DECISION SUPPORT FOR DESIGN OF SMART AND CONNECTED PRODUCTS, PROCESSES AND SYSTEMS OF THE FUTURE

Sachin Hebbale Lokesh
Plaksha Tech Leaders Fellowship, Purdue University

Introduction – The scenario

The global high-tech design and manufacturing sector is one where the competition has always been fierce. These types of enterprises are constantly seen fending of threats from other large players. The leaders in this sector have been the ones that discovered creative and innovative ways to differentiate themselves from their competition. These enterprises always keep abreast with the changing market demand and advancements in relevant technologies. It's generally observed that they always make it a part of their culture to absorb, adapt and utilize any sets of tools, techniques, and practices that will aid them in delivering greater value to their customers. For these enterprises, CUSTOMER SATISFACTION is paramount. In essence, successful global high-tech design and manufacturing enterprises are the leaders in innovation, technology adoption, and market research, and in the process, they are able to deliver greater value to their customers.

In the recent past, the advent of Industry 4.0 [1] and its growing adoption by the manufacturing sector has seen industries in the sector developing greater prospects of gaining substantial benefits in the form of improved productivity, quality, and customer satisfaction [1]. Industry 4.0 is based on the digitization of the manufacturing industry. This digitization is not limited to the way the products are manufactured but also has its implication on the product design, the supply, and logistical aspects, and on the post-sales service and support domains. With such widespread implications across the value chain, an overhaul of the existing product, process, and system design methods and practices becomes a necessity. The current system-oriented design engineering philosophy will thus give way to a novel design engineering philosophy for smart, networked, and digitized products, processes, and systems – Design Engineering 4.0 [2].

High-tech Design and Manufacturing Enterprises & Design of Products, Processes, and Systems

Global high-tech design and manufacturing enterprises can be considered as complex systems due to the complex and extensive nature of their interactions, be it with suppliers, dealers, customers, and production facilities across the globe. For such enterprises to be successful, they should be able to design products, processes, and systems that help them offer better value to their customers.

Design is essentially a decision-making process where the choices that best meet the designer's requirements are made based on the information available at a given point of time, and hence the concept of Decision Based Design (DBD) [3]. Given this nature of the design process, it is clear that the best designs are produced when the best choices or decisions are made, and to ensure the same, the existence of two factors are crucial. They are:

a. Necessary data or information (both in terms of quality and quantity), and
b. A decision support system to support the complex decision-making process, given

the complex nature of such enterprises, hence the success of these enterprises will depend on their ability to design products, processes, and systems that will help them tackle the challenges brought about by the growing adoption of Industry 4.0, which as stated earlier has its impacts across the entire value chain.

In this context, 4 core design focus domains for the future are identified. They are:

a. Smart-connected product design
b. Design of distributed, networked, and digitalized production systems
c. Intelligent supply chain design and
d. Smart service and customer support system design

These domains have been shown in Figure 1 and are discussed in detail in the following sections.

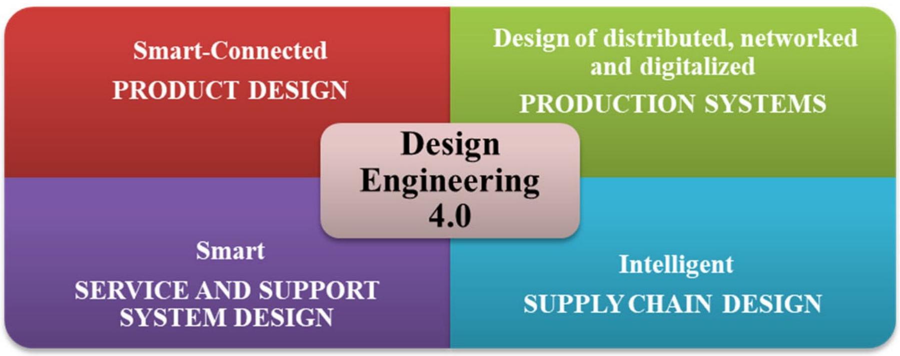

Figure 1: Design domains of the future

1. PRODUCT DESIGN

The future of product design is Co-design, where the customer or end-user and the designer work together to realize product design. This may be achieved by:

i. <u>Extensive Market Research for Product Portfolio decisions</u>

For making decisions regarding product portfolio, extensive market research is vital as it will result in a better understanding of the changing customer needs and competition. This process will result in the generation of large amounts of data. Analysis of this large pool of complex data possibly by Big Data analysis [4,5] will generate relevant information to support the product portfolio design problem. By developing a suitable decision support framework and using the generated information it would be possible to automated this decision-making process to an extent. Machine Learning could be one tool that could help with thisautomation.

ii. <u>Analysis of Product usage, environmental and health data for future design improvements – ADAPTIVE DESIGNS [6]</u>

Industry 4.0 has pushed the product design process, its visualization, and prototyping to go digital in its relentless push towards digitalization. The adoptionof IoT into product design, which also came about as a result of Industry 4.0 has made modern products smarter and connected. The embedded sensors in these newage products will help monitor the real-world usage patterns, operating environmental conditions, and health of any product and relay the same informationin real-time. These usage, operational environment, and product health data can beused to identify novel product use case scenarios, feature requirements, component or sub-system functional criticality etc., thereby aiding future product redesign decisions, through a decision support framework.

Another design problem that needs close attention is the design of productsand systems under limited data. This could be addressed by adopting agile product development methodology which is an iterative approach to product development that is performed in a collaborative environment by self-organizing teams [7].

iii. Modular design and platforms

The future of manufacturing is mass customization or personalization. Thus, the current practice of designing standardized products will not suffice. Hence, there arises a need for modularization of designs. This requires the design of modular platforms and components, which again is a decision problem. Like the product portfolio design decision problem, modular design decisions can also takeinto account customer inputs and use a decision support platform based on machinelearning, to aid decision making. [8]

The variety of design decision that needs to be made during product design is shown in Figure 2.

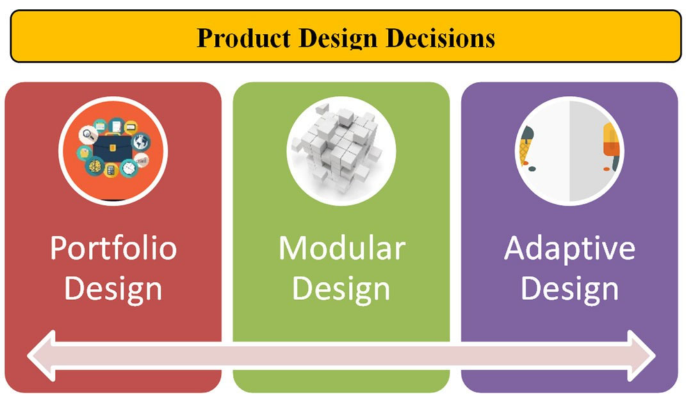

Figure 2: Product Design Decision Domains

2. PRODUCTION SYSTEMS DESIGN

For an enterprise with a global operational footprint, it is highly likely that the production facilities are distributed across the globe. For such a widely dispersed network of production facilities to be successful at delivering quality products, in the right quantities, at the right time and price as per customer requirements, it is of utmost importance that they are networked or connected for effective coordination. Hence, Industry 4.0 emphasizes the need for digitalization of production systems. Additionally, this connected nature helps with the ability to remotely monitor and control the production system.

Secondly, the design of future production systems should adopt IoT and smart sensors. This along with the networked nature of the production system should help with building a certain level of autonomy in production systems. Smart Predictive maintenance systems can be established by using condition data and allied decisions support systems which may use machine learning algorithms to predict the need for maintenance. One might also explore the possibility of designing production systems to be self-organizing. This can be done by designing a decision support system that will enable local level interactions and decision making as is the case with self-organizing systems, where it is observed that local interactions lead to a global behavior [9]. Such self-organizing systems do not need a centralized control system, rather, they use local interactions to take local decisions.

One other major area of concern in the design of future production systems is its need to be flexible, which generally comes at the cost of higher capital expenditure. This need for greater flexibility arises due to the increased need for mass customization, where customers demand customizability while maintaining the economic benefits of mass production. This being a design problem with goals that are of conflicting nature might be solved as a cDSP (Compromise Decision Support Problem) [10,11,12], to determine an acceptable level of flexibility while ensuring economy. In figure 3, we show the essential aspects that should be accounted for during the design of future production systems.

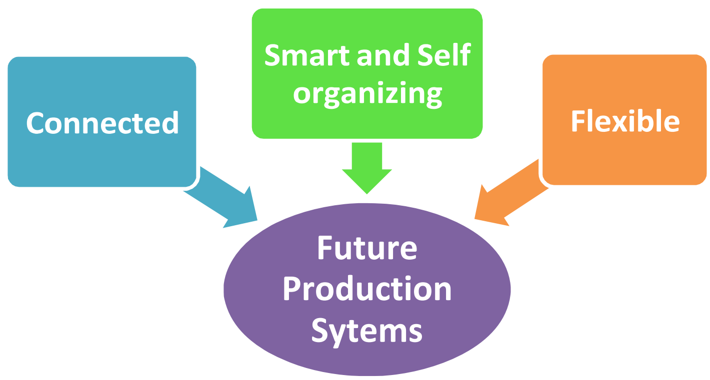

Figure 3: Production systems of the future

3. SUPPLY CHAIN DESIGN

The supply chain of the future should be designed to be intelligent to adapt most effectively to the ever-changing supply and demand patterns. This will require all the supply chain entities to be connected and communicating, which can be done over the cloud. One design aspect that can be explored is the possibility of using real-time supply chain data monitoring and together with a suitable decision support model in creating a smart supply chain. This real-time data-driven decision-making is bound to make the design more robust under uncertain operating environments [13,14]. Self-organization principles can also possibly be considered for integration into the design of the supply chain just as with production systems thus requiring reduced human intervention.

4. SERVICE AND SUPPORT SYSTEM DESIGN

The final key component for a successful global high-tech design and manufacturing enterprise is a customer support and service network that can handle the myriad needs of customers located across the globe. Hence, a smart and connected global customer service network becomes the need of the hour.

The design of such a global level connected service network may be realized using a cloud-based service network that makes it possible to provide near-uniform levels of service to all customers. Additionally, these service networks have to be designed to be smart as well. This is made possible by designing the products with smart and connected features that will enable the enterprise to access relevant usage, diagnostic and environmental data. This data can then be used to do the following:

a. Real-time fault identification and rectification based on diagnostic and operational environment data
b. Develop product updates and feature additions based on usage data analysis
c. Remote service support by ensuring cloud-based product-service connect

Using figure 4 we depict the essential aspects that should be taken into account while designing supply chains and customer support systems for the future.

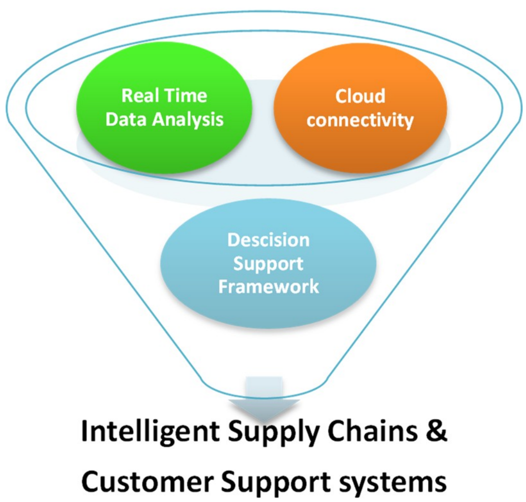

Figure 4: Components of Intelligent supply chains and customer support systems

Design Method and Decision Support Framework

The design of products, processes, and systems are essentially multilevel and multistage design problems for which a goal oriented inverse design method [9] can be adopted. The concept exploration framework (CEF) [9] is one decision support framework that can be used to identify design alternatives and generate satisficing design solutions. The primary mathematical construct used in the CEF is a compromise decision support problem (cDSP) [9,10,11]. The cDSP is a hybrid of mathematical programming and goal programming. Target values for each goal are defined in a cDSP and the emphasis of the designer is to satisfy these target goals as closely as possible under constraints by minimizing a deviation function - a function formulated using the deviations (captured using deviation variables) that exists from the goal targets. This is achieved by seeking multiple solutions through trade-offs among multiple conflicting goals.

Figure 5 depicts the architecture of the CEF. Application of the CEF begins with the designer identifying the overall end goal design requirements for the problem under study. Subsequently, the various control and noise factors, their ranges and the influence of these factors (response) are identified. In parallel, the designer identifies the models available or required and available theoretical and empirical models are identified and are communicated to the cDSP. In situations where models for the problem are not available or if there is a need to develop surrogate models so as to reduce the size of the problem, an experiment is designed using the point generator to develop them. The simulation program runs the experiments and the experiments analyzer, evaluates the simulation results and recommends additional experiments if needed. Using the simulation program results surrogate models are created and are communicated to the cDSP. The cDSP is then exercised for different design scenarios. These scenarios, which are identified by assigning different weights to the deviations associated with the goals, define a solution space which is further explored to identify feasible solution regions that satisfy the requirements. These feasible solutions are then evaluated by a human designer to make final design decision.

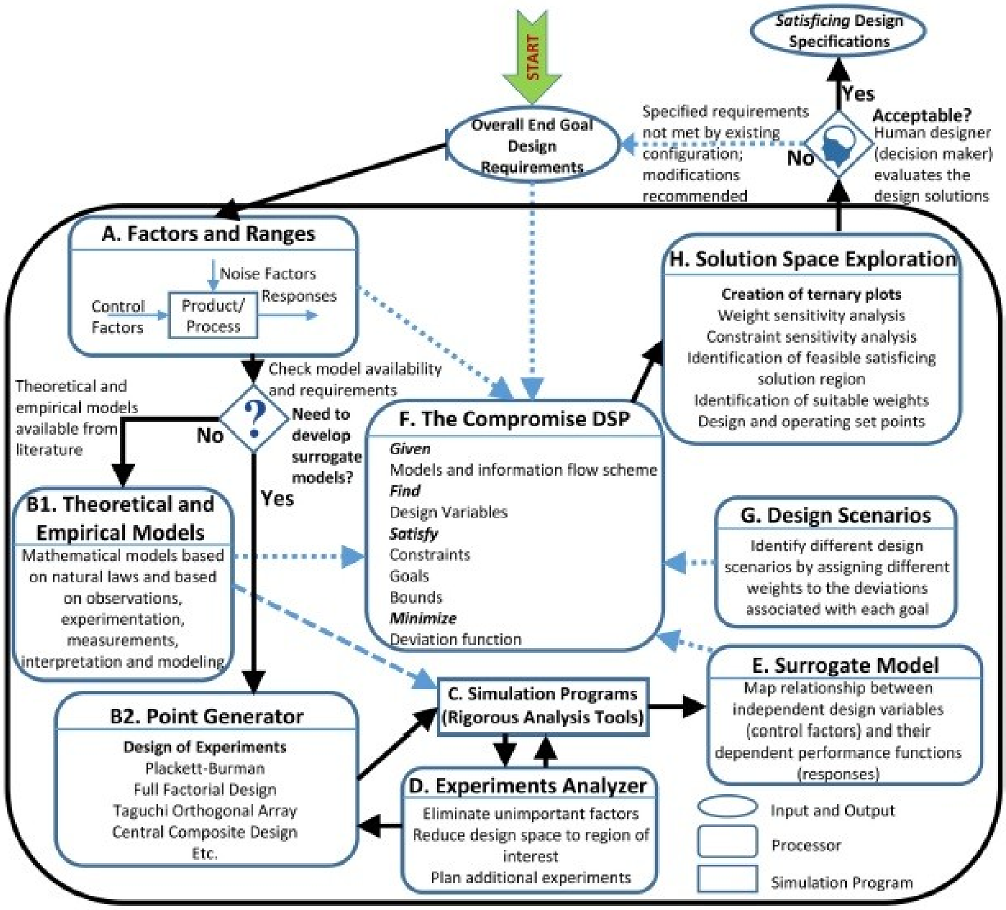

Figure 5: Concept Exploration framework (CEF) to support Decision Making during Design [9]

Figure 6 illustrates how a goal oriented inverse design method can be implemented using cDSP which is built into the CEF framework in the case of multistage manufacturing process design problem for producing products that need to meet specific performance requirements. Initially, during the forward modeling phase, mathematical models are either identified or developed for each stage of the design process and they are then connected in the correct sequence for proper flow of information. Here, the output responses of one process acts as the input factors for the next and this continues until we arrive at the final product. E.g. The output response of stage 'n' will be the input for stage 'n+1'

Next, cDSP's are formulated for various stages of the design process in the reverse direction, starting from the last stage of processing which results in the final product. The goals and requirements i.e., the inputs, for a particular cDSP are derived from the corresponding stage in the forward modeling and the output obtained by exercising a cDSP for the previous stage. Hence, such a sequential decision making across the decision chain in the reverse direction will finally deliver satisficing values of input factors for stage n that meet the end goals

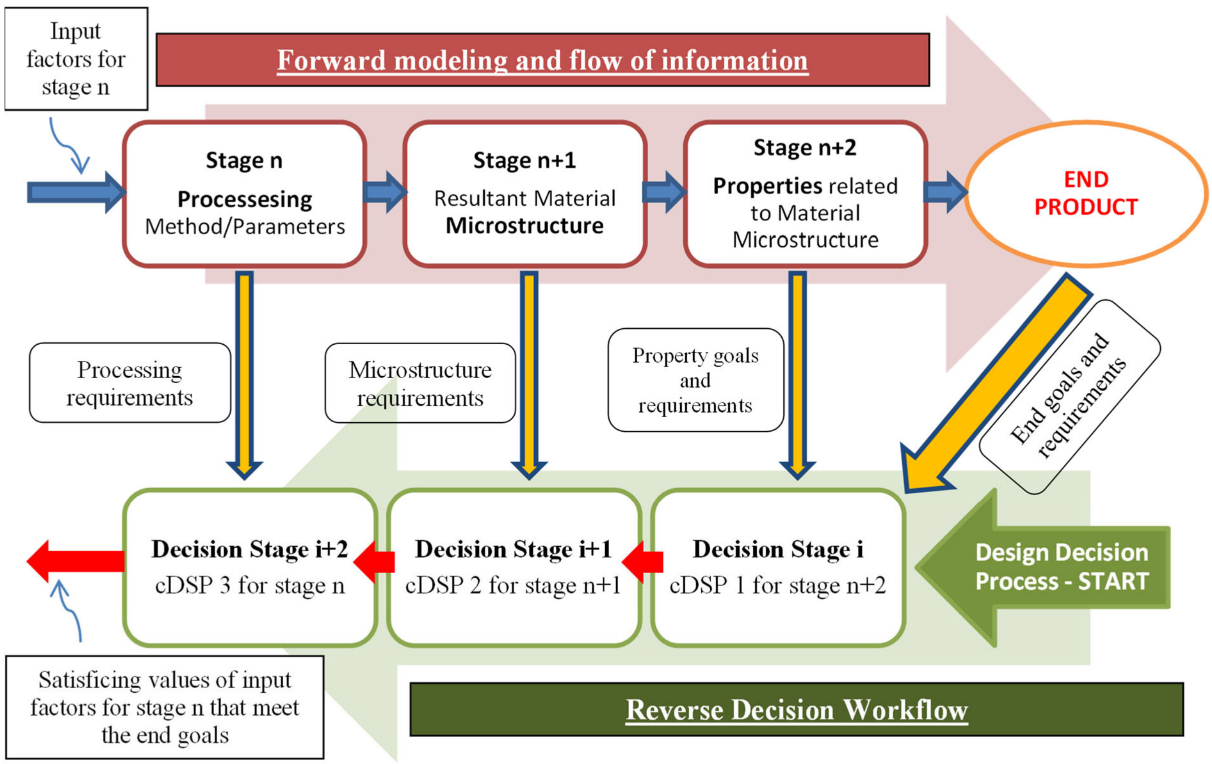

Figure 6: Information and decision flows in goal oriented inverse design method

Closing Remarks

For a global design and manufacturing enterprise to be successful, it has to remain highly competitive and offer better value to its customers. With the ever-growing adoption of Industry 4.0, its widespread effects across the value chain, constantly changing supply & demand patterns, and ever-increasing customer demand for product personalization, the key to success lies in the ability of enterprises to design products, systems, and services that can adapt to these challenges. Such designs can only be developed by designing or making use of suitable decision support models or systems. These systems use real-time data to make decisions and hence develop the most appropriate designs. Thus, key design domains that require extensive development for a global high-tech manufacturing and design enterprise to be successful in the future are:

1. Cloud-based connected production and supply chain networks
2. IoT based product design with smart sensor integration
3. Real-time data collection and big data analysis for design decision support under

conditions of uncertainty

4. Incorporation of self-organization features into production systems and supply chains

Development of suitable decision support frameworks that can effectively utilize real time big data processing will be the need for the future. One possible decision support framework that can be adopted is the CEF. Other systems like Big Data analytics, Machine Learning etc. can be explored further to understand how they can be effectively utilized to support design decisions. On the opposite end of the spectrum there lies another design problem that needs close attention -the design of products and systems under limited data. This could be addressed by using an agile product development methodology.

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