of complexity and the key attributes of complex systems pertinent to EER.

Complexity has also been studied more specifically as it relates to engineering design. There is a well-developed tradition for creating or analyzing complexity metrics for engineering design [12], [23]. Much of the work in this area focuses on complexity metrics for engineering systems, artifacts, or products [12], [23]–[26] and not necessarily the broader problem space. A variety of complexity metrics have been proposed, however, two of the most common recurring metrics deal with (1) the size of a product/system, in terms of the number of components and (2) the coupling between components [12], [23]–[26]. In general, the greater the number of components and the more connections between components, the greater the complexity of the given system. While these metrics capture some aspects of what makes a system complex, overall, they provide a limited definition that miss several key attributes such as nonlinearity of interactions and path or time dependency in systems. Furthermore, as complexity metrics, it is assumed that the components or connections can be fully ascertained or counted. Therefore, these metrics are more applicable to well-defined design artifacts or those that have moved sufficiently deep into the design process to become well-defined; this is typically not the case with open-ended problem spaces. Complexity metrics have been extended beyond engineering systems, and products, for example Summers and Shah [12] apply size, coupling, and solvability metrics for design problems, processes and products and Wolmarans and Case [27] draw on semantic density, similar to coupling, to characterize the complexity of knowledge needed for different design projects. However, these metrics suffer from the same difficulties previously mentioned. In the majority of cases, it will be desirable for engineers to reduce the complexity of real-world problems when designing systems or products, a notion sometimes called elegant complexity [28]; nonetheless designers and especially students will still need to contend with the complexity of real-world problems when developing solutions.

Thus, this work draws more explicitly on complexity theory, in particular the work of Cilliers [10] as previously described and seeks to better understand how teams to attend to complexity within real-world problems, which has received less attention in past work.

Theoretical Framework

This work is grounded in complexity theory, drawing on the work of Paul Cilliers [10]. Cilliers work is drawn on for several reasons, (1) it has been highly influential in complexity science, (2) it provides a general framework that can be adapted or applied to specific domain(s) and (3) it has been applied within engineering education research previously [21], [22]. Here we focus specifically on the key attributes Cilliers [10] outlines that define complex systems.

Complex systems have:

(1) A large number of elements

(2) System elements that interact dynamically, e.g., through the exchange of energy or information

(3) System element interactions that are rich, elements influence and are influenced by several other elements. This is related to the concept of complex causality [9], [13] where multiple factors work in conjunction to affect some outcome.

(4) Interactions that are nonlinear

(5) Interactions that are often shortrange (e.g., elements affect their immediate neighbors) but many shortrange connections can span across the system in unique paths

(6) Feedback loops in interactions, these may be positive or negative

(7) Open boundaries, the system is influenced by its environment and the systems border may be open to interpretation or framing

(8) Operational conditions far from equilibrium (e.g., a lot of energy, information, etc. going through the system).

(9) A historical trajectory or path dependency, i.e., the system past affects its present operations

(10) System elements that have local information/view, they are not aware of the full system

This framework is used to understand how students attend to complexity within real-world design problems. Note that ABET also refers to complex problems, however, when referring to complex problems or systems within the present work, we are referring specifically to Cilliers framework outlined above.

Methods

Data Collection

This work adapts an approach from policy evaluation research called Participatory Systems Mapping or PSM [14] to generate a causal "map" of a complex system or systems that affect a policy problem or topic of interest. PSM is typically run with a group of stakeholders who have knowledge about system(s) that affect the core policy problem, for example, policy planners, domain experts, and policy evaluators. Engineering design teams also need to develop a deep understanding of the real-world contexts and systems from which their problem originates, so the authors modified PSM into Design Problem Systems Mapping (DPSM). The authors modified the original PSM data collection protocol to reflect the language, practices, and processes used in engineering design and more specifically design teams. Below we describe the modified procedure used for teams to generate a design problem systems map.

The first step in creating a DPSM involves the design team identifying their problem, typically the problem central to their project. Next, to fully articulate the design problem and prepare for the activity, the team will gather artifacts from the project (e.g. design brief, final report). The team then will then define the "focal factor", or the most central aspect of their problem The focal factor could be a sentence or two about the primary challenge behind the project. Following this every team member individually brainstorms different factors that affect or are affected by the design problem. These factors could include many topics such as accessibility, aesthetics, economics, environmental impact, ergonomics, functionality, interoperability, legal considerations, manufacturability, marketability, policy, standards, sustainability, or others. The factors (which could be causes or influences) are written in separate boxes. The team members review as a group and analyze all the causes and influences. Some factors reflect the same or similar ideas. These should be either grouped, modified or removed. After grouping/sorting all the factors, the team defines connections between them. This is a crucial step in drawing the map. Connections were defined using arrows, with arrowheads indicating direction of influence. Red arrows represented a negative correlation between factors, and green represented a positive correlation. Some factors may not have a direct correlation. Therefore, black arrows are used for these connections. The connections got established between causes, influences, and the focal factor. All the factors should be covered. The last step is to check the connections. Team members work together to review the established relationships. Factors may get moved around, and the directions of arrows may change

All mapping sessions were audio recorded to capture team interactions and reflections. Audio from sessions was transcribed. Sessions were run online, and maps were created with Miro, a tool for collaborative visualization.

Data Analysis

Design teams maps were analyzed using content analysis [29]. Content analysis is a qualitative research technique used to analyze documents or artifacts in order to uncover some symbolic meaning contained within them [29]. We use a deductive coding scheme [30], deriving our codebook from the theoretical work of Cilliers [10]. Codes were developed for each of the 10 attributes of complex systems outlined above. The first and the second author then independently coded each of the teams' systems map, using a transcription of the sessions audio as a reference or secondary source to understand students maps. Authors then met and discussed their coding. Differences in how authors coded led to refinement of the codebook. The new codes were reviewed against the maps and differences were discussed until both authors agreed upon the codes and their application.

Participants

Participants for this study were senior engineering students from a Mid-Atlantic University with a large engineering college. The first team had four members participating, all from the Mechanical Engineering. Their problem involved addressing pollution in natural bodies of water particularly debris such as plastic. At the time of creating the map, the team had completed their design, a marine trash collector device that separates and collects trash from oceans and other water bodies. The device creates a vortex to separate the trash and collect it in a bin-like component that is attached to the device. The second team had one member participating from Chemical Engineering. While more team members from the Chemical Engineering team would have been preferable, they were unable participate. This team's problem involved designing a full chemical plant that would produce a given amount of polylactic acid. By the time of creating the map, their team had completed the design of their chemical plant. All the students that participated had completed at least one semester of their senior engineering design capstone sequence.

Results

Table 1 A Quick Look at How Team's Attended to Complexity in their Problems

Cillier Dimension	*Team 1*	*Team 2*
Large number of elements.	Y	Y
Dynamic Interactions between elements	Y	N
Element interactions are rich or multilayered	Y	N
Non-linear interactions	N	N
Short-ranged interactions	Y	N
Feedback loops in interactions	N	N
Open systems	Y	N
Non-equilibrium systems	N	N
System has a history	N	N
Elements have local view	Y	Y

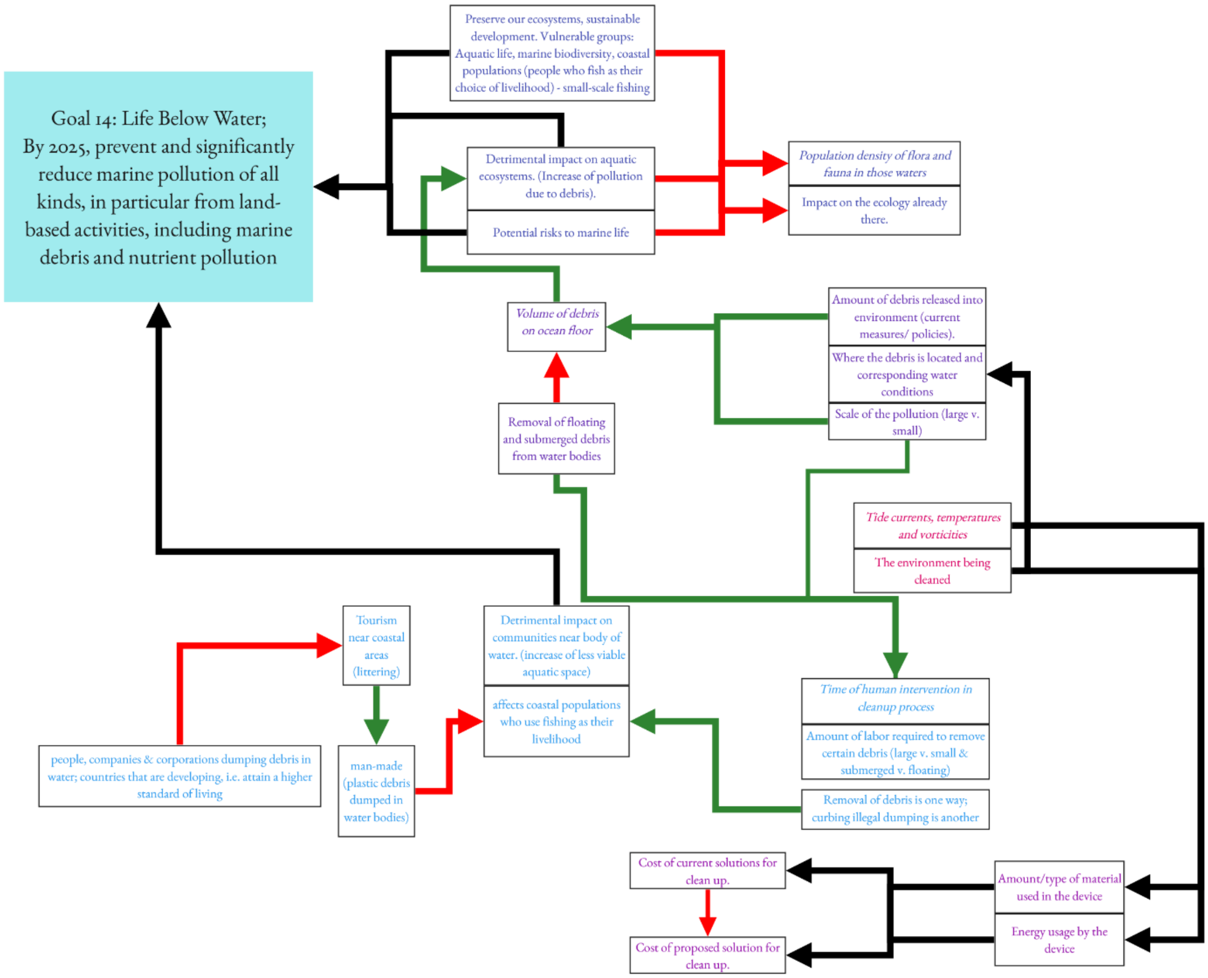

Figure 1 - Team 1's DPSM

Table 1 provides a high-level overview of the presence or absence of each of Cilliers dimensions for each of design teams. As can be seen from the table, Team 1's map, as a reflection of the teams problem understanding, exhibited a greater number of complexity dimensions. In what follows we discuss both teams in regard to the each of the dimensions.

Team 1 had four members participating in the DPSM activity. Team 1's final map is displayed in figure 1. Please note that during the consolidation stage of DPSM, the team decided to place related factors into adjacent blocks, instead of creating a new umbrella factor. In some cases, these adjacent factors are largely the same idea (e.g., in the upper middle, detrimental impact on aquatic ecology and risks to marine life) while in others the factors are associated, but unique aspects of an idea (e.g., bottom right, amount of material use in device and energy used by device).

Turning to the analysis through Cilliers [10] framework, his first dimension states that complex systems have a large number of elements. Including the focal factor, there are seventeen elements to the mapped system. If associated by unique factors are separated, this number would be even larger. Although Cilliers does not provide a metric for what constitutes large, seventeen elements appear to be more than a small system. The second dimension deals with dynamic interactions between elements. Here, we interpret dynamic to mean that interactions may happen in several different ways and/or that interactions are notably affected by context. Several of the interactions between elements on the map have a dynamic quality. For example, in the bottom left, the degree of economic development of the country/region and littering from coastal tourism may take a variety of forms (e.g., increased development could make tourism more expensive and less likely or increased development could make the area more appealing for tourism). The third dimension involves rich interactions, meaning factors may be affected by or affect multiple factors. In Team 1's map, the focal factor is affected by three factors and volume of debris and coastal population livelihoods are affected by two factors, among others. The environment (here a body of water) affects technical considerations of materials and energy needs as well as the location of debris. Other factors also affect multiple factors. Some factors only have a single input or output, however, such as littering from coastal tourism. Overall, the map has a moderate richness in its connections.

The fourth dimension is nonlinearity in interactions. Although Team 1 was told interactions between elements could be nonlinear (e.g., exponential) no interactions were marked as such. Note that the thicker or thinner a connecting line, the stronger or weaker the connection. Only two connections show a difference in degree, cost of current solution to cost of proposed solution and scale of the pollution and time for human intervention. Both of these connections are weaker, showing some difference in degree of relationship but not nonlinearity in connections. The fifth dimension states that many of the interactions between factors are shortrange. Here we define shortrange as interactions where one factors output is a direct input into another factor. For example, man-made plastics being dumped into the water has a direct impact on local fishers who use that same body of water. A long-range interaction would therefore involve indirect impacts. For instance, economic development in a country affecting marine life; between these factors there may be several other direct interactions, e.g., economic development may draw more tourism, leading to greater coast pollution, which may in turn affect marine life. With these definitions of direct and indirect affects, most of the connections on Team 1's map represents direct, and therefore shortrange interactions between factors. However, this does not mean all possible shortrange connections are present in their map, only that the connections present are predominantly shortrange.

The sixth dimension is feedback loops, where a factor or chain of related factors have outputs that return as inputs for that factor or chain. While there are many connections in their map, there are no obvious feedback loops present. The seventh dimension states that complex systems have open boundaries. Looking at Team 1's map we can see many interrelated systems or subsystems, the body of water itself, marine life within it, local populations that live off the water, corporations or tourists who pollute, the technological system itself, and current efforts to clean or create policies to protect the body of water. In short, the system is notably open with several groups, subsystems, wildlife, physical systems and others interacting. The eighth dimension deals with nonequilibrium in the system. While it is clear that interactions and exchanges are happening throughout the system(s), it is not clear if system is achieving or deviating from an equilibrium state. Team 1's map does not incorporate information about the state of the system over time, making it difficult to assess this. This extends to the ninth dimension, which states that the system history affects its current state. Changes over time, history of the system(s) or changing states receive limited attention in Team's 1 map, so this dimension also appears largely absent. The final dimension, that elements in the system are ignorant of other elements behavior, however, has more evidence. Given the predominance of shortrange interactions, elements are aware or impacted by local factors, but remain unaware or unaffected by others. Additionally, no elements have connections to more than three to four elements, further suggesting no element is "aware" of the full system.

Team 2 had one member participating in the DPSM activity. Please note, the Chemical Engineering student completely this map used two boxes (in the bottom left and right) to provide additional information on how factors related to the focal factor in the center.

In analyzing Team 2's map through the Cilliers [10]framework, we see on the first dimension there are eight factors including the focal factor. While Cilliers does not provide a metric for what constitutes a large number of elements, this is smaller than Team 1's factors. On dimension 2, dynamic interactions between elements of the system, many of the factors listed are metrics (e.g., conversion rates), data (e.g., thermodynamic data) or assumptions (see factor 4) which appear relatively fixed. It is not specified as to whether the throughput through the plant will be constant or if parts of the chemical production may result in variable output or waste. From the map, the system appears relatively stable (not dynamic) in its interactions, and this might be what we expect as this map focuses more on the technology system itself. For dimension 3, rich connections, all factors only relate to the focal factor. No factors directly affect the other factors; overall the interactions are simple and not dense. For dimension four, nonlinearity, the mapped system appears largely linear. For the fifth dimension, shortrange interactions has limited presence in this map; factors that affect the focal factor (creation of polylactic acid) often occur throughout the production process (e.g., issues of temperature and pressure, piping and packing throughout the system, conversion rates throughout the process). These represent long range interactions or indirect interactions, not shortrange interactions. For the sixth dimension, there are no feedback loops between the factors. The seventh dimension deals with the openness of the system. Looking at Team 2's map most of the factors relate to the chemical plant or chemical's being processed. The only exception to this is factor sevens consideration of direct cost and total product cost, reflecting economic issues. In general, this is a mostly closed technical system, with some consideration of outside economic issues.

The eighth dimensions addresses whether the system is in nonequilibrium. Although there are clear flows of chemical or materials and energy throughout the system, it seems plausible that when the plant has completed its production cycle, it will return to the same state as before, suggesting the system is in equilibrium. However, like Team 1, Team 2 does not address state of the system or how it may or may not change over time within their system map. As such, it remains difficult to assess how Team 2 viewed this dimension, regardless of how applicable it is to their problem as it is framed. Dimension nine, the path dependency of the system is not addressed within the map. The final dimension, that elements of the system are ignorant of other elements behavior is somewhat mixed. In terms of identified interactions, most factors only affect the focal factor and thus appear unaware or unimpacted by other factors. However, as noted for the fifth dimension, many of the interactions are long range or indirect, where a factor (e.g., piping and packing through the system) may affect multiple parts of the production process, suggesting there is some awareness or impact across the system for some factors. In short, not all factors

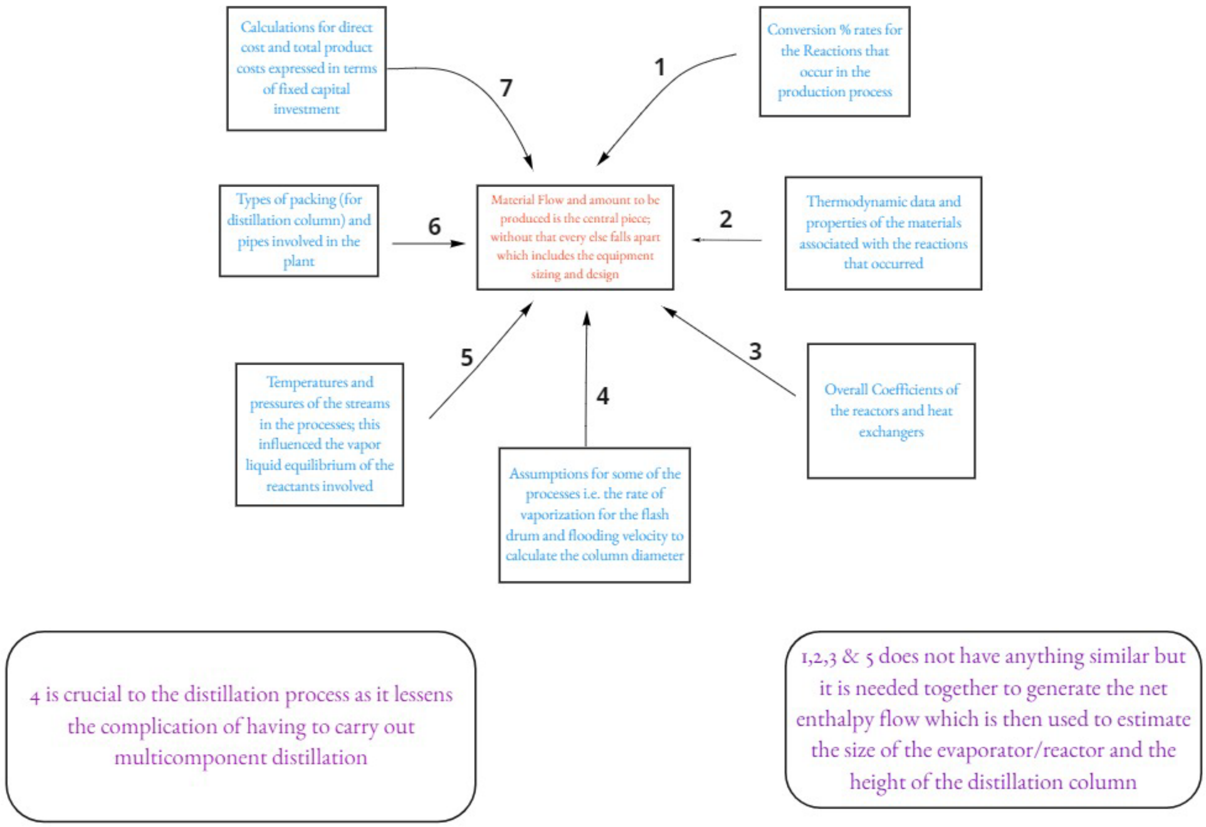

Figure 2 - Team 2's DPSM

or processes are "aware" or impact all other parts of the system, but some have repeated impact or influence across more of system, suggesting dimension ten is partially present.

Discussion

Looking at the results of the two teams DPSM, several points can be highlighted in regard to how teams attend to complexity in their design problems. First and foremost, the teams, particularly Team 1, emphasized several dimensions of complexity in their map, for example rich connections, open boundaries, and dynamic interactions between system elements. This provides some evidence that design teams may incorporate or notice some complex dimensions of a given problem, which may help them identify more appropriate, resilient, or more impactful design solutions. However, even in the two cases covered in this study, the complexity of the problem may receive greater or lesser attention. There were notable differences in how the two teams attended to complexity in their problems as revealed by their maps. For Team 1, there was some evidence for six of the ten dimensions from Cilliers [10] framework but there was only mixed evidence for two of the ten dimensions for Team 2. One contributing factor to these differences may be how the problem is scoped as an open or closed system, dimension seven [10]. Team 2's map mostly dealt with the technological system itself, which appeared largely as a closed or contained system with limited consideration of input from its environment. As Lewis [28] argues, technological or engineering systems should strive for simple, elegant solutions even if the problem space itself is complex. Nevertheless, the problem space is not the solution space. By focusing on the solution space from the beginning, other dimensions of complexity may be truncated. Another reason for the difference between teams may have to do with how the problem was framed [1], [31], [32] in the design brief from instructors. For Team 1, their design brief introduced them to the broad problem of pollutants in bodies of water, with no suggested solutions. Students therefore begin their design process at the stage of conceptual design, where they need to explore and generate different design alternatives as potential solutions [33]. In contrast for Team 2, their design brief outlined a chemical plant as the key solution direction and provided a patent and technical details on what such a plant might contain. In this way, students on Team 2 started in preliminary or detailed design [34] where a concept was already selected but many of its components, interactions and functions still needed to be tested and then refined. Given that the design brief already outlined the likely solution direction, when considering the problem, Team 2's student may have focused on the technological system and not its broader problem context. This further suggests how instructors frame design problems may influence how teams attend to complexity in the problem.

Neither of the teams attended to or highlighted aspects of their problem as it related to the state of the system (as it pertains to achieving or moving away from equilibrium) or the history or changes within the system over time. This may be a limitation of DPSM as a mapping approach, which may not easily capture time or state changes [35]. It may also reflect that time and state of the system are obvious or more easily simplified when trying to make sense of complex problems. Outside of the map itself, Team 1 described their problem in static terms about the presence of pollutants in bodies of water, not how this has changed or worsened over time. It is worth noting their focal factor does mention a future state, 2025, for which the goal is to significantly reduce pollutants in the water. Nonetheless, prior evolution of this problem (e.g., increased water pollution) is not discussed nor are the states or changes that take us from the present map to that future state. Nonlinearity and feedback loops were two additional dimensions not addressed by either team. These may also reflect potential simplifications for facilitating their design process. Nonlinearity and feedback can add substantial effort to analytical work and mathematical modeling, so these may be more likely to be simplified at the problem understanding stage.

While not all problems, as they are framed, may contain all the dimensions of complexity discussed here, a critical aspect of contending with complexity is understanding that problems or topics can be reframed to reflect greater or lesser complexity [36].

Conclusion

The problems our engineering students will face as they move into professional careers are becoming increasingly complex [4]. Complexity science offers concepts, theories, and frameworks for making sense of the real-world problems and systems [5], [9] but has received mixed attention in engineering education [4], [11] and is often under-conceptualized specifically in engineering design research [12], [16], [23], [27]. Regardless of its research treatment, design teams will need to contend with the complexity of real-world problems. However, the extent to which design teams attend to the complex systems or complexity in which their problems are situated is not well understood. To begin to understand this, we adapted an approach called Participatory Systems Mapping from policy evaluation research that is used to have policy stakeholders collaboratively map out their understanding of a problem and the complex system(s) in which it is embedded [14]. We call this adapted approach Design Problem Systems Mapping or DPSM and used it to study two design teams. Our results showed that both teams attended to some complexity in their problem, but that the amount of complexity attended to varied depending on whether the system was considered open or closed and how the problem was framed to students. Some dimensions were ignored by both teams, including the time dependencies of the system, its equilibrium or nonequilibrium states, and nonlinearity and feedback loops in interactions. Some of these may reflect limitations in using a mapping approach to capture students' problem understanding, particularly for the state and temporal evolution of the system, as mapping approaches do not always capture temporal considerations well [35]. Alternatively, these may also represent areas in which teams naturally sought out simplifications to facilitate their problem understanding and design process. Alternative framings for complex systems are often possible [36]. Further research is needed to better understand how teams attend to problem complexity, where simplifications are made and what is the impact of these simplifications. Future research will extend the approach used in this paper to a greater number of design teams and seek teams addressing different types of problems. The present work is limited by only analyzing two teams and two associated problems.

By beginning to understand how design teams attend to complexity in problems, we can start to develop ways to better support students to develop understanding of their problems and in some cases leverage simplifications that can facilitate their process without harming their solutions. The results from this study start to paint some early directions for how to more fully support our design teams when they deal with problem complexity, in particular with how problems are framed and if they are considered opened or closed.

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