Towards Model-Based System Engineering for Disruption Analysis of Complex Systems: A Case study in Semiconductor Supply Chains

ARTICLE HISTORY
Compiled December 13, 2025

ABSTRACT

In an age of complex and large-scale systems, Model-Based System Engineering (MBSE) is increasingly becoming a sine qua non in the industry due in large part to new software applications and an increased move towards standardization. In this study, we compare three different standardized MBSE tools, namely the OWL, BPMN, and SysML. Each of these MBSE methods provide different perspectives on knowledge sharing, single source of truth, and visual representation of systems in the context of system resiliency and disruption management. In order to evaluate its efficacy, each method is applied to a supply chain planning system of a semiconductor manufacturer case study. Through this comparison, we hope to highlight further opportunities for research as well as obstacles that may stand in the way and ultimately provide positive proof that MBSE is necessary for revealing sources of systematic disruptions within a complex integrated industrial information system.

KEYWORDS
model-based system engineering; disruption management; complex system; system modeling; simulation analysis.

1. Introduction

Over the past two decades, systems thinking has come to economic systems, socio-technical systems (man-made systems), and engineering systems. Within all these domains, concept modeling has become the foundation of system definition, design, analysis, and synthesis. As global systems become wider and more complex, Model-Based Systems Engineering (MBSE) has emerged as an essential tool for learning from real systems [16, 56].

According to the International Council of Systems Engineering (INCOSE) (International Council on Systems Engineering Website," n.d.), 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 phase" [62]. From this definition of MBSE it can be seen that, while MBSE has been shown to be beneficial to support system design and analysis [25], here the objective is to introduce MBSE as a proper proactive approach towards managing disruptions (internally and externally), revealing the causalities of disruptions, and analysing and synthesising the system under study. To reach this goal, we examined three different MBSE methodologies (Systems modeling Language (SysML), Business Process Model and Notation (BPMN) and Web Ontology Language (OWL)) for the evaluation of sources of disruption in the domain of a supply chain planning system.

MBSE elucidates system paradigms through which a formalized, centric, single source of truth as a core form of description for configuration management can be posited [35]. MBSE is not just a set of tools and languages, rather a systematic exposition of system description. Although system modeling with MBSE is still in its initial stage of maturation, it has been used by many real applications in large scale and complex systems. MBSE has been applied in many domains of system science such as system architecture, validation and verification (V&V), quantitative and simulation analysis, and improvement through the whole life cycle of systems [13, 25].

Disruptions are events and occurrences of a system moving from an equilibrium stable state to an unexpected state [64]. The use of MBSE for facilitating disruption management could be: (i) reactive which supports system engineers to mitigate the consequences of occurred disruption in the best possible way [65] or, (ii) proactive by delineating efficient system and adopting proper systems thinking to develop a more resilient system against disruptions [33].

To the best of our knowledge, the role of MBSE and its tools for investigating and managing disruption to find the root causes of disruptions has rarely been studied. As a result, the contributions of this paper are to:

- Introduce and extend the scope of MBSE for enterprise system analysis and synthesis.
- Present MBSE use in the context of disruption management.
- Evaluate and compare MBSE tools for system resiliency, integration and quantitative analysis.
- Examine MBSE tools for disruption analysis in a case study of semiconductor manufacturing supply chain planning.

The remaining part of this paper is organized as follows. In order to get familiarized with the expanding domain of MBSE, section 2 presents a literature review of MBSE concept and definition, tools, and application domains. To provide an example of the use of MBSE for disruption management, in Section 3, we detail our case study. In the following section, which discusses the general structure of a supply chain planning system in addition to highlighting the demand fulfilment part. Section 4 illustrates the benefits of the use of MBSE as referential and methodological system modeling for disruption management. In Section 5 we discuss the use of three MBSE modeling methodologies and compare their advantages/disadvantages and provide managerial perspectives towards the use of MBSE for system modeling and disruption management. Finally, in Section 6 we conclude the paper.

2. Literature review

MBSE can play a key role in the development of strategies for dealing with the growing complexity of Systems Engineering (SE), specifically in the areas of production and supply chain. As there is a world-wide move away from document-centric SE, as a digital representation of complex systems, MBSE is positioned to become the core of myriad applications [9]. In this literature review, we briefly discuss MBSE in different fields, but, because the applications are so varied, the main focus is on its use for modeling and decision making of complex manufacturing systems related to supply chain planning and information systems in the support of disruption management.

2.1. *Model-based system engineering*

MBSE is a framework in which a sole source of truth of the system or part of the system can be obtained, where a comprehensive history and origin are discussed in Haskins [19]. MBSE takes an integrative approach by analyzing how various perspectives and elements interact with an environment by defining which characteristics to consider or ignore based on the specific purpose in mind. In other words, a model can represent only a part of reality regarding the stakeholder requirements, but may contain several viewpoints from stakeholders regarding their questions and requirements [35]. This is because SE is an interdisciplinary domain within engineering and management, that concentrates on the design, system architecture and maintenance of the whole system through the system's life cycle [15, 19].

MBSE literature consists of many application domains and methodologies, here we focus on MBSE in design and operation of production processes and it's use for disruption analysis. Zdravković et al. [66] describes examples of MBSE advantages in disruption management. In this work, the authors discuss the domain framework for Internet of Things (IoT) within implementation and maintenance projects. They categorized MBSE into three stages, system design (with UML/SysML), application design (Domain Specific Language (DSL)), and interoperability (Ontology). This work truly delineates the importance of MBSE for efficient IoT system implementation. Besides, they emphasise the use of these approaches for the maintenance of a system, in which, disruption management is an integral part for efficient management. Also, Vallejo et al. [54] propose an enterprise integration framework and model according to physical, application and business integration. The referential model used was BPMN to monitor control and improve an extended enterprise for increasing interoperability and stability of a system. A comprehensive survey by Vernadat [55] indicates that Enterprise Modeling (EM) has become a very active area in understanding, documentation, change management, re-engineering, architecture, performance evaluation, and system integration of organizations and enterprises. Although the benefits of EM and MBSE have become clear, they have not provided all its potentials and there are still open avenues for ontological development, standardization, and language evolvement.

Great advances have been made in MBSE research in recent years [35] some of which has demonstrated the economic advantage of using MBSE environments in SE [34]. In a comprehensive economic analysis of MBSE, Madni and Purohit [34] analyzed the investment cost and possible gain of MBSE implementation and compared it with traditional SE approaches. The authors collected summary information from twelve industry sectors and defined a structured method for analysis. Of importance here are the results that MBSE implementation requires more upfront investment than traditional SE, but that in latter and longer stages of the system's life cycle (when the design is in operation) MBSE provides greater gains. Second, they showed which industry sectors, according to life span, environment complexity, and system complexity, gain more advantages from MBSE implementation. More recent surveys [17, 9, 13, 25] have shown its increasing rate of application in other domains. INCOSE also defined the 2025 vision of MBSE towards the expansion of application across industry domains [26]. Madni and Purohit [34] main focus was on different types of systems that were continuous, discrete or combined [30]. Much research work has also been carried out on discrete event systems, the case study presented in this article.

These type of systems, also known as Discrete Event Logistics System (DELS), are defined as networks of resources through which goods and people flow [40, 58]. These systems, discrete event systems, include factories, supply chains, warehouses, etc. McGinnis et al. [36] presented an article on developing an ontology for simulation using a SysML as a domain-specific language for a class of simulation applications. Other work from this group include [6] who draws from methods within software engineering and computer science, specifically Model-Driven Architecture (MDA). They present a proof of concept study where they use a DSL (SysML) to develop a conceptual model of a manufacturing system and transform this to a simulation language Arena [5]. The proposed framework demonstrated how the problem domain, modeling, and knowledge analysis are integrated to create a DSL for the system of interest for domain experts by giving them engineering, rather than analysis tool, for specifying their problem. Besides, a SC simulation and data integration review by Vieira et al. [57] identifies current challenges in simulation modeling of SC that MBSE can fill part of its gap. In the next subsection we introduce MBSE methodologies used in the article.

2.2. *Selected MBSE Methodologies*

MBSE methodologies, while seeking to be readable by both machine and human, define syntax and semantics to share the common knowledge of models between stakeholders. Comparing all the MBSE approaches requires a detailed survey that is beyond the scope and contributions of this paper. In this study, we aim to investigate the capabilities and advantages of MBSE approaches for analysing and understanding the sources of disruption in a complex supply chain system, which is a DELS.

SysML was selected as it provides a standard [52] and comprehensive system specification paradigm. And as stated in section 2.1, it has been used in analysing DELS [14, 6]. This provides a consistency in terms of model syntax and semantics, together with unambiguous graphical symbols, which can greatly improve communication. As well, since its adoption, SysML has enabled an increased adoption of MBSE practices across industry. The number of industrial partners who have contributed to its development clearly indicates that practitioners recognize the need for SysML and show an eagerness to make standardized graphical modeling notation freely available.

In contrast to SysML, one of the advantages of BPMN, which is also a standard [7], is that it is an easy tool to understand, requiring a minimal amount of training for a basic level of understanding. As noted in Onggo et al. [42], BPMN is easily understood by different stakeholders as it has been originally designed with business users in mind.

In addition to standard modeling approaches such as SysML and BPMN, OWL is World Wide Web Consortium (W3C) standard [60] which aims to represent exploitable web knowledge of computers. OWL's features include computer readability, knowledge representation and sharing, model discovery via search, or reusability.

SysML is an OMG (Object Management Group) standard that supports the specification, analysis, design, verification and validation of a broad range of systems and systems-of-systems. While SysML helps and facilitates requirements description, there are also some works on requirements verification described using SysML [14]. SysML is essentially a UML profile that represents a subset of UML 2 with extensions [18]. Although UML has also been used to represent non-software systems, it is not ideally suited to this purpose and requires non-standardised use of model elements that can ultimately lead to confusion and incorrect interpretation of diagrams. SysML is more geared toward MBSE implementation in design and architecture of production systems to develop process integration and collaboration concepts within the system [35] while it is also examined and used for conceptual modeling and simulation modeling as an external analysis of DELS[6].

BPMN provides a visual notation that is readily understandable, at the basic level, by all business users and Information Technology (IT) developers and it is mostly suitable for business entities and relations modeling. An explanatory application of BPMN in SC based on SCOR model presented in Teixeira and Borsato [53]. It allows the development of requirements for business processes with XML languages designed for the execution of business processes, such as WSBPEL (Web Services Business Process Execution Language). It has been argued that BPMN notation includes a small set of visual elements [37] that would allow a novice to understand a reasonably complex process. A formal description of the BPMN standard is given in Chinosi and Trombetta [10], which one would be required to study to understand more complex processes.

BPSim [8] is a Workflow Management Coalition (WfMC) standard to facilitate simulation of BPMN or XPD [27] models. More specifically, it allows the exchange of parameters of process analysis data facilitating structural and capacity analysis for pre-execution and post-execution optimization of a process. Critical analysis on BPMN and BPSim standard [29] states that these standards are powerful for the creation of business process models and help to promote process simulation. In addition, they facilitate the building of tools for modeling simulation independent from simulation tools. This notwithstanding, BPMN and BPSim may have limited technical capabilities in representing important features of complex flows in a business process [42] while they represent enterprise systems with business perspectives that SysML is not truly capable of capturing. Other work by this group Proudlove et al. [46] also demonstrate the application of BPMN for modeling and simulation of DELS in healthcare systems. Their aims toward fully facilitated modeling indicate the capabilities of BPMN for engaging stakeholders, facilitating communicating, and relieving coding gaps.

Ontology is a formal specification used to describe, define, and categorize the concepts and their relationships and can be applied to various domains in engineering. Studer et al. [51] defined ontology as "a formal, explicit specification of a shared conceptualisation of a domain of interest". Machine-processable languages (XML, RDF, and OWL) are used to describe the entities and their logical relationships. Before we examine the selected OWL as an ontology language, the importance of ontology in modeling and analysis are reviewed.

Ontology has been examined through two main aspects, referential ontology defined as pre-image with strong epistemic nature which capture reality utilizing semantic relationships based on the representation of the real world; and on the other side; and methodological ontology with normative nature best used for further processing as formal semantics [22]. A comprehensive review of the use of ontology for interoperability was done by Fraga et al. [17]. In this survey, the authors emphasized the benefits of using ontology and OWL to reuse knowledge, reduce semantic ambiguity, and develop a consistency in complex and big systems with various standard and models.Besides, an ontology based assessment for evaluation of interoperability presented in Leal et al. [31].

Although OWL has been approved as a standard web of data by W3C for web-accessible ontologies, it has been proposed as a standard in the doamin of simulation [49]. The authors develop a structure for DELS modeling through exploring classic and formalized DELS taxonomy (state-oriented model, event-oriented model, activity-oriented model, process-oriented model). This structure defined the hierarchy of properties with OWL and made the modeling and simulation achievable through ontology. In the same vein, Kernan and Sheahan [28] outline use of OWL for generic

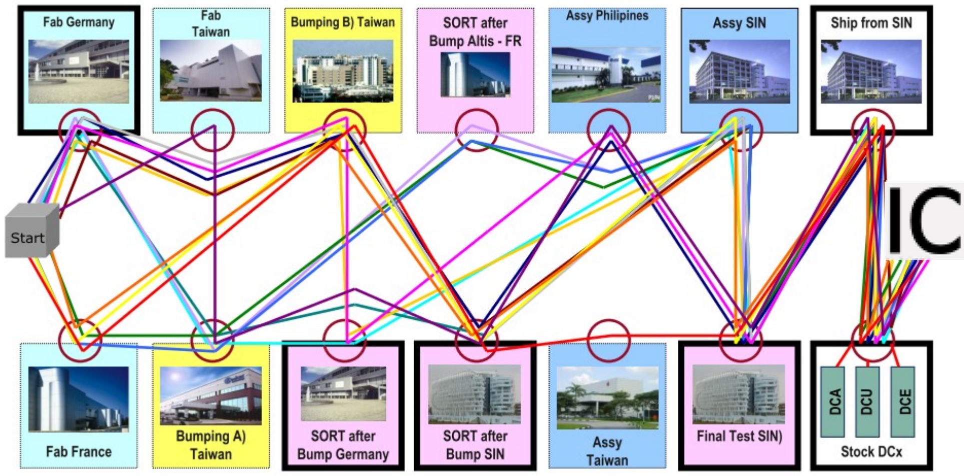

Figure 1. Complex global productions network of the semiconductor case study

data modeling of an enterprise to be used in DELS to reduce the simulation modeling effort and the maintainability of models.

Based on this short review, the approaches, frameworks, and benefits of MBSE application for analysing planning systems within an enterprise has rarely been considered in the literature. Tactical planning, operational planning, and real production systems are all sub-systems of an enterprise that, while they are independent systems of systems, they interact and cooperate. What we note in this combination of subsystems is the lack of consistency due to the involvement of different domains of expertise. In the next section, we outline the advantages and disadvantages of various MBSE approaches for disruption management as well as for the modeling of a complex supply chain case study.

3. Case study: supply chain planning system

The following case study is of a semiconductor manufacturer in Germany and the objectives are to improve the order management by finding the root causes of unexpected errors within the control system. As depicted in Figure 1, an SC planning system is required to support a global supply chain where is paramount for enabling the most efficient use of capital equipment, which is extremely expensive. Figure 1 shows an example of the SC for a single product made by the company in question. Typically, a single route in the SC is used at the start of production, but, depending on the success of the product, a new SC may evolve over time. Each colour in the diagram represents an evolving SC, with the case study company outsourcing the majority of its production. For example, one route through the SC line consists of Fabrication (label: Fab Germany) occurring in Germany, then Bumping in Taiwan (Bumping B) Taiwan), Sort in Germany (SORT after Bump Germany), assembly in Philippines (Assy Philippines) and final test in Singapore (Final Test SIN) when the final product is then distributed to the end customer.

In order to manage this SC, a complex socio-technical system consisting of several subsystems is required that can be divided into:

- Production or physical system which are sets of machines and logistics (see Figure

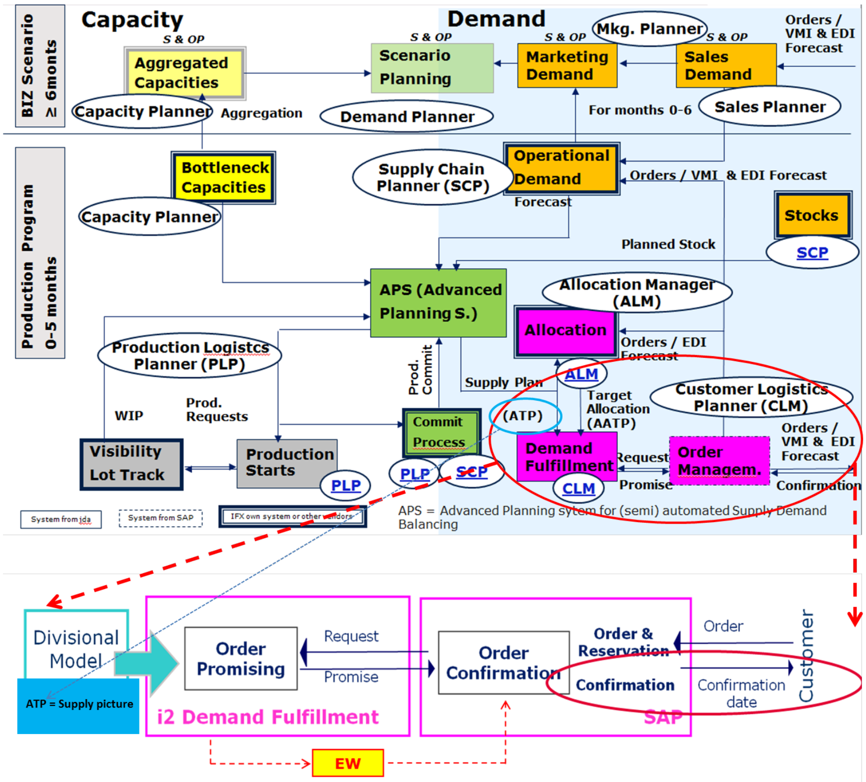

Figure 2. Supply chain planning system of the semiconductor case study (obtained from Achter et al. [1])

1).

- Planning system to maintain plans for the SC system, which differs from the IT system (see Figure 2 on page 7).
- Expertise system or human planners whose expertise are required for tuning the SC, using their cognitive insights.
- IT system which is a set of software modules and databases that interact with humans and integrate with different planning and optimization systems.

Using the SCOR model [24] the SCP system is shown in Figure 2, where capacity is balanced with demand over a six month period within strategical planning level. In short term planning (tactical) decisions are taken driven mainly by the Advanced Planning System (APS). APS match the Bottleneck Capacities, prioritized Operational Demand, Stocks level, and availability of different granularity of products in global supply chain (Visibility Lot Track). The main outputs of APS are productions/logistics targets and Available To Promise (ATP). ATP is the current or future supply of products based on visibility of the production system or developed plans. In production management processes, productions are scheduled in different parts where visibility to the flow of materials in the global production processes is ensured. Finally, order management contains the processes of receiving orders, ensuring contact with customers, and providing promises based on the ATP (see Figure 2).

Acting at the core, APS merges different software systems, experts decisions, strategic regulations, production feedback, and other relevant modules each coming from one of four SC subsystems. Within APS, the planning processes that satisfy the customer demands are called order management (which consists of allocation, demand fulfilment, and order management). The main functions of order management include: matching the available supply with dynamic demands, promising reliable delivery dates to customers, dealing with changes of customer orders, providing data regarding future demands, negotiation with customers, allocation of shortage supplies to customers, etc. [50]

Satisfying uncertain demands with constantly changing supply requires repetitive interactions of the four subsystems based on defined processes and upcoming events. Each paradigm emergence out of these interactions has chains of causalities that are not linear or even clear. For example, in consecutive runs of the ATP (which happens each day) changes occur which may be due to the modification of an order, maintenance of production for other products, lack of compatibility of IT processes, late database updates, inaccurate planner intervention or many other reasons. Thus the causalities are the result of several nonlinear interactions. This is why discovering the source of the disruption is so complex. MBSE models help us understand how all the working parts of a system and its subsystems interact, how ATP operates and how to identify the source of EW (see Figure 2 and the following subsection).

3.1. *Demand fulfillment and ATP instabilities*

The Demand Fulfilment (DF) process provides the framework for fulfilling promises on requested orders. Based on planned demands, capacity bottlenecks, and production visibility (production plans, Work In Progress (WIP) and stocks), the divisional model creates ATP which is the future supplies. ATP feeds DF software modules, allowing to generate fast and reliable promises. The first date and quantity promised to the customer by consumption of ATP creates a baseline for orders in the delivery schedule. Therefore, if there are any instabilities in the ATP, a ripple effect ensues which moves throughout the rolling horizontal plan. This inevitably leads to unconfirmed orders and customer dissatisfaction.

These instabilities, including inconsistency in promised delivery dates and quantities, may also trigger events such as changes to production plans. All of these variables are taken into account during a process called order promising (please refer to Figure 2). The order promising runs every day to peg the orders with ATP again. If the result of the reschedule is not the same as promised, a control system is triggered and generates an alert, called Early Warning (EW), to notify software modules and planners regarding the shifts in a promised schedule. An EW alert can be positive if the new promised date is earlier than the previously confirmed date; or negative if not. This control system is a part of order management and it reads data from different subsystems within the planning suite of IT tools.

3.2. *Challenges and objectives*

Because planning occurs each day, consecutive observations of EW show that a repetitive, daily pattern of changes in promises before confirmed delivery. This causes disruption, requiring planners to manually mitigate in order to reduce the ripple effects of the disruption case by case. It also creates disruption in the planning system, from which no root cause has been identified in this complex global SC planning system. To discover the origin of this error, we used MBSE to investigate and model the system as a basis for developing hypotheses and quantitative tools. This allowed us to define research questions regarding stabilizing ATP [38], which is defined in more details in the next section. It is worthy of note that this manual intervention of planners mitigates against applying Industry 4.0 concepts which is a core theme of the Productive4.0 project [44].

MBSE allowed us to model, explore, understand, share, and debug this centralized, complex, and global SC planning system. In order to pinpoint the epicenter of the ripple effect and identify the ensuing errors, a model as a single source of truth needs to be developed. With this aim in mind, we examined different modeling methodologies with their advantages and disadvantages through our study which we will be discussing in detail in the next sections.

The results of this MBSE study will shed light on our project objectives of finding the source of planning errors (disruption) observed in the operation of the control system. In the next section, we discuss our pathway towards implementing these tools in the evaluation different MBSE methodologies within the context of disruption management and instability analysis.

4. MBSE of system modeling and disruption analysis

How MBSE could be efficiently standardized is still a matter of debate. There are questions as to how it can be applied and which tools and methodologies are more compatible with each domain. To the best of our knowledge, MBSE can support disruption management from four perspectives.

(1) Firstly, MBSE increases the resiliency of a system against risks by: (1) system structuring and knowledge sharing, (2) making rigorous decisions, and (3) propelling "as is" state and proactive exploration against risks [11, 35].
(2) Secondly, MBSE with a collection of integrated models in the form of a "sole source of truth" stored in a single repository, empowers the development of quantitative and analytical investigations of a system. For instance, we can cite the benefits of using MBSE for simulation modeling [41, 32].
(3) Thirdly, MBSE reinforces system management during a disruption by creating a language for communication to allow understanding and that ensures the interconnection among the various perspectives held by stakeholders. [35, 2].
(4) The final advantage of MBSE for dealing with system disruptions is in the realm of dynamicity and technological advancement of systems. MBSE with V&V features and visual representation could ease the process of change in systems. When a new technology or change is about to be adopted by the system, the use of MBSE as a road map can facilitate the design of more resilient systems against any foreseen disruptions caused by stakeholders [47, 34].

The use of MBSE for disruption management has opened new avenues of research. In this section, we focus on the role of MBSE in defining elements and causalities of disruptions within the studied system by comparing the benefits of using different MBSE tools. With this aim in mind, we first outline the advantages of MBSE in disruption management, then go over the pathway of using MBSE tools within the project. Finally, we discuss the results of obtained tools individually.

4.1. *MBSE advantages in disrupted case analysis*

In order to formulate hypotheses and eventually propose a proper line of action, it is important to understand the SC system in question. This requires a certain level of abstraction. This abstraction as a conceptual model of a system defines the method and approach towards finding the causalities of the error within the complex planning system. During our investigation within the case study, MBSE tools were shown to provide a shared understanding with three main advantages: methodological feature, visualize out contribution and understanding, and reveals causalities.

(1) First, MBSE has two types of applications: (1) for system design and architecture and (2) for external analysis of a system, which is mostly discussed here in relation to simulation modeling and mathematical programming. There is a need within manufacturing and SC systems to share and crystallize knowledge. Unfortunately, digital and referential models are lacking. It is possible, however, to apply methodological modeling on a case by case basis as we move toward a more comprehensive referential model for development projects. An example of this can be seen in our case study. While there are different resources available as system knowledge documentation, the lack of a model in a single repository in an interconnected and maintainable method is obvious. Confusing updates, different perspectives of the same topic from different stakeholders, and loss of knowledge are the main issues experienced during investigation of material within the case study.

(2) Second, during the course of this system investigation, several challenges emerged for the gathering and sharing of knowledge. Firstly, there was a lack of a standard language to describe interactions. Secondly, different terminologies were used in the text description of the system. A case in point is that while all the learning materials in our study were available, they were developed and designed by different stakeholders. Thus, a model is required to be not only a visual representation, but an efficient method of transferring knowledge to users as well [21]. Through the use of MBSE tools, we will be able to develop a common language and visualize the shared understanding for better communication.

(3) Third, the MBSE models we developed reveal the causalities and interactions of a system's elements. Causality in a complex system is pervasive in analysis [61]. The key to finding the internal or external root causes of a disruption is being able to define reciprocal causalities in the form of linear causes and then combining them to form a system. This allows us to analyze nonlinear causality in order to find the internal or external root causes of the disruption. Understanding the causalities of complex systems without visualization and a structured standard is very difficult to achieve. The use of MBSE allows visualization of processes, requirements, interconnections, and integration, and reveals the linear causes between elements.

In the next subsection we discuss our pathway in using MBSE over the course of this research.

4.2. *MBSE case pathway*

In the project Productive 4.0, our aim is to improve order management of a complex semiconductor SC case study. The case was further complicated by the fact that the stakeholders studying the system did not have the same understanding of the supply

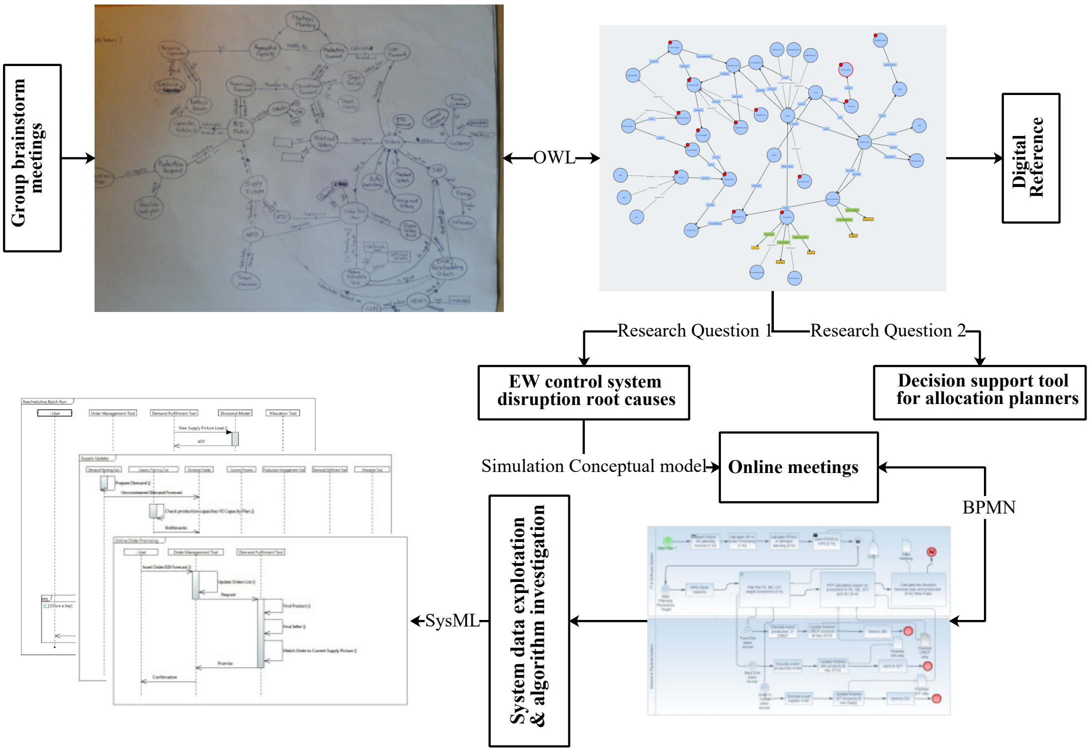

Figure 3. Pathway for implementing and using MBSE approaches for system understanding, communication with stakeholder, define research question, conceptual modeling, and depth module investigation

chain in question. The varying MBSE methodologies play the role of liaison between stakeholders for questions of reserach, definition, and communication. The pathway presented in Figure 3 illustrates the role of the three different MBSE methodologies within this research.

Figure 3 shows that we initially participated in the Digital Reference's group meeting of Productive 4.0 (Work Package 7 (WP7)) which used OWL as its MBSE methodology for analysing the planning system and relevant disruptions. These brainstorming meetings supported us to understand the planning system, define system disruption, and discuss our research questions. With the aid of two supply chain experts and five other researchers in other domains of the system, we participated in modeling a digital reference of the planning system. The hand-drawn diagram derived from the initial brainstorm meetings was then transferred to an ontology of OWL and using Protégé [45]. This indicates separable classes (subjects) of the planning system linked by the property to another class or object.

The first draft of the model was used as a baseline in subsequent meetings. These models formed digital references [12] that allowing us to communicate our research questions, and provide a common language between stakeholders of Corporate Supply Chain (Germany) and Customer Manager (Ireland) whom we were aiming to work with. The outputs of OWL lead us to define two research questions regarding order management within the planning system. First, the EW issue (defined above) for which we wanted to find the root causes and for which we used simulation (see Figure 3) and second, an allocation issue that human planners deal with manually for which we proposed a decision support tool based on operations research.

In workshops, OWL was used to map out high-level class and relations, allowing us to gather knowledge from SC experts and to identify EW using simulation, enabling us to identify root causes. In order to achieve this kind of simulation models of real-world systems, a preliminary abstraction step called conceptual modeling is needed.

Once we arrived at the system definition and defining the hypothesis using OWL, a conceptual modeling was build using BPMN which allowed us to communicate with non simulation experts, but SC experts. This provided a common language for the meeting to ensure we used the correct conceptual model to build an Anylogic [4] model [39].

Although BPMN satisfies all requirement of simulation modeling in our case, further exploration regarding root causes was needed. For this we used SysML as a system of communication. The simulation model could mimic the system behaviour and prove the hypothesis, but for extracting the correct data source we needed to know further the details of the promising algorithms and rule-based APS. To achieve this goal, SysML with different diagrams played a crucial role allowing us to map the internal algorithms with the supporting Sequence Diagrams. These diagrams were used in online meetings to plan data extraction with the lead principal supply chain manager, IT experts, allocation managers, supply chain engineers, and project managers.

To shed light on the selection of tools for understanding of systems disruption and analysis, we investigated three different MBSE methodologies with their relevant tools which are described in the next subsections.

4.3. *Web Ontology Language*

Within work package seven (WP7) of the Productive 4.0 project, the authors participated in developing the Semantic Web-based digital twin as a digital reference of a semiconductor manufacturing supply chain [12]. Within in this project the Digital Reference ontology is designed to benefit: the automation of the sales, assist in building standard simulation models, use for data preparation of deep learning, and knowledge sharing. With the aim of this ontology development as stated above, we communicated with stakeholders, improved our understanding, and explicitly shared our knowledge. It initially provided us with an easy understanding of disruption within the SC system and other challenges that we dealt with quantitatively by the means of simulation analysis and mathematical optimization.

Protégé is a tool, which provides web-based editing functionality, visualization, and model reusability. As presented in Figure 4, the OWL consists of the definition of system elements and their relationships while features of each element could also be stated. In our case, the main objective is revealing the sources of disruptions in the control system generating EWs. The OWL allows visualization of the control system when the ATP-based promised order could not be satisfied in the new scheduling run, which can be resolved automatically by the software or may need to be manually resolved by a planner. The data that it uses for the calculation and instabilities analysis depends on which IT system is used, mainly the divisional model part which has its own computational algorithms, input data, and software packages. To represent this knowledge, a part of the developed OWL is presented in Figure 4.

Negative Early Warning (nEWs) are the result of the control system that we are focusing on, which shows the orders where the promise could not be met. *nEWS*, a [**class**], is the result of, *OrdersRescheduling* (not shown fully in Figure 4), another [**class**] and *isResultOf* is an [**object property**]. *OrdersRescheduling* results in *OpenOrderBook* and its data contains *ConfirmedQuantity* and *ConfirmedDate.*

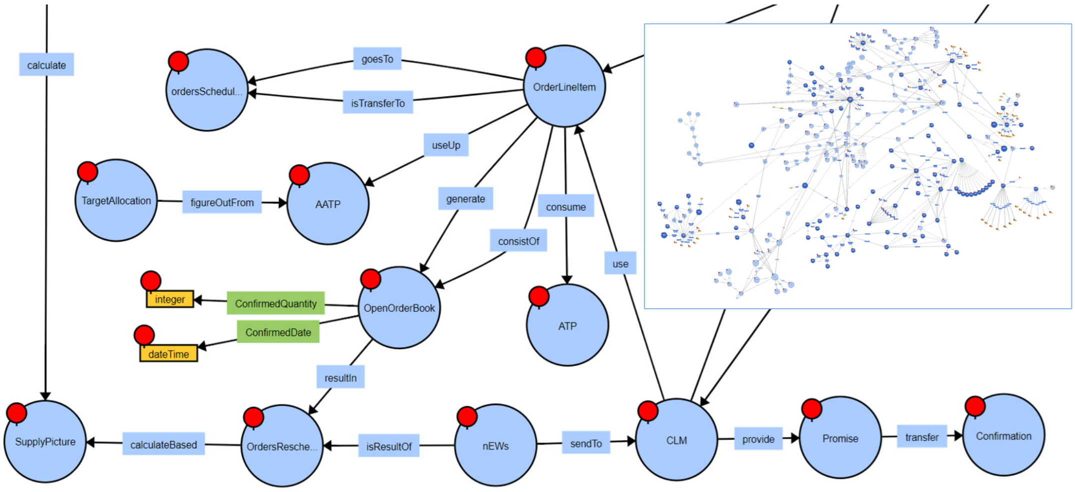

Figure 4. OWL of Order Management and Early Warning Control System developed by Protégé and visualized by WebVOWL. The whole digital references of the semiconductor manufacturing and supply chain presented in the box on top-right

OpenOrderBook consists of *OrderLineItems* which consume *ATP*. Allocated Available to Promise *AATP* provide the *Target Allocation*. Customer Logistic Manager (*CLM*) use this nEWs report to provide *Promise*. Based on this example of the OWL, one can see how it can clearly depict classes and properties for system knowledge understanding. It is case dependent and the definition of classes depends on the perspective of modelers and their objectives. It helps us to understand the essence of the planning system's entities and their relations to better create our abstraction of the studied system that we modeled later with BPMN.

4.4. *Business process modeling notation*

BPMN has become a de facto graphical process modeling language because of its comprehensive semantic, simplicity, and expressive knowledge sharing. BPMN can map processes in different business levels which is in alignment with supply chain system modeling and simulation analysis. As presented in Figure 5, we used BPMN via an Eclipse plugin for capturing the steps of the process. The notations like start (time-based or message-based) and end processes with varying types of tasks (human-based, service-based, etc.), hierarchical structure for depicting different levels or subsystems, in addition to model validation feature, make BPMN the closest MBSE approaches to discrete event simulation modeling.

Figure 5 represents essentially the developed conceptual model for the simulation of the EWs control system. The EWs system is defined by two separate business layers: (1) *Material & Physical System* and (2) *IT & Software System*. In the bottom layer, production lines in the *Front End*, *Back End*, and *Good in Transit* (distribution) get their plans from the *IT & Software System* (top layer) based on time-events which are mentioned inside the processes. The import and export of data from and to databases are also presented as *OOB1* (Open Order Book) which store the unsatisfied orders in a data store. This process was experimented with analytically using simulation with Figure 5 presented as the conceptual model to stake holders.

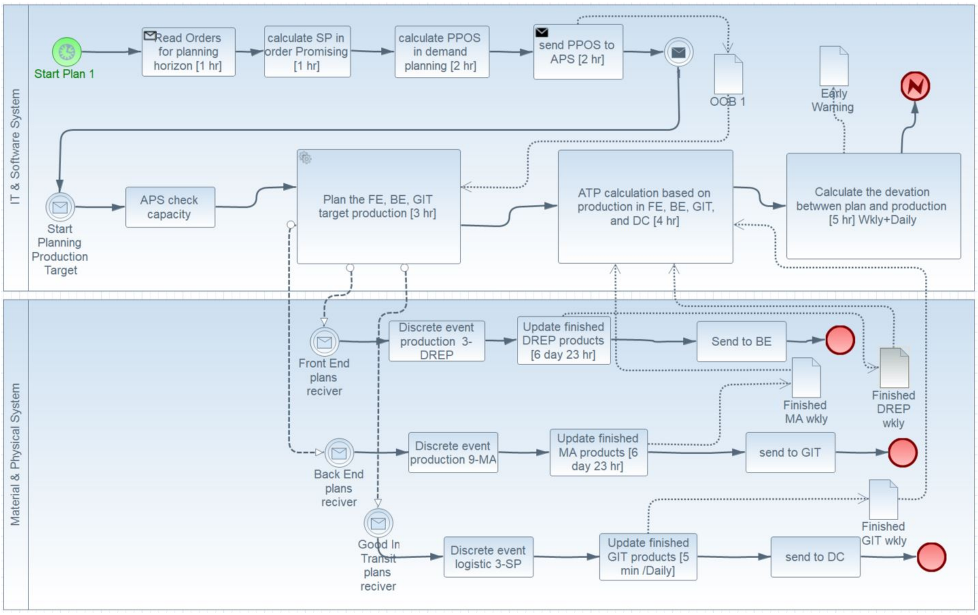

Figure 5. Business Process Modeling Notation with Eclipse. It consist of two layer of IT system and Physical system and each module (box) could be expanded in deeper layer. SP, PPOS, DREP, MA, and GIT are product granularity according to real system.

4.5. *System modeling language*

Compared to OWL and BPMN, SysML is able to express deeper levels of detail about a system. This could represent the subsystems of a system from different perspectives such as the sequences of processes and collaboration between individual entities, the system behaviour from start to finish of a specific activity, etc. We use it for requirements gathering by investigating the sequence diagrams of planning modules related to EW. In our analysis several SysML sequence diagrams were developed, here to illustrate we present one SysML sequence diagram.

The sequence diagram presented in Figure 6 illustrates the *Rescheduling Batch Run* which is designed to repromise all the orders against the last ATP/AATP every day. This module certifies the feasibility of confirmed delivery dates. As presented, the *Demand Fulfillment Tool* loads the new supply picture from the *Divisional Model*. Then, if a product is on short supply (*Product on Allocation*), target allocations are loaded from the *Allocation Tool* and the *Allocation Planning* is performed. (Note as SysMl allows hierarchical modeling this shows a lower level model.) Orders are repromised based on the new supply picture in *Orders Repromising* and *Cross Confirmation Run* processes. Once a week, another process is performed which is the *Improvement Run*. As a result of *Batch Rescheduling*, if the orders cannot be confirmed on this date, the new promised dates and quantities will be reflected and *EWs* will be issued by the system. In fact, the *Demand Fulfilment Tool* provides information regarding supply change to the *Order Management Tool* through *EWs* which will forward them to the customers.

Based on the modeled sequence diagrams understanding the modules and system entities involved in the disruption propagation in the form of EWs are easier to understand. Visually showing how the demand is inserted, how the supply is updated, and how the re-promising process is done makes the analysis of the system more practical. Theses diagrams used for defining the right databases and data extraction schedule to

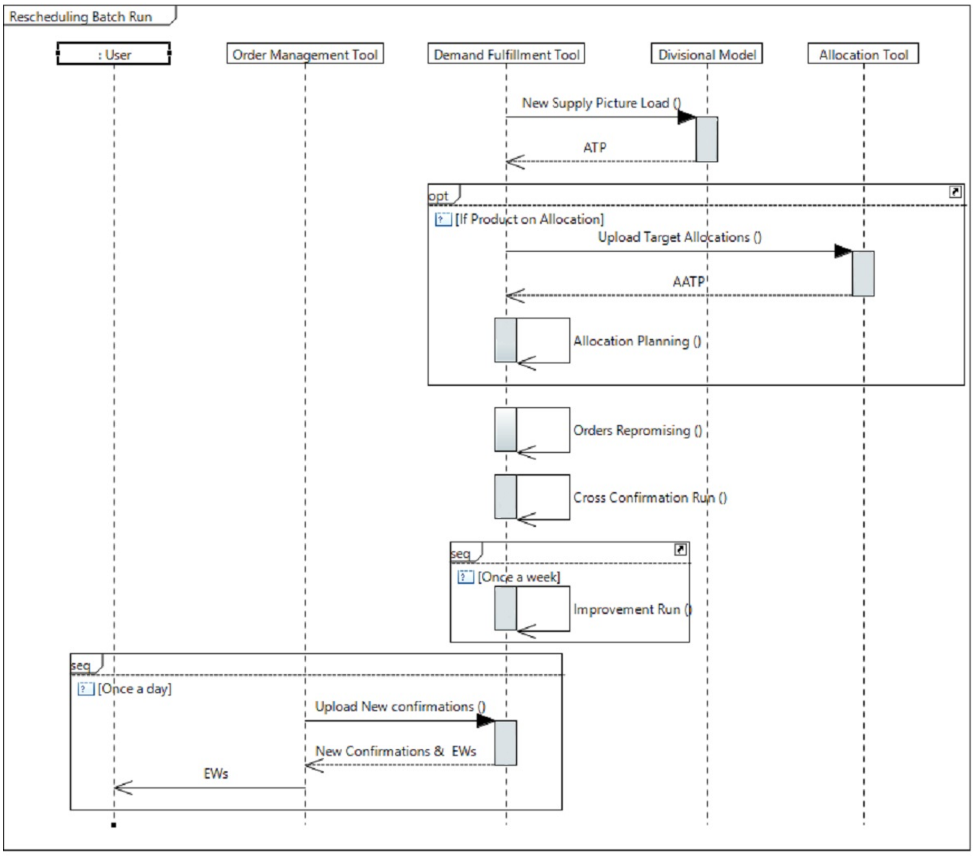

Figure 6. Rescheduling Batch Run Sequence Diagram.

be used for data analysis to find root causes for EWs. The output of SysML supported us to discover the sources of disruption that causes these EWs.

5. Discussion

In this section, with the goal of analysing disruption analysis in this case study, we provide our conclusions from the investigation of the three MBSE approaches. The rest of this section focuses on lessons learned from this case for advancing disruption analysis with the use of MBSE as initial steps in disruption management. We delineate advantages of MBSE for disruption management, advantages and disadvantages of each approach in addition to managerial perspective, limitation, and future works.

5.1. *To what extent did MBSE support disruption management?*

Disruption management is not a single process toward stabilizing the supply chain and manufacturing system. In fact, it requires concrete methodological steps to deal with instabilities and ripple effects. The ultimate objective of disruption management is to recognize the source of the instability and its effects (ripple effect) in order to improve the planning or physical system or whether to deal with instabilities actively or proactively. In order to obtain this goal, the main method for measuring disruption, evaluating networks, and proposing decisions is the quantitative one which has been the focus of many researchers and reviewed comprehensively [23]. A missing chain in disruption management that is investigated by few researchers [64] is the lack of structured requirements gathering methodology for linking the phenomena of disruption with relevant quantitative methods for improved management of the system. In our case study, the use of MBSE provide a common language between researchers and experts. A back and forth communication was the means for developing MBSE models to help us to efficiently understand the system and build quantitative models.

Having a referential or methodological MBSE of planning and supply chain systems in time of disruption support SC operators and experts. First, referential aspects provide a common language to better collaborate for recognizing vulnerabilities and viable criteria with an MBSE methodology and second, it supports decision makers to develop the conceptual modeling of quantitative analysis (for our case study simulation and optimization methods) for analysing the current situation and proposing solutions in an efficient way.

5.2. *What are the advantages and disadvantages of OWL?*

Our lesson learned from ontology development using OWL as a part of semantic web technology is that it is easy to learn and convenient language with several tools designed in alignment with machine readability technologies. It has practical applications in automation and digitization of machine processes especially Cyber Physical Systems (CPS). It is very flexible and easy to maintain during the whole system's life cycle compared to SysML and BPMN. As a referential model for SE, OWL could convey system knowledge better than other approaches by defining the relations between defined class. However, it could not visualize all the processes in the system. Moreover, it has no standard and defined structure of syntax and semantics but there is inconsistency in how it models the same system. The other weakness of ontology with OWL, especially in comparison to SysML, is that it could not keep the consistency and connection between different perspectives of system users and stakeholders within the life time of SE.

5.3. *What are the advantages and disadvantages of BPMN?*

We developed BPMN for simulation analysis of our case study. It is an easy language with visual notation to support communication with experts. Using this methodology in the conceptual model developed we could distinguish between planning and physical systems and show their interaction in addition to hierarchical structure which is demonstrated in Figure 5 on page 14.

One of the advantages of BPMN is that it is an easy tool to understand that requires a low training level for basic understanding. BPMN is easily understandable by different stakeholders as it has been originally designed with business users in mind [43]. It could easily convey vast amount of information to stakeholders and experts without in-depth knowledge in MBSE. BPMN is very useful for understanding and developing hypothesis by quantitative methods like simulation modeling. However, there are some issues with the use of BPMN in term of simulation support. Operational simulation is out of the scope of BPMN and this standard was not specifically designed for simulation modeling [59]. This may explain the limited technical capability of BPMN and BPSim to represent some important features of complex flows in a business process which limits the usefulness of these standards for complex simulation models. Onggo et al. [42] identified resources, queues and Key Performance Indicators (KPIs) as modeling elements that are relevant to closing the gap between a BPMN diagrams and simulation. As well, it should be noted that BPMN ambiguities may also raise the risk that different tools adopting different interpretations of BPMN which may influence the automatic generation of executable simulation code [42].

5.4. *What are the advantages and disadvantages of SysML?*

Detailed investigation of the source of disruption in the IT system required a deeper investigation of software algorithms, database communication, and process flow of functionalities within the planning system. These all lead us to better see the benefits of SysML as a detailed modeling approach.

SysML has more capabilities in referential modeling of a system providing a standard and comprehensive system specification paradigm [63]. This provides a consistency in terms of model syntax and semantics, together with unambiguous graphical symbols, which can greatly improve communication. It could detail individual elements of planning and the relations hierarchically. As well, since its adoption, SysML has lead to increased adoption of MBSE practices across industry.

SysML is nevertheless criticised for providing too much freedom to the modeler, allowing important information to be represented in an obscure manner in a SysML diagram [20]. A further weakness of SysML is the associated learning effort. It has been reported that it took around 1.5 man months to train project teams to an acceptable competency in SysML and a SysML tool [3].

5.5. *Managerial perspective toward the use and selection of MBSE approaches for disruption management*

Beyond the advantages and disadvantages of these tools, MBSE applications have several challenges that we highlight here to be considered to support managerial decision such as:

- Lack of concrete quantitative performance indicators to evaluate the quality of the implemented MBSE projects.
- MBSE project implementation highly depends on the domain of application.
- The selection of standards and tools depends on complete understanding of objectives, time, broadness, and budget of the project.
- The participation of stakeholders and modelers' expertise define the achievements of MBSE implementation projects.
- The MBSE implementation is tightly connected to change culture within the organization.

As a result, to efficiently deal with these challenges, developing a proper implementation methodology and choosing the right MBSE approach require consideration of stakeholders' perspectives, definition of the domain of application, making clear the requirements, planning the change management approach, and the strategic plan for project implementation to achieve lasting success.

5.6. *Limitations*

First, gained knowledge and insight with each modeling approach had impact on output of the next used MBSE methodology. As previously discussed, we developed OWL, BMPN, and SysML, respectively. Second, MBSE is a wide and vast area of knowledge, and here we restricted to the domain of one case study. The aim of these tools for us is to assist in revealing the source of disruption and modeling the system based on the developed hypothesis. Third, each of these approaches have several features which we did not need to cover in our cases study. Finally, here we aim to evaluate MBSE in the initial stages to help understand disruption in SC systems and to assist in the support of quantitative methods, where the MBSE methodologies were used to communicate with the different stakeholders within the system.

6. Conclusion and future work

Advanced MBSE methodologies and tools have been introduced as referential and methodological SE approaches. MBSE has several benefits over document-centric SE and wider domains of application such as system architecture and improvement, change management, and quantitative analysis. Several tools and approaches have been developed and evaluated according to the requirements of SE. It has been shown that keeping the MBSE up-to-date throughout a system life cycle is harder than its initial application. Although MBSE is still maturing, the cost of SE analysis with MBSE tools is decreasing in overall costs [34]. In addition, MBSE has undeniable benefits on improving the systems resiliency and validating its performance in possible occurrences of risks [35]. As demonstrated in this article, the advantages of MBSE are unambiguous and they have been proved in many research projects and in real applications [25].

In this work, we introduced MBSE approaches, its domains of application, and a brief investigation on current approaches and relevant tools. We selected three different MBSE methodologies and their tools for evaluating MBSE in the context of analysing disruption of a complex supply chain planning system. We examined these tools according to a real case application where the scope is analysis of disruption within this system. This case study is related to our work on debugging and improving a semiconductor SC system. OWL, BPMN, and SysML where the examined methodologies in this work. However, selecting the best one depends mainly on the objectives and domain of application [48] which we try to shed light on in this regard.

MBSE application for disruption analysis of DELS require more investigation by researchers. For filling gaps, we suggest further case application, tools evaluation, and categorization of application domains. Furthermore, developing ontology for transferring MBSE to quantitative analysis could add value to disruption management studies. Investigating the reasoning capabilities of MBSE tools in analysing developed model is another open avenue that need to be considered by researchers.

Acknowledgement(s)

This project has received funding from the Electronic Component Systems for European Leadership Joint Undertaking under grant agreement No 737459. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation program and Germany, Austria, France, Czech Republic, Netherlands, Belgium, Spain, Greece, Sweden, Italy, Ireland, Poland, Hungary, Portugal, Denmark, Finland, Luxembourg, Norway, Turkey. This publication has emanated from research conducted with the financial support of Science Foundation Ireland (SFI) under Grant Number SFI 16/RC/3918, co-funded by the European Regional Development Fund.

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