Model-based Systems Engineering in Smart Manufacturing - Future Trend toward Sustainability

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Abstract. Creating a more agile and productive industrial base using intelligent and emerging technologies relying on systems engineering is not only a progress key for any entity regardless of its size but also is the durability factor in the nowadays competitive industrial environment. Therefore, to promote the traditional document-based information exchange, serial design procedures, and single disciplinary analysis, systems of systems thinking would need to be expanded in organizations. This strategy should be implemented from the beginning of the project definition and stakeholder needs to the entire product development process throughout the V-diagram and persists throughout the product's operational life. Despite recently developed tools and significant growth and movement from the level of Industry 1.0 to 4.0 toward smart manufacturing, many researchers are still trying to push the boundaries of manufacturing. However, companies have faced many challenges in addressing such technology growth trends in their long-term enterprise strategy and design. Although the Model-based Systems Engineering (MBSE) tools by visual modeling of the communication of the information alleviate some difficulties for companies in many respects, bridging between systems-level decisions, design requirements, and sustainability dimensions through connecting MBSE and Multidisciplinary Systems Design Optimization (MSDO) can promise strategic advantages and innovation. Providing such a combined tool with visual modeling helps manufacturers trace the effect of their decisions and achieve sustainable manufacturing goals faster. By reviewing the application of MBSE in smart factories, this paper will provide future research fields for further development to enable sustainable innovation in manufacturing and factory design.

Keywords: Smart Manufacturing, Sustainable Manufacturing, Systems Thinking, Model-based Systems Engineering, Multidisciplinary Systems Design Optimization.

1 Introduction

Despite supply crosswinds and instability of the marketplace, the manufacturing industry strongly persists to surpass the expectations of previous years [1]. Leading companies strive to create a digital environment that allows them to achieve dimensions of sustainability space (i.e economic, environmental, and social sustainability) as much as possible through a concurrent procedure. On the other hand, the level of innovation maturity within factories has a remarkable impact on their competitiveness and profitability. Therefore, creating a more agile and productive industrial base using intelligent and emerging technologies relying on systems engineering is not only a progress key for any entity regardless of its size but also is the durability factor in the nowadays competitive industrial environment. As the level of digital transformation defines the level of innovation maturity companies have achieved, leaders should leverage digital technologies, adopt intelligent strategies for future products, and drive whenever possible toward sustainability [2, 3]. In this respect, this paper explores that Model-based Systems Engineering (MBSE) relying on systems of systems thinking strategy should be at the top of the agenda for many companies which try to survive and improve productivity. Therefore, the triangle of intelligent manufacturing should cover Innovation, Digitalization, and System Thinking, to companies keep pace with technology (Fig. 1).

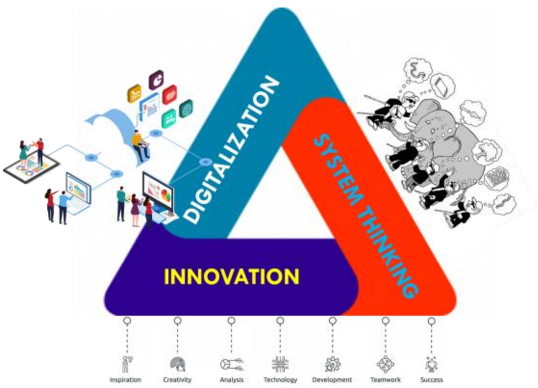


Fig. 1. The triangle of systems engineering induced intelligent manufacturing.

On the other hand, with the substantial increase in demand for personalized products, manufacturing architecture has become extremely complex both in terms of concept and structure. Designing such a factory deals with several internal and external collaborations at the system level as well as mechanical, electrical, automation, and other relevant fields at the sub-system level, which further reveals the need to consider a Multidisciplinary Systems Design and Optimization (MSDO) framework. In the last decades, lots of research addressed the topics of digital twins (DT) [4, 5], MBSE [6, 7], and MSDO [8, 9] separately. Also, several literature reviews have been done on each topic [10, 11]. Despite many followers in these fields, today we need all of them in one framework. While MBSE is expanding in the manufacturing industry, new methodologies based on Systems Engineering (SE) concepts have been developed to adapt the manufacturing procedure to new demands, in which the system's architecture and requirements are followed concurrently through the product life cycle from design and development to manufacturing and retirement/replacement. These new methodologies which call the agile approach and rely on MBSE and MSDO have been trying to bridge the gap between mentioned critical subjects [12]. The ability of agile methodologies as practical improvement in engineering and other fields has been demonstrated in many companies [13].

However, one of the vital challenges in current manufacturing processes is that DT, MBSE, and MSDO are performed as three different activity streams, based on separate tools and requiring specific expertise. In the future industry should benefit from the capabilities of all three SE, DT, and MSDO methodologies in dealing with complex manufacturing problems.

To address these issues, in the following, a brief overview of key parts of this paper including the industrial revolution, MBSE, and MSDO presented. Then, in the discussion section, some research initiatives with a focus on bridging between MBSE and MSDO are highlighted. Finally, the paper is ended up with an outlook on future directions within manufacturing toward sustainability.

2 Design and Optimization Methodologies

The topic of optimality and productivity in presence of variation and uncertainty that are inevitable parts of any manufacturing and assembly of complex real-world systems is not a new one. It goes back to Six Sigma and the reliability concepts in the early 1990s when William Smith, a reliability engineer at Motorola, proposed the concept of Six Sigma to alleviate the high failure rate of Motorola's products. After that, many companies like Motorola, General Electric, Allied Signal, Black and Decker, Honeywell, ABB, and Bombardier proclaimed that they had impressive business performance achieved through this strategy [14]. Design for Six Sigma (DFSS) behaves as a management strategy that helps companies provide an efficient roadmap to improve manufacturing procedures to eliminate defects in products, processes, and services. According to DFSS, many procedures such as DMAIC (i.e. Define, Measure, Analyze, Improve, and Control) or DMADV (comprising Define, Measure, Analyze, Design, and Verify) had emerged to help certify the final quality of the product [15]. The role and situation of considering DFSS and DMAIC/DMADV in the product life cycle are presented in Fig. 2.

Fig. 2. DFSS and DMAIC/DMADV in the product life cycle

However, the traditional optimal design process which is based on a sequential approach although has its advantages, it does not include online interdisciplinary interactions and finally leads to local optimality and complexity in the decision-making as well as a gap between product design and prototype manufacturing [16]. Despite these challenges and as the traditional method is time-consuming with inevitable iterations on the whole design and development process, the engineering community had been needed a paradigm shift in design methodology for complex engineering systems. To overcome or at least alleviate those problems, new methodologies known as Concurrent Engineering (CE) and Multidisciplinary Design Optimization (MDO) had been developed which are relying on parallelization. A schematic comparison between the traditional and CE methods is illustrated in Fig. 3 [17]. CE aims to provide a balanced design through full and formal multi-disciplinary integration and optimization concurrently in all disciplines [18]. Also, one of the popular definitions of MDO is "*a methodology for the optimal design of complex engineering systems and subsystems that coherently exploits the synergism of mutually interacting phenomena using high fidelity analysis with formal optimization*"[19]. Publishing lots of literature in these fields demonstrates the successful application of CE and MDO on various engineering projects from design to manufacturing in the last decades [20-22].

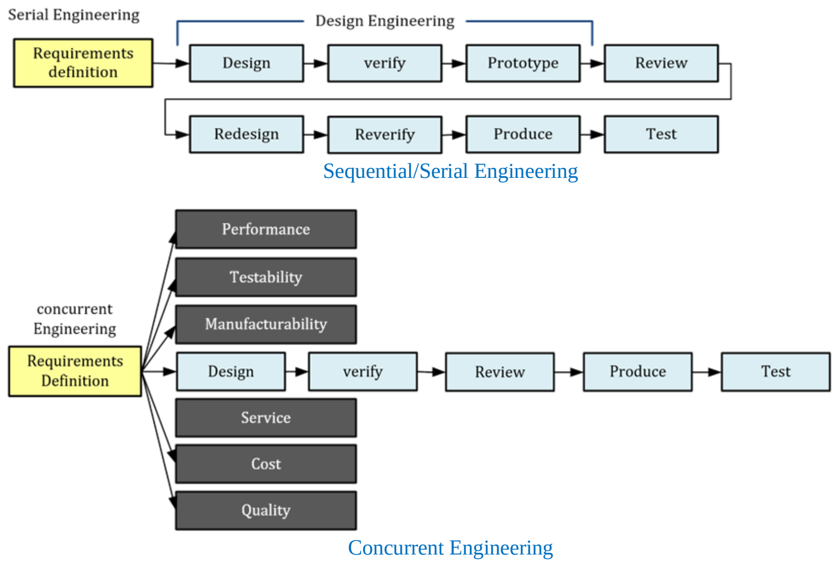


Fig. 3. Traditional Sequential Engineering versus Concurrent Engineering [17]

Furthermore, although real-world manufacturing mainly suffers from the various system and sub-system requirements, the curse of dimensionality regarding considering disciplines, and the multi-disciplinary nature of the involved disciplines, these issues may be intensified by considering different sources of uncertainties in the product lifecycle realization. The uncertainty sources can be divided into the following general categories: mission, design, manufacturing, and operation [23] (see Fig. 4). To alleviate such challenges, features like flexibility [24], modularity [25, 26], and automation [27] have been utilized within the manufacturing industry. Besides, Systems Modeling and Simulation (SMS) through Uncertainty-based Design Optimization (UDO) methodologies like Robust Design Optimization (RDO) and Reliability-based Design Optimization (RBDO) are other major enablers for fulfilling system requirements and constraints in presence of uncertainties. The RDO is a design methodology for achieving a product less sensitive to various uncertainties. Also, RBDO is a methodology to have an optimal product that fulfills a predetermined and acceptable level of failure [23].

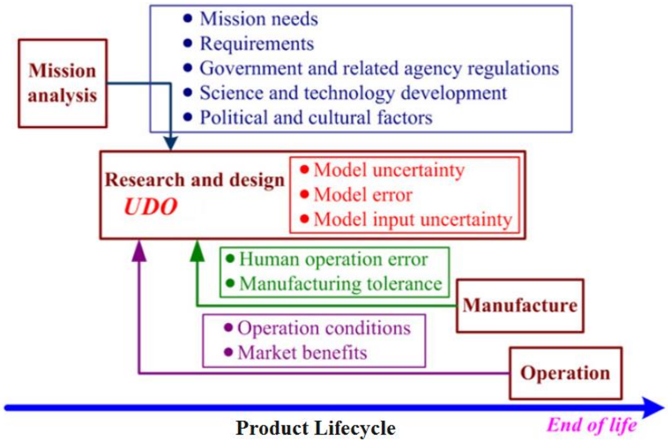


Fig. 4. Uncertainty sources in product life cycle [23]

The main challenges and future research in UDO fields of study have been addressed in [28]. By introducing computational burden as the main problem in applying UDO methods to real-world problems, new research fields like Surrogate-Assisted Optimization (SAO) and Evolution Control Strategies (ECS) as powerful paradigms have emerged over the last two decades [29-31].

Another design methodology that has been developed in parallel with the concepts of DFSS, CE, and MDO is Axiomatic Design (AD), which is based on deriving the Functional requirements (FRs) and related Design Parameters (DPs) [32]. DPs are the key solutions that have to logically satisfy the specified set of FRs. Although numerous research has been done on AD and its application in the design of manufacturing systems, some researchers are still working on both the theory and practical application aspects [33-37]. According to the basis of AD (Fig. 5), it models the interactions between FRs as what we want to achieve and the DPs as what physical implementation we choose to achieve the FRs [34].

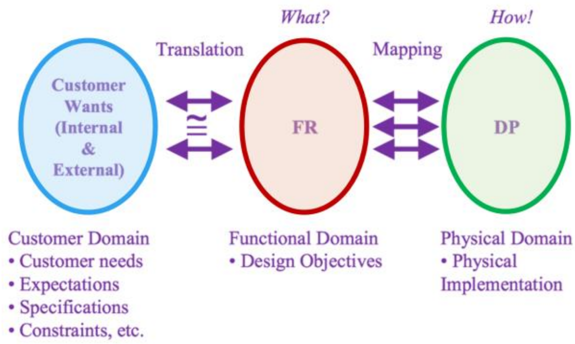


Fig. 5. The basis of AD [34]

3 Model-based Systems Engineering

The traditional document-centric SE of real-world products always involves thousands of created and maintained documents meanwhile the product life cycle. Some of these documents include requirements specification, requirements traceability, design structure matrix, test scenarios and specifications, interface control documents, and so on. It is important to note that the information in these documents is not independent and in contrast, the change of information in any document needs to be traced and exchanged manually in all the other affected documents [38, 39].

In recent years, SE followed by Model-Based Systems Engineering (MBSE) has undergone major changes. The transition from traditional systems engineering to MBSE (i.e. document-centric to model-centric) is depicted in Fig 6 [38]. As an alternative to the traditional document-based information exchange, MBSE has received more popularity within the industry. In MBSE, visual modeling of communication has made it easier to trace requirements and stakeholder needs. According to the *SMS_ThinkTank*™ [40], a global resource and leader in systems modeling and simulation, the best definition for MBSE is provided as follows: "*MBSE is the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases*".

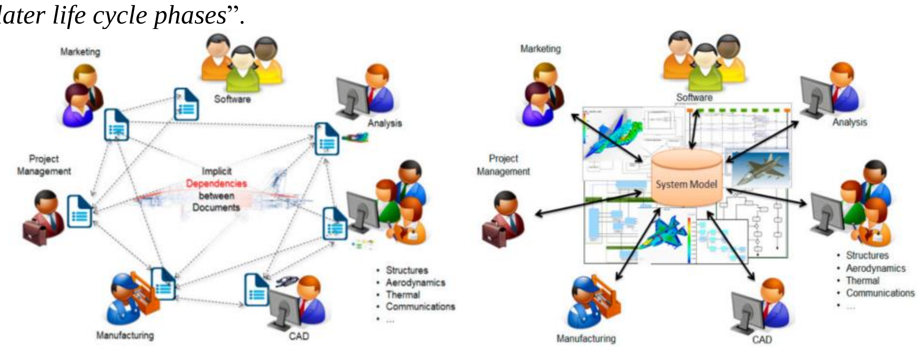
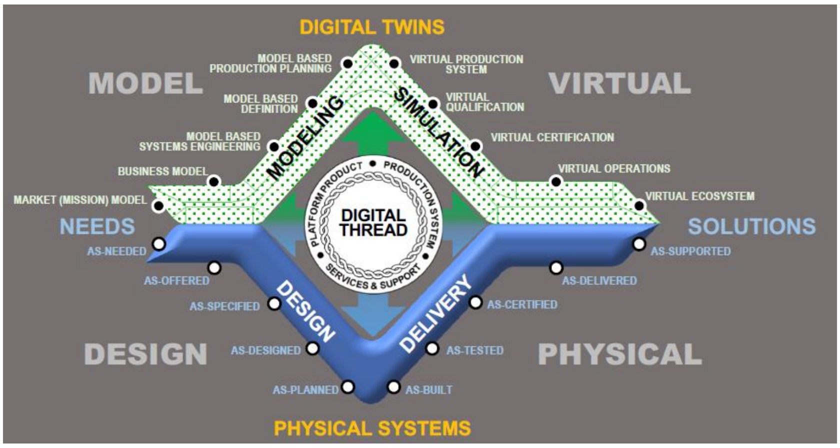


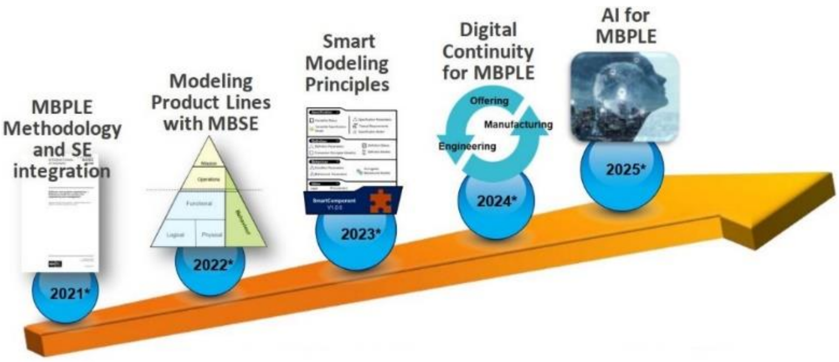
Fig. 6. Traditional SE (left) in comparison with MBSE (right) [38]

The International Council on Systems Engineering (INCOSE) has pointed out in its vision 2025 report that MBSE has provided a basis for profitable success in today and future industries [41]. In this way and relying on the traditional understanding of the lifecycle of a product or process (i.e. V-diagram), researchers develop a lot of frameworks based on the System Model Language (SysML). The Cameo [42], GENESYS [43], Modelica [44], and Capella [45] are some of the common MBSE tools. Therefore, the importance of diving into MBSE, whenever possible, is clear to the overall engineering community as asking for it. On the top, we have industrial companies like Boeing [46] and Airbus [47] which are pushing more and more MBSE and virtual integration as the way to interact with their suppliers in the future (Fig. 7).

While MBSE has progressively been used in industrial applications, many open issues still confine the execution of MBSE [48]. The teamwork nature of the MBSE, lack of knowledge of experts to work with relevant tools, information security, resistance to organizational culture change, and refrain from investing in new methods/software are some of these barriers. In any case, although companies are compelled to move in this direction, their steps depend on their organizational capabilities and are different for small to medium-sized enterprises.



Boeing MBE Diamond [46]



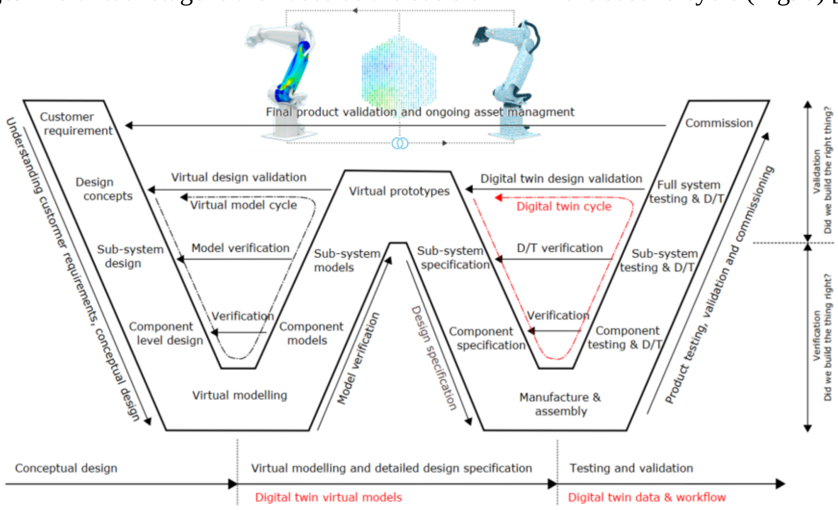
Airbus MBPLE Plan [48]

Fig. 7. Boeing and Airbus industries' MBSE and virtual integration Plan

4 Smart and Sustainable Manufacturing

The industry is undergoing an era of digital transformation. Since the dawn of the industrial age, despite recently developed tools and significant growth and movement from the level of Industry 1.0 to 4.0 toward smart manufacturing to achieve higher levels of innovation maturity, manufacturers have been evolving and adapting in response to new technological innovations and changing market demands. Also, many researchers are still trying to push the boundaries of manufacturing [49, 50].

During the last decade, the engineering community relying on Industry 4.0 technologies and specifically digital twin technology tries to connect systems and operations to achieve smart manufacturing. To attain this, virtual capabilities are required at many stages of the product life cycle. Therefore, the main transformative aspect of the digital twin is to position the DT in the SE life cycle by expanding the traditional understanding of the V-diagram from a sequential to an iterative view (like a W-diagram) at every stage based on a closed-loop process through including a specific virtual prototyping stage. The virtual stage is then used as the basis of DT in the second cycle (Fig. 8) [51].



Digitalized W-diagram

Fig. 8. Shifting from V-diagram to W-diagram toward digitalization [51]

Furthermore, both DT and the physical could be sustained by a linked MBSE tool, which supports data and workflow. Such a configuration guarantees bidirectional information transmission between the DT and the physical twin by serving MBSE as a digital thread [6, 52]. It is expected that digitalization become a distinguished capability within MBSE because of its four different levels of execution in the products life cycle (i.e. Pre-DT, DT, Adaptive DT, and Intelligent DT) while at the same time connecting cutting-edge technologies to MBSE push it toward new features in smart manufacturing to penetrate impressively in various industries.

On the other hand, in recent years, various sources forced the industry to move toward a new step of evolution, the step that sustainability is its core [53, 54]. It could be seen that this major factor with three dimensions of economic, environmental, and social sustainability (also known as Triple Bottom Line), not only is a multidisciplinary problem but also could be considered as a multi-objective optimization problem. When we consider different weights for the environmental, social, and economic, it deals with weak sustainability and aims to balance them. In contrast, strong sustainability focusing on the whole system dealt with the three subjects as nested and admits different weightings for the dimensions [55, 56]. Therefore, it is better to seek Pareto solutions in dealing with such problems to represent the best feasible design points that can be achieved (Fig. 9) [57]. It seems that sustainability is more of an organizational culture than a structure or goal. Therefore, since sustainability is considered a major competition criterion between companies today, a reorientation of the manufacturing society is necessary, utilizing knowledge and values to generate notable changes.

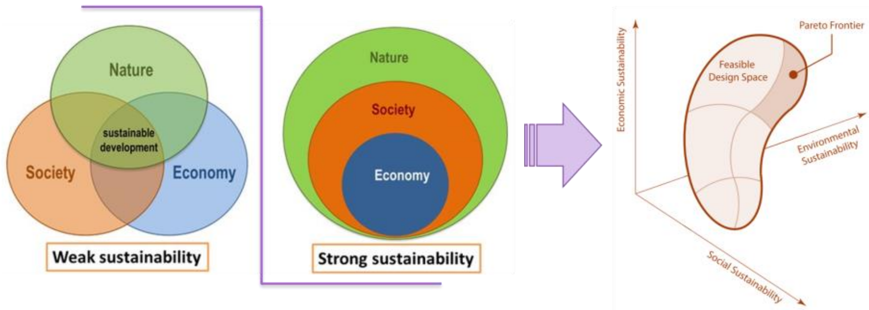


Fig. 9. Sustainability as a multi-objective optimization problem [56, 57]

5 Bridging the Gaps toward Smart and Sustainable Manufacturing Systems Design

As aforementioned, by facing ever-increasing complexity in industrial systems and marketplace demands, and an uncertain environment, organizations have already begun transitioning from traditional SE to MBSE and digitalization to achieve agile procedures. Therefore, it is clear that this transition is no anymore a plus, it is a must. But, despite some successes, this shift is a challenging and time-consuming process. There is no straightforward and unique path to attain this. It depends on many factors, culture, facilities, maturity, experts' knowledge, level of communication and interactions, managers' and leaders' adoption strategy, and way of thinking.

Although different approaches like MSDO, MBSE, and DT have been taken and developed, it's time to bring them into an integrated framework. Currently, companies such as MathWorks [58] and GENESYS [59] are trying to provide the platform for this integration with the possibility of communicating different software on the MBSE platform. Furthermore, according to INCOSE Vision 2035 [60], a family of unified, integrated MBSE-SMS frameworks develops by 2035. They will leverage MSDO methodology and DTs and would fully integrate with the digital thread foundation to provide life cycle management systems.

For the practical integration of MBSE tools with MSDO and achieve sustainability in smart manufacturing, which is a multi-objective as well as multidisciplinary problem, the Free University of Bolzano and Purdue University Fort Wayne are starting a research project entitled "SFDD - Sustainable Factory Design Decomposition". Using MBSE approaches along with MSDO could alleviate difficulties in dealing with such multi-objective complex systems. MBSE is taking over the role of a formalized and digitally supported application of modeling to derive system requirements, evaluate system architectures, and analyze, verify, and validate design activities. Whereas MSDO focuses on numerical optimization (e.g. MATLAB-Simulink) for the design of systems that involve several disciplines or subsystems with multiple and interdisciplinary objectives and interactions due to sustainability goals. Providing such a combined tool relying upon visual modeling helps factory designers and stakeholders easier follow up on the effect of their decisions and achieve sustainable manufacturing goals easier and faster.

6 Conclusion and Outlook

This paper proposed a general review of the field of systems engineering from the systems design and optimization view to digitalization and digital twin perspective. In this regard, after a brief introduction and illustration of the intelligent manufacturing triangle, the concept of Six Sigma and its procedures to increase reliability in the product life cycle is explained. In the next step, to find an alternative to traditional sequential design methodologies, we described the emerged CE and MDO approaches. To include different sources of uncertainties in design and attain feasible manufacturing and decrease the gap between design to practice, RDO and RBDO methods are explained. Meanwhile, SAO approaches based on machine learning and artificial intelligence have been developed to alleviate complexities with the computational burden of the mentioned design methodologies. Parallel to design and optimization, some research has been focused on methods like AD to work breakdown structure to clarify the problem definition in different levels of the system providing trees of information from stakeholder needs to requirements and physical solutions to find alternatives to make better decisions. With technology advancements and a competitive environment toward innovation and digitization, organization and Small and medium-sized enterprises have to change their thinking culture. MBSE is the master key and the best tool for the transition from traditional document-based information exchange space to digitalization in the least possible time.

Although different software has been developed in each era and now each is functional, reliable, and mature software separately, there is still a gap between their practical combination from the system of systems perspective and not a single-disciplinary view [61]. Therefore, as near-future research in the SFDD project, we will try to accelerate manufacturing factories' transition towards both profitable and ecologically and socially sustainable factories by combining SE, MBSE, and MDO. To achieve this goal, the research team will collect direct data regarding needs through semi-structured interviews asking users and stakeholders of factories (owner, manager, production engineers, associations, innovation clusters) and evaluate the relevance of collected data in focus group workshops. Afterward, AD will be used for translating these needs into technically sound functional requirements (FRs). Collected user needs containing non-solution-neutral data will undergo an AD reverse engineering approach for retrieving the underlying FRs. Candidate design parameters (physical solutions) (DPs) will be derived for each FR and metrics will be identified to make candidate solutions measurable and comparable. MBSE tools will be applied for supporting the modeling of requirements, design, analysis, verification, and validation. The full set of systems requirements and interactions will be evaluated afterward through MDO by establishing the mathematical model for each subsystem and using optimization algorithms to achieve finally an optimized design. Based on the Manufacturing System Design Decomposition (MSDD) approach [62] an evaluation tool will finally be developed to create a hands-on assessment tool evaluating the sustainability status of manufacturing companies and to guide factory and process designers in making their factories greener and socially sustainable.

Acknowledgments

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