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Aditya Akundi
The University of Texas Rio Grande Valley

Viviana Lopez
The University of Texas Rio Grande Valley

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A Review on Application of Model Based Systems Engineering to Manufacturing and Production Engineering Systems

Aditya Akundi and Viviana Lopez

Department of Manufacturing and Indsutrial Engineering
Complex Engineering System Laboratory, The University of Texas Rio Grande Valley
Brownsville, Texas, 78520 , United States.

Abstract

Increasing complexity in today's manufacturing and production industry due to the need for higher flexibility and competitiveness is leading to inconsistencies in the iterative exchange loops of the system design process. To address these complexities and inconsistencies, an ongoing industry trend for organizations to make a transition from document-centric principles and applications to being model-centric is observed. In this paper, a literature review is presented highlighting the current need for an industry-wide transition from document-centric systems engineering to Model-Based Systems Engineering (MBSE). Further, investigating the tools and languages used by the researchers for facilitating the transition to and the integration of MBSE approach, we identify the most commonly used tools and languages to highlight the applicability of MBSE in the manufacturing and production industry.

Keywords: MBSE; Manufacturing Engineering; Production Engineering; Modeling Language; Modeling Tools;Modeling Methods;SysML; Industry 4.0

1. Introduction

Model-Based Systems Engineering (MBSE) is a system engineering modeling application that emphasizes modeling principles in the evolution of system requirements, design, analysis, verification and validation (V&V) activities beginning in the conceptual design phase and continuing through product end of life [1]. MBSE methodologies address the inconsistency document-centric approaches generate in system development. This shift allows engineers to develop models of systems that focus on developing, managing and controlling a set of models of the system instead of creating and managing documentation on a system that becomes inconsistent and unrelated [2]. Today's industry has seen an increase in both competitiveness and system complexity. These collective trends can generate a variety of issues for manufacturers. MBSE tools and applications enable organizations to develop system

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models in varying stages of system development from a wide-ranging system of systems perspective to a comprehensive component level behavioral model. MBSE strives to improve communications between system stakeholders, engineers, and other system contributors. Studies in MBSE industry applications validate the benefits of enhanced system quality, productivity, and decrease in risk and cost. Furthermore, to elucidate the advantages of MBSE implementation, these applications could help in the coordination of systems design and development across various design teams at different disciplines to optimize for cost, schedule and performance by providing a way to capture all the information from different disciplines and share it among them and other stakeholders [3]. As Systems Engineering (SE) transitions into virtualized and conceptual systems, MBSE supplies the necessary tools and applications to communicate system information in varying collaborative models to authenticate logic and information sources. Models can communicate complexities of system architecture and software structure. It is highly beneficial for manufactures and organizations to invest in MBSE applications for improved system development phase interaction, consistency, efficiency, and profit.

The International Council on Systems Engineering (INCOSE) express in their vision 2025 report the need for MBSE methodology normalization in prospecting systems engineering projects. There are many challenges present organizations face such as the increase in faulty systems testing due to inconsistent systems design that lead to project risk-based decisions affecting product end success [4]. MBSE provides a foundation for profitable success in today's and future industry. MBSE allows for modeling to be the principal means for communication in the system development phase, between engineers and stakeholders, and removes irrelevant data, stream-lining the processes. As production systems become increasingly complex in today's multi-disciplinary industry the application of MBSE could enable to keep track of information created through each phase of the design process allowing system contributors to identify requirements, risks, and performance analysis that would otherwise not be achieved through document-centric methodologies. There are a multitude of languages and software tools that enable organizations to deploy MBSE activities that allow for more efficient production systems and customizable pristine products for their customers. Organizations could see a profitable impact on their ROI (Return on Investment) when making the necessary changes to implement MBSE such as training their staff in MBSE principles and hiring system engineer experts.

In this paper, a brief literature review is first presented identifying the use of MBSE by researchers in manufacturing and production engineering applications to portray the current efforts addressing the need for an industry-wide transition from document-centric systems engineering to MBSE. Further, investigating the tools and languages used by the researchers for facilitating the transition to and the integration of MBSE approach, we identify the most commonly used tools and languages to highlight the applicability in the manufacturing and production industry considering the attempts observed in literature on the use of MBSE to, facilitate the shift towards Industry 4.0, for Life Cycle design and management activities, handling complexity in automated manufacturing and production systems, and implementation in industries.

2.0. Application of MBSE in Manufacturing and Production Engineering – A Review

2.1. MBSE for an Industry 4.0 Approach

Industry 4.0, coined to be the fourth industrial revolution refers to working with a higher level of automation for operational productivity and efficiency by connecting virtual and physical worlds [5]. Literature indicates that Industry 4.0 will transform current manufacturing systems into a smart, flexible, and collaborative environment for making value-added decisions focusing on industrial scenarios developing smart products and processes [5] [6] [7]. Here we provide an overview on the application of MBSE in the manufacturing and production engineering activities working towards Industry 4.0 especially product planning and concurrent engineering.

Product generation planning involves the planning and designing of new product generations. Technical models are the industry norm in depicting reference products. According to Albers et al. [8] this industry norm does not provide the necessary amount of information for Internet of Things (IoT) features. To validate this method the utilization of MBSE in collaboration of IOT canvas with a German manufacturing company by means of Action Design Research (ADR) was evaluated. An IoT Canvas is created for one application scenario and one or more of the associated activities. The content of the Canvas provides an overview of the relevant information (e.g., networked systems, involved stakeholders, and relevant data flows) for the identification of new IoT features.

Designers and manufacturing engineers must be able to collaborate in early stage of the design process to decrease the number of iterative loops. Borchani *et al* [9] propose a MBSE approach (use of SysML diagrams) to address complex systems that tend to develop iterative loops. The use of SysML language will allow system contributors the ability to design and organize around these constraints. Smart Manufacturing Systems (SMS) optimize manufacturing capability by improving cost, delivery, flexibility, and quality while focusing on energy reduction and efficiency. If organizations take the necessary steps in integrating MBSE into their processes, it could lead in a path forward for smart manufacturing systems. According to Borchani *et al*. set-based concurrent engineering developed by Toyota Motor Corporation has since shown an increase in market share growth, consistency, and profit. SysML diagrams have been identified as a medium to identify requirements and constraints to define system design space.

Wortmann *et al*. [10] highlight the application of MBSE, through systematic mapping, showcasing the increase organizational use of Industry 4.0. A systematic literature review was conducted to detail the concerns in digital representation of automation systems, which prevent organizations from transitioning to Industry 4.0. While Industry 4.0 and MBSE carry many benefits for organizations, there is a found lack in willingness to transition. Research on modelling for Industry 4.0 currently focuses on digital representation and integration using established techniques, but also that there is an increasing trend towards customized modelling techniques to address the more specific challenges of Industry 4.0.

2.2 MBSE for Lifecycle Design and Management Activities

Considering the present norm of rapid product manufacturing, several core constituents' factors such as product performance, product quality, and manufacturing costs play an important role in introducing products to the market. Additional factors such as product safety, environmental impact, and the effect of the product on the customers are also to be considered. This spread of factors introduce a need for optimal system technologies and tools that can parallelly consider a broad spectrum of factors related to product manufacturing and streamline the decision-making process [11]. Here we expand on attempts that explore the application of MBSE in product life cycle.

Systems Lifecycle Management (SLIM) is a new MBSE and project lifecycle management combination workspace that will increase modeling language usability across all stages of a system development lifecycle. Bajaj *et al*. [12] developed SLIM to address the lack of modeling languages that have this interdisciplinary ability. SLIM allows users to wrap discipline-specific models (such as CAD, CAE, and STK) as SysML elements and plug-and-play with the system model. Today's industry implementation usually has two gaps; namely that MBSE lacks continuity as it primarily focuses on the early system development phase and not latter phases. The second being there is a lack of holistic models that range from different aspects of a system. SLIM provides analysis tools to compute system MoEs and KPPs, orchestrate simulations, perform trades, analyze risk, automatically verify requirements, and more directly from SysML.

Modern technical systems are designed with a variety of complexities that require system checks to identify inconsistencies to prevent expensive rework and system failures. However, according to Herzig *et al.* [13] identifying all inconsistencies for a system is near impossible and system contributors should focus on system management to regulate and resolve inconsistencies. The implementation of MBSE can help system contributors identify any potential inconsistencies. To achieve this, in a set of disparate, distributed, heterogeneous models, pattern matching was used. Inconsistencies must be included in graphical models to help manage future and current inconsistencies.

There is an ongoing rise in the manufacturing of complex products (systems) e.g. aircrafts, turbines, automobiles, etc. According to Wang [14] in order to develop complex products efficiently and economically, there is a need for manufacturing companies to extend conventional product data management to product lifecycle model management (PLMM), which shift emphasis from data managements to model managements throughout a whole product lifecycle. It can be assumed that document centric approaches for product lifecycle management better support expeditious data operations, however model-based approaches, like PLMM, allow for a more consistent management of "mappings, transformations and interoperations among heterogeneous data sources, by appropriately managing and executing interconnected models". In order to effectively carry out MBSE applications, organizations must provide the necessary means for engineers and personal to obtain model management knowledge.

There are many benefits when engineers transition their manufacturing processes from document centric methodologies to MBSE. According to Hummel *et al.,* [15] the implementation of MBSE in Product Line Engineering will allow product models to be customized while still preserving the manufacturer's original product line model. Specifically, Hummel and Hause provide a breakdown on how development lifecycle can be optimized to increase an organization's Return on Investment (ROI) by integrating MBSE, SysML, and UML. Orthogonal Variability Modeling (OVM) addresses the need for modeling variation as it allows product line engineers to design product line variants that can be used for specific end products. This gives manufactures the ability to customize their products without spending the time or funding needed to develop a new product line. The use of these modeling languages streamlines the product line system design for engineers, specifically within the automotive industry.

An increase in benefits in production for manufactures is reported to be observed when MBSE is introduced into the early stages of development and throughout the development lifecycle. Bretz *et al.,* [16] promote the integration of MBSE and workflow management systems to manage the information in early stages of production system development as it offers the potential to significantly ease access to information, reduce the time for searching of information and brings the breakthrough for MBSE as it connects engineering and process activities. The goal is to provide an interdisciplinary model that interconnects the different domains within system development. As it is with any organization, stakeholders play an important role in a system's development meaning that their understanding of every phase in a system development lifecycle is of the upmost importance. To address these issues a Workflow Management System was developed to support information requests and distribution based on the foundation of MBSE languages and tools e.g. SysML and product data management systems (PDM).

2.3 Industrial Application Perspective of MBSE

While MBSE has increasingly being used in industrial applications there are still many challenges that restrict the implementation of MBSE. According to Tschirner *et al.,* [18] parallel to traditional systems engineering methodologies, MBSE is not an individual concept but rather a variety of interdisciplinary approaches for industrial applications. While MBSE is not an answer for every industrial application, small to medium sized enterprises highly benefit from the implementation of MBSE. It is suggested that larger enterprises do not have widely spread methodical working and usually refrain from investing in new methods/software. There is much to be improved upon in the implementation of MBSE, however the trends so far within industry have shown an increase in efficiency and productivity.

There is a continuing trend of growth in complexity in multiple disciplines where organizations are turning to MBSE methodologies to address their needs to enable consistent development scenarios, increase profitable communication between collaborators, and develop traceability from requirements to system and software architectures according to Suryadevara *et al.* [19]. A variety of studies have introduced MBSE in large-scale industrial application and seen an increase in efficiency, however it is not attainable in one instance. Both system engineers and stakeholders must recognize the need for cultural change as these changes will affect the success of their system engineering processes. There were many concerns introduced involving MBSE integration, specifically on how to integrate non-model-based artifacts within a MBSE framework, highlighting the need for industry change.

Successful aircraft designs can be extremely complex. There are many considerations to take when developing a new aircraft. According to Li *et al*. [20] the aircraft landing dynamics are one of the greatest concerns for modern aircraft design in today's industry. The use of Model-Based Design (MBD) in aircraft design may combat the multifaceted challenges aircraft manufactures experience. Benefits of implementing a MBSE framework applying Object-Process Methodology (modeling language) as a replacement for a document centric system engineering approach in aircraft design with dynamic landing constraints is portrayed. The benefits derived from the use of MBSE were in enhanced complex system management and improved communication across stakeholders and development stages.

The weapon system industry is becoming both increasingly complex and competitive in today's industry. However, this increase in complexity requires the need for an effective test and evaluation (T&E) process to identify and address technology hazards. To accurately integrate T&E and system safety precautions Shin *et al.* [21] lay out a MBSE approach based on a process model. Following a series of identifications and steps, a design structure matrix (DSM) is developed which successfully integrates the T&E and system safety processes. System Safety process is the engineering and management principle application which can identify risk within the effectiveness of system lifecycle phases. To fully understand the use of these two factors, DSM was used to evaluate the effectiveness of MBSE integration.

2.4 MBSE for Automated Manufacturing and Production Systems

According to Feldmann et al [22] automated production systems become profitable and efficient when MBSE is implemented in the development phases, allowing stakeholders to translate their requirements to designers and engineers. Automated production systems require multi-disciplinary design and development approaches that can clearly be laid out when models are clearly communicated between all system contributors. Feldmann et al propose that the effective management of inconsistencies in MBSE can improve both the communication and understanding of modeling languages and tools. Addressing inconsistencies in models, within any discipline or field, is met with a variety of challenges. Achieving heterogeneity of models, clear separation, and participant knowledge of models is key to addressing inconsistencies involved in the development stage of automated production systems.

Automation systems continue to grow more complex in today's industry. There is an increased need for flexibility within industrial facilities to develop successful automation systems. As these systems become increasingly complex, automation engineers must implement control schemas and underlying architectures to support efficient system development. Fay *et al*. [23] present an approach to supporting model-based engineering (MBE) of distributed manufacturing automation systems. The approach is based on the combination of notation, characteristics, and design patterns across multiple levels of an adapted development process. MBSE approaches for MAS software applications are promising in handling software complexity that will significantly reduce engineering effort and improve software quality.

Scheeren and Pereira [24] highlight the increasing necessity for system interconnectivity for the development of industrial automation systems. An integrated approach was used to validate the adoption of model-based systems engineering, domain engineering, and cyber-physical systems in developing industrial automation systems over a document-centric approach. Under the product portfolio of General Electric Inspection Technologies (GEIT) a water circulation system (WCS) was modeled using OpenModelica to demonstrate the increased benefits of using a model-based system engineering methodology approach. This allowed the engineers (mechanical, electrical, and control) working on the WCS the information needed to make the required changes and constraints to get the system properly functioning.

Systems Modeling Language (SysML) is a MBSE modeling language that addresses non-functional requirements, software applications, and properties of proprietary requirements within the context of system development. Vogel *et al.* [25] evaluated the adaptation of SysML-AT (SysML for automation) for Parametric Diagrams (PD) inside an industrial automation software development tool focusing on automation systems controlled by Programmable Logic Controllers (PLCs) software. To effectively address software complexity, model-driven methodologies were implemented. An integrated modeling of hardware and software (SysML-AT) leads to improved results in connection model, and SysML-AT provides better software maintenance. The study presented an improved manufacturing automation software architecture addressing each of the hypotheses. While implementing SysML-AT may require extensive engineering efforts, its influence in better manufacturing automation software designs is highlighted.

Automated production systems (APS), in today's industry, require an increasing amount of mechanical, electronic, and control software integration. This increase in complexity has led to the implementation of MBSE to create an effectual multi-disciplinary workflow. Li *et al.* [26] clarify how MBSE methodology can be integrated in system development through the combination of SysML4Mechatronics modeling language and Product Lifecycle Management (PLM) creating consistency for different discipline collaboration. The purpose of a multi-disciplinary engineering workflow, within the context of the development process, is to allow system engineers to design systems with a central information model that contains all relevant information e.g. requirements, discipline-specific information and interdisciplinary dependencies. SysML4Mechatronics is then used for system modeling and becomes the information center where it can be transformed into the different discipline-specific models.

Iterative exchange loops can be an expensive issue in the development of mechatronics systems. The integration of MBSE methodology, according to Borchani *et al.* [27], will decrease the amount of exchange loops between system participants. Based on information flow, upstream and downstream, the exchange of information between system engineers and different specialists can be efficiently achieved. The benefits of using MBSE approach compared to a point-based approach include avoiding costly rework in design stages, ensuring all the system functions are considered during the system design process, and facilitating effective communication of artifacts.

Quality inspection of a mechatronic system requires inspection systems, which are often mechatronic systems themselves, and are typically designed for a single product with large expenditure of time. Along with the designing phase of a mechatronic system, inspection system equipment must be designed, developed, and ready by the start of production (SoP) to be sure that the product requirements are transferred to the product development. Lukei *et al.* [28] portray the applicability of MBSE product models to determine inspection equipment requirements in early development phases. Following a requirement analysis of the design and development of an innovative modular inverter system (IMIS) that needed to supply auxiliaries in commercial vehicles, both functions and requirements for the early development phases of the IMIS are identified. Inspection properties were derived from this MBSE (V-series macrocycles) analysis that allowed for an efficient inspection system design which was not easily attainable without the use of models.

3. Discussion

Model based Systems Engineering address the inconsistency that document-centric approaches generate in system development. MBSE facilitates the focus on developing, managing, and controlling a set of models of a system instead of creating and managing documentation on a system that becomes inconsistent, unrelated, and eventually obsolete. A rapid increase in number the of published articles addressing MBSE efforts in industries and academia especially in manufacturing and industrial engineering applications for transforming traditional systems engineering projects has attracted attention in the research community and practitioners. Based on the literature review conducted, in nearly all the attempts identified the authors reported the use of MBSE in enabling the effective management of the systems models considered. Identified in Table 1 are the most often used languages and tools for the transition towards MBSE, classified based on the efforts for facilitating the shift towards Industry 4.0, for Life Cycle design and management activities, handling complexity in automated manufacturing and production systems, and implementation in industries.

Table 1. Frequently used Languages and Tools facilitating the transition to MBSE in Manufacturing and Production Engineering domains

	Language	Tools
Industry 4.0	Systems Modeling Language (SysML); SysML4CONSENS; Unified Modeling Language (UML); Architecture Description Language (ADL); Automation Modeling Language (AML); Early-Relationship Modelling (ER); SysML4Mechatronics; UML4IoT	Papyrus; MATLAB/Simulink
System/Product Lifecycle Design and Management Activities	SysML; UML; Orthogonal Variability Modelling (OVM); Lifecycle Modelling Language (LML)	MATLAB/Simulink; OpenModelica; MagicDraw
Industrial Application Perspective	SysML; UML; Object-process Language (OPL); System definition language (SDL)	MS Visio; Rhapsody (IBM Rational); MagicDraw (NoMagic); Modelio; Papyrus; PTC Integrity Modeler; Capella; CORE
Automated Manufacturing and Production Systems	SysML; UML; SysML4Mechatronics; SysML for Model Integrated Mechatronics (SysMl4MIM); Automation Modelling Language (AML); ModelicaML; SysML for Automation (SysML-AT); Extensible Mark-up Language (XML)	PTC Integrity Modeler, MagicDraw, Eclipse, OpenModelica; MATLAB/Simulink

It is observed that Systems Modeling Language (SysML) is the most commonly used for facilitating the transition to MBSE among manufacturing and production engineering systems. This indicates that Systems Modeling Language (SysML) is the most sought after by the community for developing system structural and behavioral requirements as well as constraint models. Considering the tools to facilitate the transition, MATLAB/Simulink, MagicDraw, Papyrus, and Open Modelica are more often used. Interesting observation is the attempt at the use of Microsoft Visio despite of high effort needed for modelling. SysML is an extension of Unified Modeling Language (UML) profile that enables architecture centric analysis for integrated analytics, capturing analysis contexts, requirements and architectural parameters [29]. The embrace of SysML use can be attributed to the fact that SysML was developed as a general-purpose modeling language for systems engineering applications and It supports the design, specification, and verification and validation activities of a broad range of systems. More interestingly, tailored extensions of SysML and UML such as SysML4Mechatronics, UML4IoT, SysML for Automation (SysML-AT), SysML4MIM have been used. Brief descriptions of the profiles identified are given below.

SysML4Mechatronics: Based on Systems Modeling Language (SysML), SysML4Mechatronics was developed as an approach to model and specify the dependencies and interactions of the components involved in different domains of mechatronics such as mechanics, electronic, and software. SysML internal block diagrams are used as a means to identify and illustrate the connections of respective system elements. Kernschmidt and Vogel-Heuser [30] first use SysML4Mechatronics to illustrate its application in mechatronic production plants.

SysML for Automation (SysML-AT): SysML-AT is a model driven approach developed to facilitate the development of automation software for manufacturing systems for integrating hardware and software models. This approach covers the modelling of functional ad non-functional requirements along with inclusion of hardware elements like sensors and actuators and their interfaces and properties [31].

UML4IoT: UML4IoT is an UML-based approach to facilitate model driven development of Internet of Things (IoT) systems that automates the generation of IoT complainant layer needed for integration of cyber physical components [32].

4. Conclusion

Production systems are becoming more and more complex in the current multi-disciplinary industry environment and the adoption of the use of Model based Systems Engineering approach will enable to keep track of information and artifacts created through each phase of the system design process. There are several approaches and software tools that enable to deploy MBSE activities that allow for more efficient manufacturing and production systems. In this paper, we review the use of MBSE by researchers in manufacturing and production engineering applications to portray the current efforts addressing the need for an industry-wide transition from document-centric systems engineering to MBSE. Further, investigating the tools and languages used we identify the most commonly used tools and languages to highlight their applicability in the manufacturing and production industry by the researchers for facilitating the transition to and the integration of MBSE approach.

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