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NEXT GENERATION MANUFACTURING: DATA DRIVEN AND DECISION-BASED DESIGN PERSPECTIVE

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1. Frame of Reference

The realm of technology is constantly evolving. As time progresses, the regular introduction of advanced technology and products has been a common occurrence. Amidst this rapidly advancing landscape, sustaining a position as a leading global high-tech materials manufacturing company poses significant challenges. The industry is filled with numerous competitors, each striving to outperform others through innovative strategies. This competitive pressure compels companies to adopt new technologies, provide innovative solutions, and establish distinct market niches in order to gain a larger market share.

Furthermore, with the progress of technology, client expectations also evolve, compelling manufacturers to consistently adjust to these shifting demands. The primary objective for any manufacturing company is to achieve customer satisfaction. This objective requires organizations to continuously monitor market trends, incorporate improvements in technology, and utilize the most recent scientific innovations and techniques to their advantage. Hence, a successful manufacturing company with a global customer base must not only be a leader in innovation and technological adaptation but also embed these qualities into its core values. This integration ensures that the enterprise consistently remains at the forefront of its industry.

In the past decade, the emergence of Industry 4.0 has greatly accelerated the advancement in manufacturing research fields [1]. Industry 4.0 is characterized by the integration of smart machines and autonomous systems within factory settings, which is facilitated by advancements in machine learning, Artificial Intelligence (AI), and the Internet of Things (IoT) [2]. However, this technological revolution faced critique due to its limited human engagement, as the initial focus was predominantly on technological enhancement without sufficient consideration of the human and social aspects [1]. This critique led to the evolution of Industry 4.0 into Industry 5.0, which emphasizes the reintegration of human involvement in manufacturing. In contrast to the technology-focused approach of Industry 4.0, Industry 5.0, also known as the Fifth Industrial Revolution, advocates for a balanced integration of human capabilities and advanced technologies. This approach places high importance on the welfare of the human workforce and focuses on achieving ecological and societal sustainability. Industry 5.0 seeks to establish a harmonious partnership between humans and machines, with the objective of technology augmenting human work rather than supplanting it, thereby fostering a more sustainable and socially responsible manufacturing environment [3].

As a global manufacturing company with the goal of being the industry leader by 2040, successfully navigating the challenges of the ever-changing technological landscape will require incorporating principles from both Industry 4.0 and 5.0. Industry 4.0 represents a significant shift towards utilizing advanced data analytics and machine learning to improve operations and augment decision-making processes. This technology facilitates the efficient analysis and utilization of extensive datasets, thereby enhancing industrial efficiency and innovation. Industry 5.0 incorporates a crucial human element into the manufacturing paradigm by prioritizing human cognition and decision-making alongside automated systems. This shift emphasizes the symbiotic relationship between human intellect and machine precision, which is crucial for addressing intricate, nuanced challenges that completely automated systems may not fully comprehend.

In order to gain a competitive edge, a forward-looking manufacturing enterprise must strategically integrate these technological breakthroughs with human insights. By implementing such an approach, the enterprise not only improves its operational efficiencies but also increases its flexibility to adapt to changing market conditions and consumer expectations. This dual-focus approach will enhance the provision of exceptional customer satisfaction by utilizing both the accuracy of advanced technologies and the ingenuity and flexibility inherent in human contributions. In order to achieve exceptional performance in 2040, a firm must incorporate these comprehensive tactics into its fundamental operational structure, guaranteeing its position at the forefront of industry advancement and customer-focused solutions.

2. High Tech Global Manufacturing Company in 2040

A global manufacturing company comprises a comprehensive process that encompasses the acquisition of raw materials, the manufacturing of final products, and their delivery to customers. The process is supported by the complex interaction between three fundamental disciplines: Materials, Manufacturing, and Product. Each discipline has a distinct role in creating the final product, requiring a complex system of interactions not only within the company among these disciplines but also externally with customers, raw material suppliers, and dealers. While designing a high-tech global manufacturing enterprise, designers must carefully evaluate these complex interactions and information flow between different internal disciplines as well as external entities in order to improve the performance of the overall system. The complexity of such a design stems from the need to integrate and synchronize these various elements (such as the internal disciplines and the external entities) effectively.

In order to be successful, a manufacturing enterprise must not only address these complexities but also ensure that the system design improves the efficiency of each discipline. This entails fulfilling customers' needs while simultaneously meeting the requirements of suppliers, dealers, and the operational goals of the manufacturing enterprise. In order to accomplish the conflicting targets of the enterprise, it is crucial for the company to integrate human decision-making capabilities into the design process alongside advanced data analysis. By employing this dual strategy, the corporation is able to anticipate market trends, improve product designs and performance, and make informed decisions that maximize both production and distribution. A well-designed, high-tech manufacturing system is characterized by its ability to not only meet immediate production requirements but also adjust to the ever-changing market conditions, thereby ensuring long-term success and competitiveness.

A successful manufacturing company needs to have certain characteristics to make it stand out amongst its competitors. In Figure 1, the characteristics of a successful high-tech global manufacturing company are mentioned, which entail:

a) Interconnectivity
b) Data Analytics
c) Sustainability
d) Human Centricity
e) Robustness

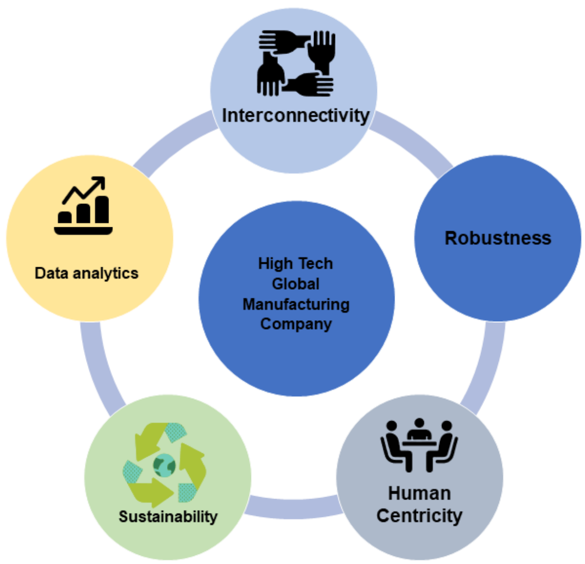

Figure 1. Characteristics of a successful high-tech global manufacturing company

(a) Interconnectivity:

Within a manufacturing system, various subsystems interact, requiring connection across multiple engineering and management disciplines. These disciplines are inherently interrelated, with a continuous flow of information between them, where changes in one discipline can have a substantial influence on others. For instance, in the realm of materials manufacturing, the properties and performance of a product are directly influenced by the material's processing history data and the microstructure developed at each stage of the process. Efficient sharing of information is crucial for effective communication between an enterprise's internal departments, as well as with external entities like suppliers of raw materials and dealers. Furthermore, when making manufacturing decisions, it is crucial to take into account the customers' preferences, which serve as another crucial connection that the enterprise must maintain. In Figure 2, we can see the connection between a high-tech global manufacturing enterprise within its discipline and external entities. Customers' needs drive the whole system, who receives their product from the dealers. Dealers and suppliers directly share information with the enterprise. The dealer conveys information about the customers' needs, whereas the supplier shares information about the raw materials. The internal disciplines of the enterprise use information from external entities and share information between them.

Given the interconnectedness of the company structure, it is vital for a manufacturing enterprise to build a systematic connection between all internal disciplines and external entities. Such systemic connectivity allows seamless information flow and enhances collaboration between all internal disciplines and external entities. By creating seamless interactions among all the connections, the organization can improve its ability to fulfill its overall goals while ensuring that each component of the system performs to its full potential and achieves the individual targets. This integration not only improves operational efficiency but also supports a more holistic approach to product development and manufacturing processes.

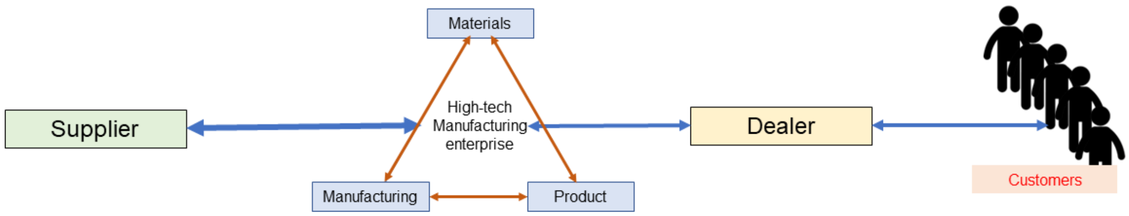

Figure 2. Interconnectivity between the disciplines of a manufacturing enterprise

(b) Data Analytics

Engineering design and manufacturing processes are rich sources of data [4], with research data deriving from experiments of varying scales, diverse development processes, and complex manufacturing planning. These data streams encompass process-related information that is often complex and non-linear, presenting challenges for human cognitive abilities when dealing with the interactions among variables from many different disciplines. Utilizing advanced design support and synthesis methods is advantageous for enhancing the cognitive capacities of system designers. These methods enable designers to gain a more comprehensive understanding of the potential consequences of their design decisions [5]. This is particularly important when the interactions among the variables and disciplines are complex and have significant implications for the final product.

Within a manufacturing context, the subsystem disciplines (i.e., manufacturing process, materials, products) are effectively represented by combining data from multi-fidelity models. These models integrate physics-based approaches, which directly simulate physical phenomena, with data-driven or surrogate models. Surrogate models serve as an abstraction of reality - they approximate or interpolate the underlying physical phenomena (i.e., responses) across specific regions of the design space [6]. This approach not only simplifies the representation of complicated systems but also establishes quantitative links and interdependencies between disciplines [4]. By amalgamating data from these diverse models, designers can create a cohesive and predictive framework that supports more informed decision-making. The incorporation of advanced modeling techniques is crucial in improving the design process, resulting in more efficient and productive production results.

(c) Sustainability

In today's global landscape, sustainability has become a crucial concern, driven by growing awareness of environmental issues and the implementation of strict rules by governments and international regulatory bodies. Sustainable practices are crucial for preserving ecological, social, and economic health since they reflect the principle that natural resources are finite and must be used conservatively and strategically, with consideration for long-term implications. The concept of Industry 5.0 emphasizes the integration of human-centric technology and sustainability and highlights the importance of incorporating sustainable practices in manufacturing [3]. This industrial paradigm shift prioritizes not only technological advancements and efficiency but also highlights the importance of achieving a harmonious coexistence between the environment and society. In Figure 3, we can see a ven-diagram showing the three aspects of sustainability- environment, social, and economic impacts coming together.

For a high-tech global manufacturing company targeting to be successful and lead this new era, it is crucial to adopt an environment that prioritizes sustainable development as a core business strategy. Implementing such an environment means reassessing every aspect of the production process. This encompasses the procurement of sustainable raw materials, streamlining production processes to minimize energy usage and waste generation, and developing products that exhibit enhanced durability and recyclability. Furthermore, it entails allocating resources towards renewable energy sources and using green technologies that can effectively reduce the environmental impact of manufacturing operations. Sustainability in manufacturing encompasses more than just environmental factors. It also encompasses social obligations, such as guaranteeing equitable labor standards and making positive contributions to the well-being of the community. This holistic approach not only ensures compliance with regulatory requirements but also improves the company's standing among consumers, who are increasingly making purchase decisions based on corporate social responsibility. As the leaders of the modern world, enterprises must prioritize minimizing the negative impact of their actions on the environment and society. By doing this, they not only comply with international sustainability norms but also stimulate the development of environmentally friendly technologies, establishing new standards in the industry.

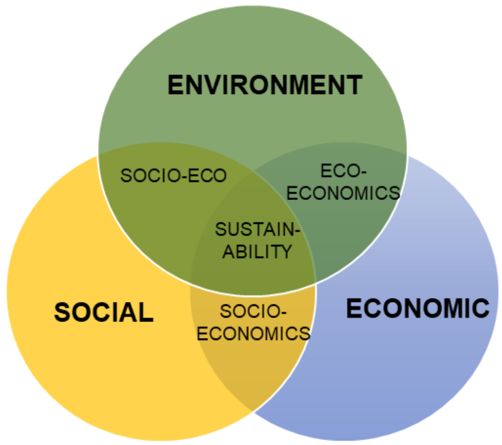

Figure 3. Aspects of Sustainability

(d) Human Centricity

Industry 5.0 marks a significant paradigm shift from the profit-oriented approach of Industry 4.0, prioritizing human-centered development goals [7]. This new phase recognizes that the unwavering drive for technological progress has resulted in considerable challenges, such as social inequality, ethical dilemmas, environmental degradation, and significant skills gaps within the workforce. In order to address these problems, Industry 5.0 advocates a model in which technological progress is balanced with the needs and well-being of the human workforce. A human-centric approach in high-tech global manufacturing enterprises prioritizes enhancing the interaction between humans and machines. This approach utilizes state-of-the-art technologies like Virtual Reality (VR) and Augmented Reality (AR) to construct immersive environments that enable workers to develop a more profound understanding of their operational surroundings while staying connected to the real world. Moreover, the integration of advanced human-interface technologies, including speech recognition, gesture and motion detection, and even emotion-sensing tools, are pivotal in augmenting human capabilities and performance.

For a high-tech global manufacturing enterprise, implementing a human-centric approach involves creating systems and processes that maximize both the well-being and productivity of employees. This entails not only deploying ergonomic and intuitive technology but also cultivating a climate where technology functions to augment human labor rather than supplant it. By implementing these measures, such companies can ensure that their technological advancements contribute positively to the workforce and society, promoting a more equitable, sustainable, and ethical industrial future. The success of a future-oriented manufacturing company will increasingly rely on its capacity to harmonize technological innovation with human-centric principles.

(e) Robustness

In the ever-changing landscape of global manufacturing, adaptability and robustness are critical characteristics for any future-oriented company. The volatility of market trends, combined with fluctuating customer demands, generates a company environment filled with uncertainties. Conventional models for system design frequently fail to completely comprehend the intricacies of real-life situations, emphasizing the necessity for a robust approach. In order to thrive, a high-tech global manufacturing company must, therefore, focus on the development of robust systems that are capable of withstanding diverse and challenging environments. This entails developing processes and systems that are not only robust but also intrinsically adaptable, enabling the enterprise to prosper amidst volatility. Implementing such systems involves adopting sophisticated techniques and models that will be able to manage uncertainties and can be easily adjusted as situations evolve.

Moreover, robustness also refers to the ability to strategically handle uncertainties without attempting to completely eliminate them, as this is unfeasible. Instead, the emphasis should be on establishing robust operational frameworks that sustain functioning and consistently offer acceptable performance, especially in the face of unforeseen adversities. This strategy not only guarantees a competitive advantage but also ensures long-term viability in a future where adaptability is synonymous with survival and success.

3. Challenges and gaps

A successful high-tech global manufacturing company must embody the above-mentioned characteristics. Nevertheless, incorporating these characteristics into the company system does not occur automatically. While designing a system of such characteristics, the designer faces significant challenges in incorporating those traits into the structure of the company. In order to address the challenges, a designer needs to have a clear understanding of the issues and then formulate effective methods to overcome them. The challenges that a successful manufacturing company faces while adopting the above-mentioned characteristics are shown in Figure 4.

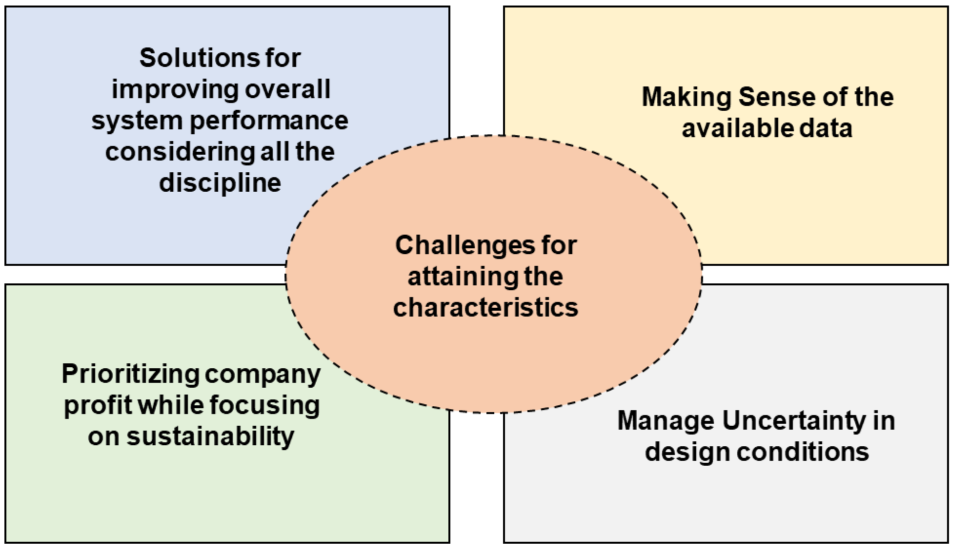

Figure 4. Challenges for attaining the characteristics of a successful manufacturing company

A detailed explanation of the challenges is as follows:

a) A high-tech global manufacturing company comprises various interconnected disciplines, each of which is sequentially linked to contribute to the realization of the final product. All the processes involving material selection, material supply, product manufacturing, delivery to the customer, and meeting the customers' requirements are connected and affect the final product. For example, manufacturing involves sequences of processes, each critically defining the properties of the product. However, enhancing the performance of one process can inadvertently have a detrimental effect on another due to the complex interdependencies within the system. In such an integrated system, in which multiple connections and diverse disciplines coexist, developing a system-wide solution that optimally enhances both the overall system performance and individual subsystems presents a significant challenge.

b) The pursuit of sustainability in a corporate enterprise requires the harmonization of three interconnected yet frequently contradictory elements: economic viability, environmental responsibility, and social equity. For many companies, profitability is the primary goal that traditionally influences their business decisions and strategies. However, incorporating sustainability into the business model often entails embracing activities that may not first prioritize financial returns. This presents a significant challenge: finding and executing solutions that effectively tackle both profitability and sustainability.

c) In the realm of engineering design and manufacturing, there is a widespread availability of data. When it comes to understanding and making use of the data this creates a significant challenge. The immense volumes of data produced by diverse research endeavors surpass the cognitive capacity of humans to evaluate and understand efficiently. Moreover, the selection of models that are suitable for the business enterprise and the proper utilization of research data in the industry pose another challenge in the data analytics implementation of a successful company.

d) Dealing with uncertainty during the design process is a major difficulty in the manufacturing industry, especially for enterprises that aim to maintain robustness in volatile market situations. The complexity of this challenge is further intensified by the inherent limitations in the models employed throughout the design phase. These models, which are often incomplete and differing in fidelity, might result in the adoption of solutions that, although beneficial in certain circumstances, are highly vulnerable to unforeseen factors and changes.

Addressing the complex challenges faced by high-tech global manufacturing companies leads to finding the presence of several critical gaps in the systems design approaches used by the industry. These gaps can be outlined using three main categories:

1. A systematic approach to look into the design spaces of the enterprise that involves multiple different disciplines, which are contradictory in nature.
2. A systematic approach to visualize the design space and the solution space and make sense of the research data.
3. A systematic strategy to carry out robust design exploration by managing uncertainty.

From a systems design perspective, design is a top-down, goal-oriented, decision-based process. This approach has led to the development of Decision-Based Design (DBD) [8, 9]. Decision-making in the engineering process is largely sequential. This is particularly helpful for designing systems that do not have the complex integration of different subsystems. However, while a designer is trying to improve the performance of an overall system comprised of subsystems with intricate connections by simultaneously looking into individual subsystems, sequential decision-making may cause the deterioration of the overall performance due to potential conflicts or inefficiencies that arise between the subsystem decisions. Therefore, we require an approach that facilitates the simultaneous design exploration of complex design spaces across multiple disciplines. This approach should facilitate the efficient identification of satisfactory solution regions that satisfy both the individual goals of the various disciplines involved and also improve the performance of the overall system. Such an approach ensures that decision-making is holistic and integrative rather than isolated and sequential.

To facilitate all these and address Gaps 1 and 2, the idea of "co-design exploration" can be used. Co-design exploration is using the capacity of distributed designers or decision-makers from different disciplines to collaboratively share their information, knowledge, and resources in an integrated fashion to achieve the simultaneous design exploration of the overall system. In Figure 5, we show the avenues that co-design exploration brings together. The idea allows the integration of multiple disciplines with information sharing between the disciplines and finally creates a visualization of design and solution space for better comprehending the system.

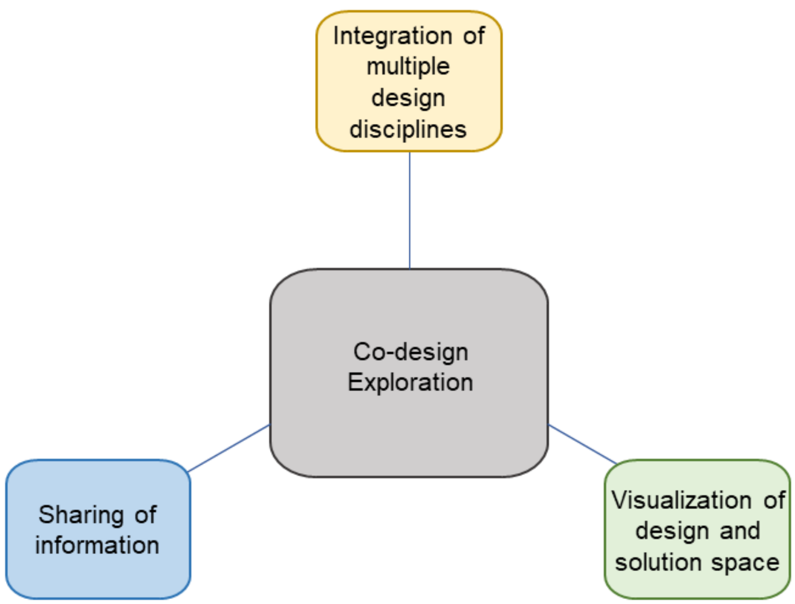

Figure 5. Avenues of Co-design Exploration

The challenge of uncertainty in design scenarios can be handled by employing two main strategies: mitigation and management. Mitigation or reduction of uncertainty requires identifying perfect models, collecting more data, and developing improved methods to model, calculate, and quantify uncertainty. Although effective, this approach typically necessitates extensive computational resources and can be both time-consuming and costly. Alternatively, managing uncertainty is less computationally expensive. This involves designing systems relatively insensitive to uncertainties without reducing or eliminating them, termed *'robust design.'* The focus of robust design is on ensuring that the system's performance remains stable under varying conditions. Three types of robust design - Type I, Type II, and Type III deal with uncertainties associated with random noise, design variables, and models, respectively [10]. In order to facilitate robust design, specific metrics such as the Design Capability Index (DCI) [11] and the Error Margin Index (EMI) [12] are employed. These indices help identify robust solutions that can withstand variations in systems while maintaining satisfactory performance levels.

4. Framework for the design of a multidisciplinary enterprise

The design of a multidisciplinary system is quite complex due to the presence of complex interactions of the subsystems present in the system. Several multidisciplinary design optimization (MDO) approaches [13-16] can be used that focus on the couplings between the disciplines to identify solutions that satisfy the designers' requirements at the individual disciplines. However, MDO approaches employ rigorous and iterative optimization techniques that involve extensive optimization loops within and between disciplines to identify unique single-point solutions. When the designers are focused on design exploration in the early stages of design and quickly identifying satisfactory regions of interest, MDO approaches pose a challenge. Designers tend to look for regions that both satisfy and suffice the designer's requirement for multiple disciplines and are relatively insensitive to uncertainties. Such solutions are defined as 'robust satisficing solutions' [17].

Based on the idea of finding satisficing design regions, a Co-Design Exploration of Multilevel systems under Uncertainty (CoDE-MU) framework [18] is developed that supports the co-design exploration of multilevel design spaces and identifies satisficing solutions that are common within and between disciplines and insensitive to uncertainty. A multilevel decision support framework for simultaneous design exploration is used in material structures and processes to demonstrate the usage of a common design variable for information propagation between disciplines [19]. Using the ideas and tools used in these frameworks, in this essay, we propose a multidisciplinary co-design framework that,

(i) Uses the research data available.
(ii) Considers the interaction of multiple different disciplines and the conflicting goals for improving overall system performance.
(iii) Uses the human designer's capability for decision-making.
(iv) Manages uncertainty.
(v) Allows simultaneous visualization and exploration of the design space to support co-design.

This framework adopts the co-design method. In the framework, three primary constructs are employed.

(a) Coupled-compromise Decision Support Problem (c-cDSP):

In DBD, design problems are modeled as Decision Support Problems (DSP) using Decision Support Problem Techniques (DSPT) and constructs [20, 21]. In DBD, decisions are made using information generated from simulations. The compromise Decision Support Problem (cDSP) [22] construct is used to formulate and solve design problems involving many conflicting goals. Using the cDSP, designers seek satisficing solutions through design exploration and trade-offs. The c-cDSP [23] is a cDSP construct that supports designers in modeling decision problems involving multiple goals within and between multiple decision levels. The c-cDSP construct is used to model the relationships and consider the decisions across various design disciplines. The primary focus of using the c-cDSP is to identify solutions that *minimize* the total deviation of all the design goals in the system from their target values, referred to as the 'd*eviation function*.' The deviation function in c-cDSP is modeled using a combination of the Preemptive and Archimedean formulations.

(b) Robust Design Constructs: Design Capability Index (DCI) and Error Margin Index (EMI)

The DCI and EMI robust design constructs, in combination with the DSP construct, help designers manage uncertainties by facilitating the identification of robust solutions. Using the DCI construct, designers can account for design variable uncertainties, whereas using the EMI construct, designers can consider uncertainties in the models. Identifying solutions with values of DCI ≥ 1 and EMI ≥ 1 will ensure system robustness to uncertainties. The higher the DCI or EMI values, the higher the safety measure against failure due to uncertainties.

(c) interpretable Self-Organizing Map (iSOM) visualization tool

interpretable Self-Organizing Map (iSOM) [24] is a machine-learning-based visualization tool that helps to efficiently visualize high-dimensional data using two-dimensional (2D) plots. Specifically, it is a modified form of the conventional Self-Organizing Map (SOM) [25]. The modifications to SOM help avoid self-intersection, making the iSOM plot interpretable. iSOM is a scalable visualization tool that can be used to visualize any number of dimensions.

The multidisciplinary co-design framework is composed of three modules – Modules 1, 2, and 3. The framework, along with the functionality of each module, is depicted in Figure 6.

Module 1: Data Utilization Module

Within the context of Decision-Based Design (DBD), decisions are mostly influenced by information obtained from simulations. And there is an abundance of data present in engineering research. These two are the foundation of this module, which highlights the importance of using the available data and formulating models for efficient system design. When starting the design of a system, a designer initially looks for established mathematical models that describe the system's behavior and the interactions between its components and disciplines. The mathematical models are crucial for comprehending how different disciplines in the system influence each other. Designers may choose to create surrogate models for cases where specific mathematical models are absent or insufficient to describe the system thoroughly. Surrogate models are created by utilizing existing data to simulate the behavior of the system. These models are crucial for the problem formulation module as they help formulate the goals and constraints and identify system variables in the design problem. These models are crucial, as they not only depict the system but also establish the connections between different disciplines engaged in the design process. By establishing a clear and precise model of the interactions between disciplines, surrogate models facilitate a more integrated and holistic approach to system design, ensuring that all relevant factors are considered in decision-making.

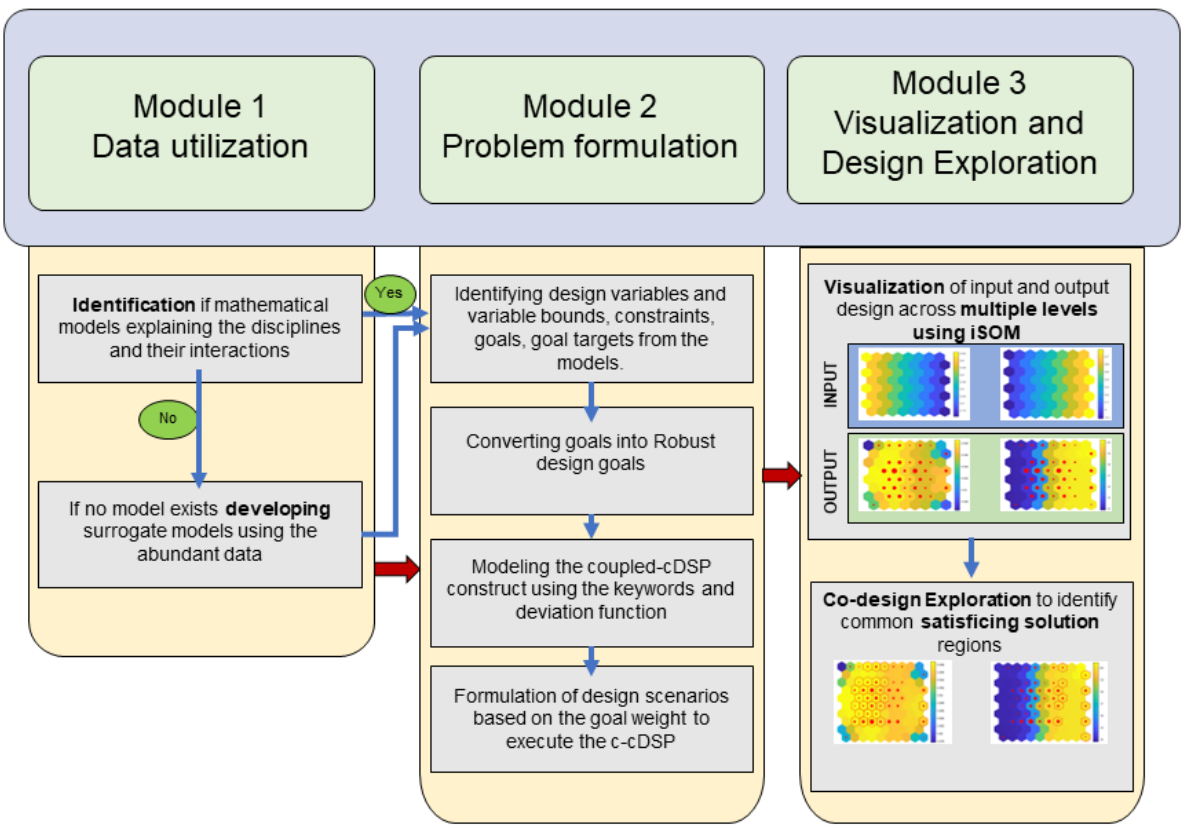

Figure 6. Multidisciplinary co-design Framework

Module 2: Problem Formulation Module

Module 2 represents a critical part of the framework, which focuses on problem formulation once suitable models have been identified or developed in Module 1. Within this module, the designer utilizes the identified/developed models to define discipline-specific goals, constraints, variables (including shared design variables), and information propagation among the disciplines. Then, the design goals of the specific disciplines are formulated as robust goals using the DCI and EMI construct. Goals affected by design variable uncertainties are formulated as DCI goals where, whereas goals impacted by model uncertainties are modeled as EMI goals. Taking the robust goals, constraints, and variables, we formulate the c-cDSP construct, which is the core section of this module. This construct is essential in modeling multidisciplinary design problems and capturing the complex interactions across multiple disciplines. In the c-cDSP, separate instances of the c-DSP construct are used to model decision problems in the individual disciplines. The *Given*, *Find*, and *Satisfy* keywords of the cDSP constructs help capture discipline-specific information. The interactions among the cDSPs for each discipline are modeled using the shared design variables and other propagated information connecting the discipline. The deviation function of the c-cDSP is modeled using a combination of Preemptive and Archimedean formulations. After the formulation of the c-cDSP, different design scenarios are created based on the weight of the individual goals. Finally, the c-cDSP is executed for the different design scenarios to generate multiple solutions that define the solution space. This concludes the problem formulation module.

Module 3: Visualization and Design Exploration Module

Module 3 is the final module of the framework. This module utilizes the results generated from Module 2 to visualize the solution space. The iSOM visualization tool is utilized in this module. The iSOM algorithm is trained using the design scenarios' weight and the corresponding goals' values. The trained iSOM generates 2D plots for each input weight and output goal across multiple disciplinary levels. Designers use the iSOM plots of the output goals to carry out co-design exploration. The iSOM plots for the goals are then simultaneously explored to determine common satisficing solution regions for the goals across multiple levels. A systematic co-design exploration method is used to determine the common satisficing solution. When a common satisficing solution is identified, the designer then identifies the design scenarios and the variables and goal values for the satisficing design solutions.

The multidisciplinary co-design framework that we present in this essay helps effectively tackle the complex challenges a manufacturing enterprise will experience by 2040. By utilizing this framework, the enterprise can cultivate the essential characteristics required for success by proactively addressing the challenges. This framework functions as a crucial tool for designing, guaranteeing that the essential characteristics of a successful company are incorporated from the beginning. Using the modules of the framework designers are able to address each of the gaps and instill the characteristics of a successful enterprise in the company. Gaps 1 and 3 can be addressed using Module 2, which allows for the co-design of the system with uncertainty. The research Gap 2 of making sense of research data is addressed using Module 1, while using Module 3 the visualization and design space exploration part of Gap 2 is addressed. During the design, the interconnectivity and the sustainability of the company are prioritized through the co-design exploration of Modules 2 and 3. This approach facilitates the development of a company structure that is advantageous to all parties and systems concerned. Using the framework, it is guaranteed that all interactions are considered and improves overall systems performance. Using Module 1 designers develop suitable models to incorporate data analytics into the structure of the enterprise. The utilization of iSOM visualization tool facilitates the conversion of intricate data into easily readable visual insights, hence improving decision-making processes. The use of this framework strongly emphasizes on human-centricity, meaning that decisions are based on and responsive to studied data, guaranteeing that human judgment is important for the final decision which is facilitated by the visualization tool in Module 3. Furthermore, utilizing several matrices to address uncertainty in Module 2 strengthens the robustness of the system.

5. Closing Remarks

With the advancement of technology, a high-tech global manufacturing company needs to adapt and thrive. In order to maintain a competitive edge and meet customer expectations, such organizations must include the characteristics of a successful enterprise within their organizational structure. In this essay, we explore interconnectivity, data analytics, sustainability, human centricity, and robustness, which define a successful manufacturing enterprise. Interconnectivity emphasizes the necessity of the enterprise to be more connected by sharing information among internal disciplines and external entities. Sharing information between the internal disciplines and external entities allows the manufacturing enterprise to be aware of the customer requirements, supply chain issues, and the ability to produce a required product, which helps the company decide on a solution that satisfies the requirements of different individual sectors. The sustainability of a manufacturing enterprise comprises environmental factors, social obligations, and economic growth. This characteristic is crucial for an enterprise to adapt as it helps preserve ecological and social health while also giving importance to the company's economic development. Introducing data analytics into the company structure allows the company to take advantage of the available data and modern technologies such as AI, machine learning, and IoT. The models built using the data help the human designer analyze the complex interactions between multiple internal disciplines and external entities. Introducing a human-centric approach in a company culture allows the enterprise to prioritize a system that focuses on the company's well-being and allows the human to play a vital role in the decision-making process. And finally, robustness enables the enterprise to handle uncertain scenarios, which ensures the long-term viability of the enterprise. To continue to thrive in the future, a manufacturing company must integrate these characteristics into its organizational structure, enabling it to adapt to technological innovations, comply with government regulations, and meet customer demands.

In order to address the challenges that a company encounters when incorporating the characteristics to be successful, we propose a multidisciplinary co-design framework. Using this framework a designer is able to incorporate these characteristics into the enterprise's structure during the design phase, resulting in several significant contributions to the company culture. Firstly, via the framework, the enterprise can take advantage of the years of research data through data analysis and then involve human decision-makers to interpret the data. The decision-making prioritizes the human centricity of a manufacturing enterprise while taking advantage of the strength of data analytics. Secondly, using the framework, the designer is able to consider multiple disciplines simultaneously under uncertainty. With the co-design of multiple disciplines, the designer is able to improve the interconnectedness of the enterprise, facilitating interaction among different internal disciplines and external entities. Using the co-design approach the designer considers the interactions between disciplines and entities and aims to find satisfactory solutions for all conflicting goals, simultaneously enhancing overall system-wide performance. In addition, using co-design in the context of sustainability goals enables the organization to effectively handle and satisfy several conflicting goals related to sustainability and performance simultaneously. Using the robust design matrices in the co-design allows the framework to address uncertainty and be robust. The framework is generic and is able to be used in any system with suitable models and research data that will improve the system's performance.

For a company operating in 2040, adopting such a framework in the design of the company is crucial, using which the company is able to integrate the characteristics of a high-tech global manufacturing enterprise into its culture, ensuring it remains competitive and relevant in a rapidly evolving technological landscape.

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