2024 NSF/ASME Student Design Essay Competition

DESIGN AND MANUFACTURING PRODUCTS IN A WORLD OF ENGINEERING SYSTEMS

Graduate Category Submission

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1. The World of 2040

The world is increasingly connected by systems. This trend is displayed in Figure 1, which shows how advancements in the sciences led to the development of inventions and how inventions became connected to form engineering systems [1]. Initially, individual inventions provided new capabilities. The automobile enabled the ability to travel further, the telephone enabled the ability to communicate over longer distances, and the lightbulb enabled the ability to work at night. Over time, the capabilities afforded by individual inventions have been expanded by connecting them, either through direct interfaces or through supporting infrastructure. Today, highways and multimodal transportation hubs enable quicker travel and shipping than ever. Satellite communication systems are expanding to provide phone and internet services in the most distant areas of the planet. The electric grid delivers power to many devices in millions of homes and is currently evolving to deliver power more sustainably with renewable energy sources.

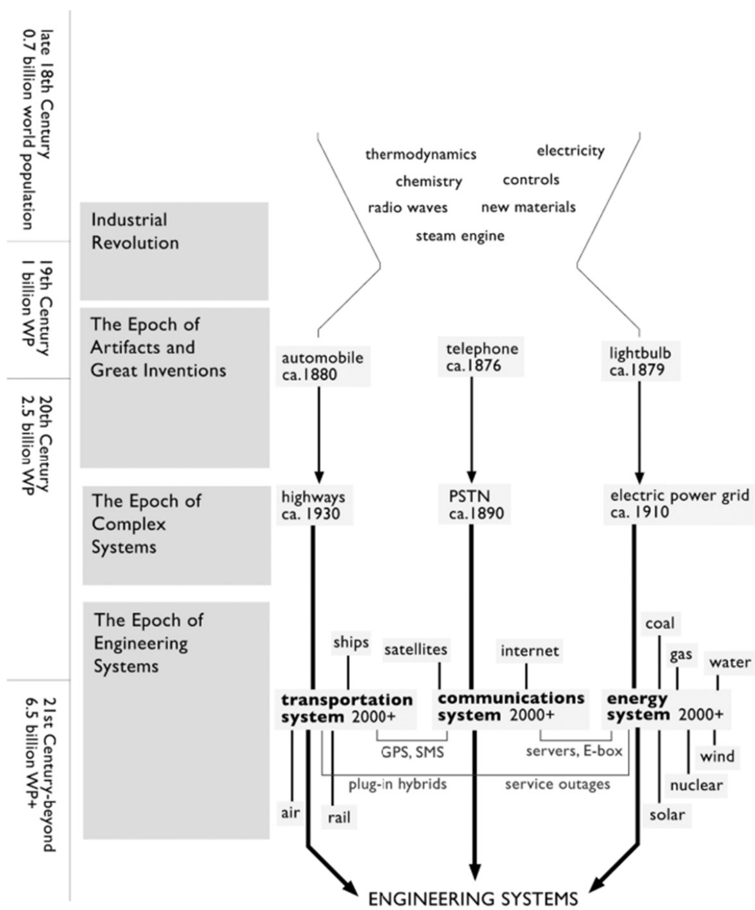

Figure 1. The evolution of engineering systems driven by connections between artifacts [1].

As inventions have become more connected, engineering systems have emerged. de Weck et al. define engineering systems as “a class of systems characterized by a high degree of technical complexity, social intricacy, and elaborate processes, aimed at fulfilling important functions in society” [2]. Engineering systems include transportation, energy, and communication systems, among others. In 2040, it is likely that these engineering systems will become even more entangled as engineers develop new technologies and find new ways to connect them. Isaksson and Eckert describe the increasing entanglement between products and their operating environments as an emerging trend that will pose design challenges in 2040 [3].

While design and manufacturing firms are not independently responsible for the creation of engineering systems, they often develop products, or artifacts, that will become part of them. For example, cars, trains, solar panels, batteries, phones, satellites, and many IoT (Internet of Things) products are all artifacts that become part of engineering systems. Given the increasing entanglement between these products and their operating environments, Isaksson and Eckert argue that systems thinking will become more important in and that engineers will need to consider wider system boundaries in product design [3].

In 2040, firms will need to design products for integration in engineering systems more intentionally. To be successful, these firms will have to consider how their products will interact with other system elements and how their products' performance and value will be influenced by the surrounding system. A product's failure to integrate into its operating environment is a failure to meet customer needs. On the other hand, a product's seamless integration into engineering system environments could surprise and delight customers, increase market demand, and improve brand reputation. By designing products to effectively integrate into engineering systems, companies could increase the likelihood that their products will be valuable to customers in the 2040's complex and dynamic operating contexts.

Product ecosystems (ex: Apple's iPhone, Airpods, Apple Watch, etc.) feature connections between a defined set of jointly managed products. In such ecosystems, engineers must consider interfaces between products, but the system boundary is relatively easy to define, and engineers have significant control over the products and interfaces that comprise the system. Newer products feature greater connections with artifacts in the surrounding environment. For example, electric cars interface with transportation infrastructure, the power grid (both in terms of consuming and providing power), and act as entertainment centers. Home automation systems interface with the internet, communication systems, and entertainment systems. When designing systems, engineers must consider interfaces between products and elements of the surrounding system environment that are out of their control. These complex connections blur the lines of where to define system boundaries and create a world of interconnected engineering systems.

Yet, it is challenging to design products to effectively integrate into engineering systems. These systems are difficult to understand and are incredibly dynamic. System behavior is shaped by human involvement in design, operation, use, and regulation. As a result, the behavior of engineering systems can be emergent, and the evolution of these systems can be highly unexpected. Intentionally designing products as elements of engineering systems is difficult because of the many uncertainties associated with system interactions, environments, and use. This paper describes the challenges of designing products as part of engineering systems and how they could be addressed by firms of 2040.

2. Designing Products as Part of Engineering Systems

The role of engineers has changed greatly over time, and the role of the engineer will continue to change in the future. While early engineers narrowly focused on creating standalone inventions, modern engineers must also consider how new inventions will interact with engineering systems. This includes considering how the needs for new products are driven by engineering systems, how the performance of new products is impacted by their integration into engineering systems, and how new products impact the behavior engineering systems. To design products that integrate successfully into engineering systems, engineers must consider system interactions and various externalities as described in Section 2.1. Firms must also consider how products will perform in and adapt to dynamic regulatory, economic, technological, and social environments as discussed in Section 2.2

2.1 Considering System Interactions

New products increasingly interact with each other and with elements of the built environments. As a single example, modern electric and autonomous vehicles interact with cellphones, satellites, charging stations (and the power grid), drivers, other vehicles, and transportation infrastructure, among other things. Many other products also interface with many other elements of engineering systems, including personal solar panels, commercial planes, and communication satellites. To effectively design these products, engineers must consider complex system interactions. System interactions may influence the performance of the product and in turn its marketability. When designing an electric autonomous vehicle, engineers might consider the following questions:

- How convenient is it for drivers to use the vehicle (considering the driver's intended destinations, the range of the vehicle, the availability of charging stations, the duration of charging, etc.)?
- How are the performance and future upgradability of the vehicle impacted by the current infrastructure (roads, road markings, traffic signals and signs, etc.)?
- Is the vehicle safe for drivers, passengers, and surrounding pedestrians (considering elements of the surrounding environment, other drivers, other autonomous vehicles, the vehicle's control software, regulations, etc.)?
- Are the expenses of operating and maintaining the vehicle comparable to other existing vehicles (considering costs of charging, fueling, maintenance over the lifecycle, etc.)?
- How does the value of the vehicle change over time (considering whether electric vehicles maintain their value on the resale market, the procedure for disposing of batteries, etc.)?

Addressing these questions requires system models that extend beyond the car, or generally the product, itself. Engineers must model elements of the vehicle's environment to answer these questions, including transportation infrastructure, charging infrastructure, pedestrian behavior, driver behavior, other autonomous vehicle behavior, economics trends, user preferences, and regulations, as shown in Figure 2. These aspects of the engineering system are outside the boundaries of the vehicle model, but they heavily influence user perceptions of product value. Therefore, when designing products that will engage with an engineering system, engineers must consider wide system boundaries that account for how the performance and value of a product is influenced by its interactions with the greater system. These broad yet detailed models could enable engineers to make better design decisions that improve the product's marketability.

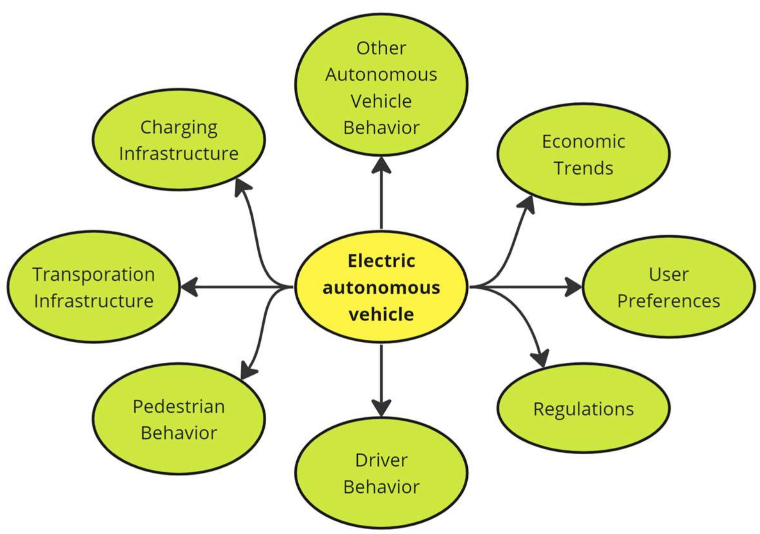

Figure 2. Elements of the engineering system surrounding an electric autonomous vehicle.

Yet, it remains challenging to define appropriate boundaries for an engineering system model in a product design context. Engineers may struggle to identify what elements of an engineering system are influential enough to model. Further, it is difficult to quantify relationships between elements in an engineering system model. As a result, engineers may omit or abstract relationships between elements in their models, which could introduce uncertainty in model results. Existing methods for developing engineering systems models and the challenges of developing such models are discussed further in Section 3.1. Section 4.1 discusses how engineering system modelling methods could be further improved to support product design activities of 2040.

2.2 Designing for a Dynamic Environment

Engineering systems are characterized as dynamic – their elements and interrelationships change over time [2]. Even with advanced modeling, certain aspects of engineering systems will remain unpredictable. For example, the values and preferences of system users may change, supply chains may be disrupted, economic recessions may occur, new technologies may develop, and policy and regulations may evolve. While these uncertainties may impact the success of any product design activity, these uncertainties have salient impacts on the products used in engineering systems. This is because engineering systems are shaped by dynamic and unpredictable human activity. Products becoming part of an engineering system may be subject to uncertainties associated with human behavior and the collective emergent behavior of the system.

It is unlikely that models will ever be detailed enough to simulate the performance of an engineering system accurately over time. There will always be uncertainties in the behavior of engineering systems linked to human activity and emergence. Engineers may not be able to design products strategically with respect to known unknowns or to unknown unknowns, but they can design products to be easily changeable with respect to them. Changeability may enable products to be quickly redesigned for next-generation releases or adapted while in service through software updates, product feature add-ons, or parts replacements. Changeability enables efficient modification of products (or systems) to meet changing customer needs in a dynamic engineering systems environment [4,5].

Consider again the example of the autonomous electric vehicle. During the vehicle's service life, congress may pass new legislation regulating autonomous vehicles, competing firms may develop their own autonomous cars that will interact with the vehicle on the roads, or the costs of electric vehicle charging may dramatically change. None of these futures could be predicted with certainty in advance of the design and release of the autonomous electric vehicle, and designing for all of these futures simultaneously may be prohibitively expensive or generally wasteful. As an alternative, engineers could develop their vehicles to be easily changeable so that if these futures develop, the vehicles could be updated to adhere to new regulations, to implement better sensors and controls, or to operate in different modes for fuel efficiency.

Designing changeable products will become increasingly important as product operating environments become more complex. With engineering systems becoming more prevalent, firms should adopt design for changeability methods to prepare for the product design challenges of 2040. Existing methods of designing products and systems for changeability and the challenges of designing for changeability are described in Section 3.2. Section 4.2 discusses how design for changeability methods could be further improved to support product design activities of 2040.

3. Design Tools for an Engineering Systems Environment

Many existing design tools could be applied to better design products for integration in engineering systems. These products will be designed by engineers spanning multiple disciplines. Maintaining design efficiency will require that design work is conducted in a digital environment. Effective digital design environments will establish a common infrastructure so that many different types of engineers can share and discuss information. This section describes existing methods that could be used to address the challenges of designing products for integration in engineering systems introduced in Section 2. Methods for modeling and representing engineering systems are described in Section 3.1, and methods of designing changeable products or systems are discussed in Section 3.2.

3.1 Engineering Systems Models

There are many methods that could be applied to model engineering systems or aspects of them. Most notably, model-based systems engineering (MBSE) has been developed to analyze systems and manage them throughout their lifecycle. MBSE enables this analysis through the creation of "a unified model that cuts across disciplines" [6]. MBSE can be applied to make heterogenous models interoperable, facilitate discussion with stakeholders, and encourage questions about design problem framing [6]. Given these capabilities, it has been argued that MBSE could be applied to address new systems engineering challenges of managing the complexity and breadth of sociotechnical systems [7].

MBSE can be used to create and connect a wide range of models. One of the main challenges of using such a powerful modeling tool is determining what elements of a system to model [6]. Madni and Augustine explain that omitting important elements could undermine model integrity and accuracy, while including irrelevant elements could add unnecessary complexity [6]. Martin describes an additional problem framing challenge as an "agony of abundance," in which there are many options for how to model a system. To address this problem, Martin proposes an approach for selecting models that have the greatest utility and that provide the greatest insight into performance outcomes [8]. In addition, Noguchi, Martin, and Wheaton have proposed $MBSE^2$, a method for architecting an MBSE system using MBSE principles and methods [9]. The existence of these methods and approaches implies that MBSE models are themselves complex systems that are difficult to design and manage.

Further, it is difficult to model some elements of engineering systems in MBSE. When relationships between system elements are not well characterized, the models leveraged in MBSE may be approximations or abstractions [10]. While MBSE model users can access all aspects of the model and question model form, it may be difficult to thoroughly interrogate the model, especially for a large complex system. In addition, it is likely that many modeling decisions are made through engineering judgment when uncertainties in system representation cannot be adequately addressed. It is unclear whether MBSE can capture the rationale for why elements are modeled in a certain way and how uncertainty was managed in the modeling decision. Finally, research on model-centric decision-making explores how decision-makers develop trust in models and use them to make decisions [11]. Shane German and Rhodes find that many technological factors, including transparency, documentation, and uncertainty, may affect a decision-maker's trust in a model [11]. This implies that the justification of modeling decisions and consideration of uncertainty in models could influence model trust, adoption, and use in decision-making.

Therefore, methods of modeling engineering systems exist, and firms could leverage them to study how products may perform in engineering systems contexts. Design and manufacturing firms who aim to be successful in 2040 should consider adopting some form of MBSE to support their system modelling needs. However, before adopting MBSE, firms must carefully consider how MBSE will be managed and applied. Section 4.1 discusses how challenges of implementing MBSE could be addressed and how MBSE methods could be improved to better address the engineering systems modeling challenges of 2040.

3.2 Design for Changeability Methods

An extensive body of literature is focused on how to design for changeability. Within this body of literature, different methods address different aspects of changeability. Fricke and Schulz have defined the four aspects of changeability to be robustness, flexibility, agility, and adaptability. The four aspects of changeability are defined in Figure 2 [12]. Each of these aspects of changeability could support the design of products for use in engineering systems.

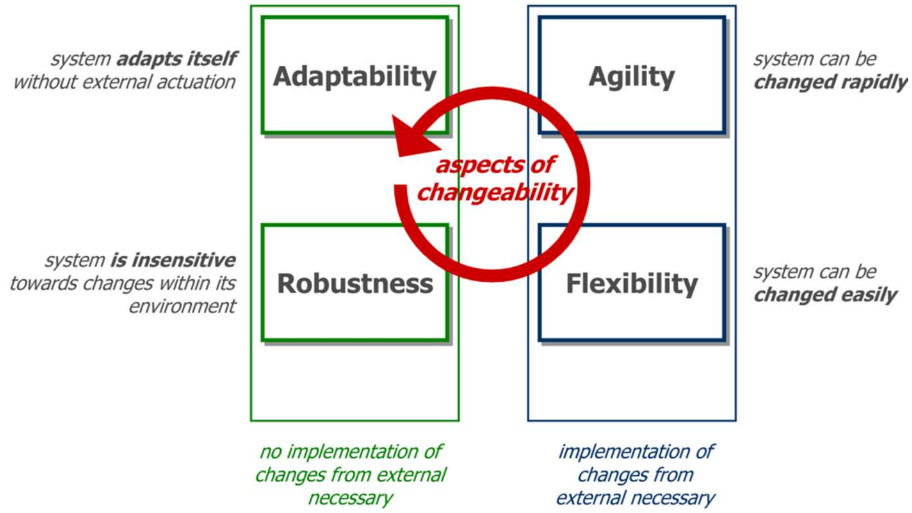

Figure 3. The four aspects of changeability [12].

- Robustness, a system's insensitivity towards changes in its environment, helps ensure that a product will achieve acceptable performance despite changes in the surrounding engineering system.
- Flexibility, a system's ability to be changed easily, could enable a product to be easily modified or updated with respect to changes in the engineering system.
- Agility is an extension of flexibility in which system change is rapid. Agility may enable a product to be changed such that periods of poor performance are reduced.
- Adaptability combines elements of flexibility and robustness, as a system could easily adapt itself without any external changes. Adaptability may enable a product to be changed with minimal redesign effort or cost.

An autonomous vehicle may be designed to have each of the four aspects of changeability with respect to safety requirements. A robust autonomous vehicle may be overdesigned to exceed safety requirements so that if new legislation on vehicle safety is passed, the vehicle could meet the new requirements without physical modification. A flexible autonomous vehicle may feature modular sensors that could be easily exchanged for new sensors capable of detecting objects earlier to improve vehicle safety. An agile autonomous vehicle may support software updates that improve the safety of its control algorithm, only limiting the speed of the change to the speed at which new software could be developed and downloaded. Further, an adaptable autonomous vehicle could use performance data to adjust its control algorithm and safety performance, enabling changes to be made without human intervention.

To achieve robustness and flexibility, engineers must mitigate change propagation. In engineering design, change propagation has been defined as the process by which "a change to one part or element of an existing system configuration or design results in one or more additional changes to the system, when those changes would not have otherwise been required" [13]. The tendency for change to propagate makes it difficult to limit the scope of system modification. Within this paper, robustness can be considered as preventing change from propagating from the engineering system environment to the product. Further, flexibility is generally enabled when the extent of change propagation is limited. Extensive change propagation requires many modifications to be made in redesign and makes system change more difficult.

Researchers have proposed several methods for mitigating change propagation. Many of these methods involve preventing change propagation during a redesign process. For example, it has been proposed that designers should avoid changing highly coupled components that could have significant change impact

[14–16]. Other researchers propose performing analysis to determine favorable (or possibly "optimal") change pathways [17–19]. These methods operationalize changeability in a product or system by leveraging existing change pathways. There are also insights about how to enable changeability in products and systems by creating change pathways in initial design. Some researchers suggest that adding flexibility to elements may be valuable but provide little explanation about what flexibility means or how elements can be made flexible [20–22]. Other researchers argue that strategic modularization of systems could prevent change propagation [23–25]. Recent research suggests that including margins in a system can limit change propagation [26–29], but within the change propagation literature, there is little understanding of how to allocate margin efficiently (where should margin be included and to what extent).

To achieve adaptability and agility, engineers must first ensure that change will not propagate extensively when making a desired modification. Such extensive propagation would make desired modifications difficult to implement at all, let alone rapidly or autonomously. Additionally, engineers must integrate technologies into the product or its environment to facilitate the change. For example, software, sensors, and actuators, are all technologies that can facilitate rapid and autonomous modification. Software can be updated to rapidly change a product's mode of operation and performance. Sensors collect data which may inform a need for adaptation. Actuators can be used to facilitate a physical change.

There are many methods of design for changeability, and there are many technologies that support the rapid and autonomous implementation of change. Design for changeability methods could be beneficial in modifying products over their lifecycle as surrounding engineering systems evolve. Design firms who aim to be successful in 2040 should adopt models and methods that allow them to enable and operationalize changeability. Firms could also further study how to enable changeability in their products, which may give them a competitive advantage. Section 4.2 discusses how design for changeability methods could be improved to better address the product design challenges of 2040.

4. Areas of Future Improvement

While existing methods can be applied to better design products embedded within engineering systems, these methods have notable limitations. This section describes how engineering system models and design for changeability methods could be advanced to better address the product design applications of 2040. Further, this section provides insights about how engineering education should evolve to better prepare the next generation of engineers to address the product design challenges of 2040, as products are increasingly designed in a world of engineering systems.

4.1 Improving Engineering Systems Models

The modeling of engineering systems support engineers in characterizing the performance and marketability of complex products, as described in Section 2.1. These models also serve as a representation of the engineer's thought- and problem-framing process. Existing methods provide a foundation for modeling engineering systems. Most notably, MBSE connects interdisciplinary models that each represent elements of an engineering system. However, there are challenges with implementing MBSE to support product design in engineering systems environments. Even with the ability to create and connect models, engineers still struggle to scope the models, quantify certain aspects of the models, to clearly define the uncertainty associated with the models, to communicate about the models, and to interrogate the models.

To effectively model product performance in an engineering system, firms should work to address these challenges of implementing MBSE. This may involve developing and maintaining documentation to justify modeling decisions or implementing rigorous processes to interrogate the models developed by MBSE. Including paradata about modeling choices could provide further transparency about model structure and representation [30]. It is also possible that system safety approaches could be applied to MBSE models to investigate the possible risks of modeling elements of a system in a certain way. Such an approach could consider how the modeling choice impacts model results and how those model results may impact design decision-making.

Further, engineering firms should investigate how uncertainty is represented in engineering system models and how that uncertainty may impact decision-making. It may be valuable to develop more rigorous methods for classifying the uncertainty underlying MBSE models. Specifically, uncertainty matrices could be used to communicate the location, level, and nature of uncertainty in system models [31] or system analysts could measure and record uncertainties using level of precision the levels of precision described by van der Bles et al. [32]. Such acknowledgement of uncertainty could provide justification for modeling decisions, promote trust in the system models, and prevent poor decisions from being made due to misunderstandings of model uncertainties.

4.2 Improving Design for Changeability Methods

Designing for changeability would help engineers ensure that products maintain adequate performance throughout their lifecycles, even as surrounding engineering systems evolve. When engineering systems evolve, designers could simply update the software of an existing product, exchange parts of the product, or develop a new generation of product that better meets customer needs. The ability to change products to meet emerging customer needs quicker than competitors could provide a market advantage. Researchers have proposed many methods for operationalizing changeability in products. Design and manufacturing firms should leverage these methods where possible.

It is possible that MBSE could support the operationalization of changeability. Researchers have proposed integrating aspects of complexity management into MBSE, including change propagation analysis [10]. Developing a capability to track margins within MBSE could support operationalization of changeability, given that knowledge of margins in a product could be used to identify tradeoffs and redesign opportunities [33]. Directly integrating design for changeability techniques into modeling methods could produce a very powerful tool for efficiently operationalizing changeability or even for enabling it in initial design.

Firms would also benefit from investigating how to better enable changeability in their products. Many of the proposed methods for enabling changeability in products and systems could be further developed. One promising area of future research would be investigating how system architecture decisions (ex: subsystem structure, modularization, etc.) and design margin allocation could enable changeability. Combining change propagation analysis and margin allocation may provide insight into how to create change pathways.

4.3 Educating Engineers of 2040

Future product design challenges will require engineers to apply systems thinking. Even when designing a specific product, engineers will often be required to consider the product's interactions with an engineering system. It is unclear to what extent current engineering students are exposed to systems thinking in their curricula and to what extent exposure to systems thinking varies across engineering curricula. For example, civil engineering students may be exposed to more systems thinking in their coursework as they are more directly involved with designing systems (in the form of infrastructure). In contrast, mechanical engineering students focus greatly on physics and may have less opportunities to practice systems thinking. To better prepare engineers to address the design challenges of 2040, engineering students need additional opportunities to practice systems thinking, problem framing, and design under uncertainty throughout their coursework.

Engineering students most commonly engage with systems thinking, problem framing, and design under uncertainty in their capstone design courses. It is less common for students to engage with these skills in the core engineering science courses (ex: statics, dynamics, thermodynamics, fluids, etc.) that make up most of their curriculum. Yet, students should exercise these skills many times throughout the curriculum to better develop them. Additional opportunities to practice systems thinking could improve the learning of systems thinking. Further, these additional opportunities could allow students to put their learning in context in real world design activities. By "playing the whole game" of design, rather than engaging with disparate pieces of design analysis throughout the curriculum, students could also gain a better appreciation for how their learning is connected and develop further motivation to continue learning [34].

Design and manufacturing firms should investigate how they could partner with academia to develop systems thinking skills in future engineering students. While faculty could develop engineering design problems that involve systems thinking, problems provided by design and manufacturing firms would provide students with more authentic insight into the design challenges they may face throughout their engineering careers. By introducing students to authentic design problems that require systems thinking, design and manufacturing firms could help students learn the skills required for them to develop products for integration into engineering systems. If industry engaged students with real problems that they faced, students could also understand design challenges from the perspective of a company and gain more insight into how these challenges are practically addressed. Providing students with this learning and insight could help ensure that there would be a future workforce that is sufficiently skilled to meet the design challenges of 2040. Brunhaver et al. support this claim, having collected evidence that suggests that engineering students need a better understanding of engineering practice to prepare them to work in the field [35].

5. Conclusion

Many of today's products operate in engineering systems, and engineering systems are becoming more complex. To be successful in 2040, design and manufacturing firms will need to intentionally design products to perform well in complex engineering systems. Designing products for integration in engineering systems is challenging due to complex and dynamic system behavior. To address these challenges, design and manufacturing firms will need to develop more rigorous engineering systems models and design for changeability. While methods for developing engineering systems models exist, firms will need to carefully consider how to implement these methods, how to frame engineering design problems within the models, and how to manage uncertainty in decision-making. Additionally, firms can begin implementing existing designs for changeability methods, but they may gain competitive advantage by further developing these methods to create additional change pathways. Finally, firms should consider how they could partner with academia to help students develop systems thinking skills. Future engineers will need these skills to meet the design challenges of 2040, as products are designed to operate in an increasingly complex and dynamic engineering system environment.

Appendix

Generative AI tools were not used in the creation of this work. All of the words in this work are my own.

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