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A Maturity Model for Data-Driven Model-Based Systems Engineering for Producing Companies

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Abstract: With recent trends in artificial intelligence and data analytics, producing companies are shifting their development processes to digital methodologies. This allows to manage the complexity of produced systems more efficiently and effectively. By this data from different lifecycle phases can be integrated into engineering models to optimize their properties. A promising approach that combines the model-based and data-driven worlds is data-driven model-based systems engineering (DDMBSE). DDMBSE focuses on a data-driven system model to continuously manage and update engineering artifacts with multiple data sources. But DDMBSE is difficult to practice due to a lack of guidance. Therefore, a DDMBSE maturity model has been developed. It structures an organization's DDMBSE maturity into six levels and organizes the criteria into model-based and data-driven categories. Each criterion includes a description and recommended actions to reach the next level. The maturity model was evaluated by two companies in the consumer electronics and electronic components industries.

Keywords: complex systems, data driven design, maturity model, systems engineering (SE), advanced data analytics

1 Introduction

It appears that data analytics is becoming a guiding principle for many domains and companies in the current era. The exponential growth in the volume of data generated by the Internet, network infrastructures, software solutions, platforms, and a wide variety of new products, including cyber-physical systems (CPS), has generated considerable optimism, particularly in light of the advent of digitalization (Statista, 2021, 2022). This is because they all generate and use data for a variety of integrated functions. The field of autonomous driving, for example, provides a useful illustration of this phenomenon. In order for the system to drive independently and autonomously, it requires a large amount of information in real time, such as camera systems and lidar, to carry out its functions safely. Data analytics (DA) is a fundamental component of this process, serving to provide the requisite functionality. In addition, data analysis can be employed to examine higher-level behaviors, such as those exhibited by fleets, or to conduct retrospective analyses of problematic behaviors, with the objective of enhancing the overall performance of the system. Nevertheless, the implementation of DA is a challenging process. As stated by Martinez et al. (2021) DA projects present three levels of challenge: *team management*, *project management*, and *data and information management*. In the context of *team management*, several issues have been identified, including poor coordination, difficulties in collaboration across teams, and a lack of transparent communication. Additionally, there is a deficiency of individuals qualified for the role of data analyst, which results in an over-reliance on leading data analyst and difficulties in the formation of multidisciplinary teams. *Project management* challenges include low process maturity, unclear business objectives, unrealistic project expectations, and a biased emphasis on technical issues. This can result in the delivery of incorrect solutions and projects that are not utilized by the business. The *management of data and information* presents significant challenges, including a lack of reproducibility, and accumulation of knowledge, as well as low data quality for machine learning. Furthermore, there is often a lack of sufficient quality assurance checks, an absence of data validation, and concerns regarding data security, privacy, and investment in IT infrastructure (Martinez et al., 2021).

A comprehensive examination of these challenges reveals several parallels with the development of modern technical products, which are known as CPS (Tränkler and Kanoun, 2007). As technologies become increasingly integrated, the development of CPS is affected by the diverse perspectives of the various stakeholders and the respective domains involved. Projects in this context are inherently interdisciplinary and highly complex. The management of such projects and the provision of information traceability present significant challenges. Model-based systems engineering (MBSE) addresses these challenges by providing a system model of the system-to-be-developed (INCOSE 2023). To achieve this, it is necessary to utilize a modelling language (e.g. SysML), a modelling method (e.g. FAM) and modelling tools (e.g. CAMEO). The system model enables stakeholders to view the system from different perspectives and provides access to the specific information required by each domain, e.g., mechanical engineering (INCOSE 2023). A multitude of industries, including aerospace, military, and consumer electronics, utilize MBSE to understand their products and services, their environment, trace relations and changes, and coordinate processes (INCOSE 2023). Nevertheless, as DA is just emerging in the engineering domain, particularly in MBSE, the integration of DA domain is not yet complete (INCOSE 2021).

Data-driven model-based systems engineering (DDMBSE) by Tissen et al. (2023, 2024) tries to solve this issue, by combining MBSE and DA into one methodology and offers an integrated view of both domains. However, applying DDMBSE due to its scares research is challenging for users and companies. A lack of methods is specifically mentioned by Tissen et al. (2023, 2024). Lead by this motivation the paper at hand addressed the research questions: *How can companies be supported in applying DDMBSE in their organization and process? What criteria are necessary to be fulfilled for this?* This paper begins with an overview of the scientific background in Section 2, which includes an examination of DDMBSE and maturity models, as well as an analysis of the current challenges associated with these topics. In Section 3, the research methodology is described, followed by the results in Section 4 and the evaluation of the maturity model for DDMBSE in Section 5. The paper concludes with Section 6 outlining future research steps.

2 Scientific Background

In the following section, an overview of data-driven model-based systems engineering, and maturity models is given. Both sections describe the status quo in each domain and serve as a foundation for the proposed approach presented in this paper.

2.1 Data-driven model-based systems engineering (DDMBSE)

Tissen et al. propose that data-driven model-based systems engineering (DDMBSE) represents a promising approach for the continued evolution of MBSE. The authors define DDMBSE by six core aspects, which are illustrated in Figure 1 (Tissen et al., 2023):

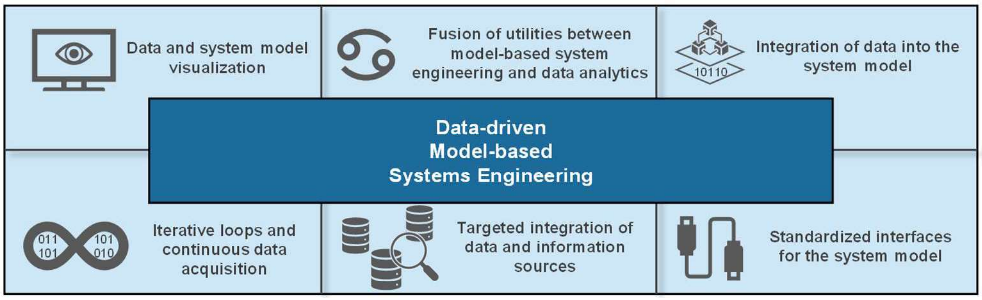


Figure 1. Six core aspects of DDMBSE after Tissen et al. (2023)

In its initial form, DDMBSE integrates the capabilities of MBSE and DA. The term "utilities" is used to refer to domain-specific processes, methods, techniques, languages, and tools that originate from MBSE and DA. This combination enables the construction of a data-driven system model that integrates data from disparate, targeted sources. The crux of the matter is that the data is iteratively looped and continuously acquired, ensuring that every change in the system model can be reflected in real time. The system model itself gains a dynamic characteristic, as opposed to the static system model that is characteristic of MBSE. As a requisite condition, standardized interfaces must be employed between the data sources and the system model. The integration of data-driven methods into MBSE will result in more efficient and effective development of complex technical systems (Tissen et al., 2023, 2024).

2.2 Maturity models

Maturity models represent a structured framework for evaluating current capabilities, identifying areas for improvement, and guiding the enhancement of processes to achieve higher levels of maturity. They have been well established within research and industry for this purpose. Maturity models are designed to assess and improve various aspects of processes or systems within organizations, thereby allowing for standardization. Organizations utilize these models to assess their actual status in a specific area (e.g., digitalization) and define target status to be achieved (Khoshgoftar and Osman, 2009). A review of the literature reveals that numerous maturity models have been developed in the context of research. Notable examples include SPICE, CMMI, and BPMM (Khoshgoftar and Osman, 2009, Ilin et al. 2022). In the field of data analytics, Król and Zdonek (2020) conducted a comparative analysis of eleven analytics maturity models, including APMM, DAMM, Gartner's Maturity Model for Data and Analytics, and SAS Analytics Maturity Scorecard. In general, the analysis indicates that most analytics maturity models lack transparency in their guidelines for assessing. In addition, they stress the importance of *human resources*, *information technology*, *software infrastructure*, and *organizational aspects* in the development of maturity models for data analysis (Król and Zdonek, 2020). In the field of systems engineering (SE), maturity models are employed for a variety of purposes. The SE-CMM, as proposed by Cusick (1997), is focused on the processes within a company, in alignment with the approach presented by Cornu et al. 2012. In the field of requirements engineering, Solemon et al. (2012) propose a four-level model called REPAIM (Requirements Engineering Process Improvement and Assessment Model). Bretz (2021) presents a maturity model for the introduction of systems engineering and model-based systems engineering. The evolution and extent of maturity models in DA and MBSE are both increasing. Nevertheless, the integration of these two domains has yet to be explored (Tissen et al. 2023, 2024). Given that DDMBSE is a new research field with limited research, this is understandable. However, it also presents an opportunity for further investigation. Although the presented approaches are all focused on their respective domains, a shared view has not yet been achieved as it lacks supporting methods and tools (Tissen et al. 2023, 2024). However, DDMBSE is dependent on this shared perspective, which leads to the conclusion that the application and measurement of DDMBSE is not straightforward using current maturity models from DA and MBSE. To enable companies to actively position themselves within DDMBSE and to use it in their organization and processes, it is necessary to provide them with supporting materials. The following approach addresses this need.

3 Research Methodology

This chapter outlines the research methodology employed in the development of the DDMBSE maturity model. The methodology is based on a six-phase approach, as proposed by Bruin et al. (2005), and is presented in Fig. 2 which is followed in this paper:

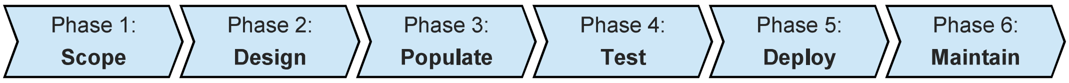


Figure 2. Six phases for developing a maturity model after Bruin et al. (2005)

The **initial phase (Phase 1)** of the model development process involves defining the scope of the model. This includes determining whether the model will be domain-specific or general. A domain-specific model is characterized by a fixed subject of investigation, providing tailored solutions for a specific area or industry. In contrast, general models focus on overall improvements in quality, time, and cost, such as in product development (Bruin et al., 2005). In this case, the focus of the model is domain specific since it addresses DDMBSE particularly. The development stakeholders come from academia, but with a near relation to practitioners and or pre-knowledge in practice. In the **design phase (Phase 2)**, the fundamental structure of the model is established (Bruin et al., 2005). This phase is guided by several key questions: *Who the audience is? How and where should the model be applied? Who needs to be involved in its application? Who will be a respondent?*. Answering these questions helps define the model's purpose, application process, stakeholder involvement, and expected outcomes, ensuring that it is relevant and actionable. For the DDMBSE maturity model the audience will be practitioners and executives of DDMBSE, but currently most likely MBSE and or DA in a company, since DDMBSE is just at the horizon of being used widely. The application focuses on a self, or third party supported assistance, depending on the intention of potential users but allowing a self-assessment of the model. As a result, the respondents of the DDMBSE maturity model will be the company's management and staff, including the users of maturity model. Since the application of DDMBSE is not yet widely researched, not all development directions can be anticipated. Apart from that, several maturity models in MBSE and DA (see Section 2) are available with a more diverse focus and practical assessments. They can be used for domain specific aspects in DA and MBSE, but do not allow a combined view. Taking this into mind, the maturity model should allow an easy usage and support users in taking action to achieve individual next maturity levels. The **populate phase (Phase 3)** involves the detailed development of the model's structure (Bruin et al., 2005). The primary focus is on defining the subject of investigation and identifying its success factors. This phase ensures that the model is comprehensive and addresses all critical aspects necessary for its effectiveness. Following the proposed vision of DDMBSE after Tissen et al. (2023, 2024), a central artifact in DDMBSE will be the data-driven system model. Setting this vision as the goal to reach and achieve DDMBSE, the current counter state is (MB)SE. With these two banks defined, the figurative pillars (levels) can be graded and characterized. Following the widely used and suggested level concept by Bruin et al. (2005), the maturity levels separation will set between six levels (SE Level 0 – DDMBSE Level 5). For the assessment areas, the identified potentials, challenges, and preconditions after Tissen et al. (2023, 2024) are used as a base. Deriving clusters from this, the assessment areas are defined. By the defined maturity levels and assessment areas, the specific assessment criteria in each area and level were defined. Following an iterative approach, the maturity model was filled out. In parallel, necessary actions to reach each level in each area were considered into this. During the **test phase (Phase 4)**, the model is validated in real-world scenarios (Bruin et al., 2005). This phase assesses the practicality and effectiveness of the model by testing it in practice. The focus is particularly on the applicability of the success factors. The testing process is iterative, often requiring multiple rounds of feedback and adjustments to refine the model further. For this phase we tested the maturity model with two producing companies, currently in different stages of integrating DA and MBSE into their processes. In separate interviews of 1 to 1,5 hours with two leading practitioners and executives from each company. The results show a clear practical applicability, offering an important aid for the wider application of DDMBSE. In the **deployment phase (Phase 5)**, the maturity model is made available to users within the organization (Bruin et al., 2005). This phase entails a gradual introduction, typically commencing with a pilot implementation in a specific area before expanding to other parts of the organization. This two-step approach facilitates the transition and ensures a smooth adoption, allowing the organization to adapt progressively to the new model. The **final phase (Phase 6)** of the model development process is dedicated to the ongoing maintenance and enhancement of the model (Bruin et al., 2005). As the needs of the organization and external conditions evolve, it is imperative that the model be continuously updated to maintain its relevance. Furthermore, this phase entails the standardisation of the model with the objective of facilitating its broader acceptance and integration within the organisation. The continuous adaptation and improvement of the model ensures its continued effectiveness over time. By adhering to this structured methodology, it is ensured that the maturity model developed is both robust and applicable, thereby providing a reliable framework for organizational improvement.

4 Results

By application of the research methodology, a **maturity model for data-driven model-based systems engineering (DDMBSE)** was developed. It defines the transition from classical SE, over MBSE towards DDMBSE in steps of six levels. The assessment criteria for each level are clustered into five areas: *competencies*, *organization*, *data-driven system model*, *IT & tools*, and *data*. Each area contains several sub areas to rate the maturity level. As an addition, **recommendations for action** for each sub area are developed, describing necessary actions to evolve from one level to another in each sub area.

4.1 Maturity levels for DDMBSE

The maturity model for DDMBSE comprises a **six-level grading system**, commencing with **Level 0**, which encompasses SE as a foundational base (see Fig. 3). **Level 1** represents the transition from SE to MBSE, whereby models are employed for the development of technical systems without any contact or involvement of a software modelling tool (usually done in a workshop). At this juncture, **Level 2** is attained, signifying the establishment of a robust foundation in MBSE with software modelling tools. At **Level 3**, it is established that the company has nearly fulfilled its commitment to the use of MBSE, and that the first involvement with DA is underway. The two domains operate independently, with minimal interconnectivity. The initial concepts for data analysis are presented and subjected to evaluation. At **Level 4**, there is a shift in focus, with MBSE now integrated with DA. The initial demonstrators, which include the linking of data sources from the system of interest (SoI) to the DA and MBSE domains, are constructed and linked between the aforementioned domains and their underlying tools. Both domains now communicate about the results of analysis and potential actions based on them. The highest level of development, **Level 5**, represents the fully applied DDMBSE. This is a data-driven system model that is connected to a multitude of data sources, both within and outside the company. It is capable of autonomously managing itself (Tissen et al., 2023, 2024). The decision-making regarding the necessity of a given action is then conducted by the developer (systems engineer).

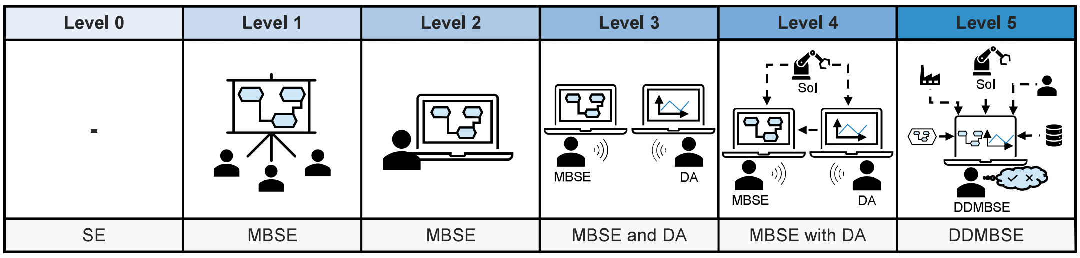


Figure 3. Levels in the maturity model for DDMBSE

4.2 The maturity model for DDMBSE

With the level grading described in section 4.1, now the complete **maturity model for DDMBSE** can be described (see Fig. 4). It contains five areas and twelve sub areas called action elements (AE). Each area including the AE will be described in the following.

Area Competencies: In this action element group, competencies within MBSE, DA and the integration of both are measured. For the MBSE competencies, grading goes from *"The user has not MBSE competencies."* (Level 0) to *"MBSE knowledge is at an expert level and is applied at the highest level in all projects"* (Level 5). A similar grading is available for DA. Also, the integration of both domains is graded, whether they have no overlaps or are completely linked. As DDMBSE is based on MBSE and DA, both areas need a high level of knowledge, theoretical and practical wise (Tissen et al., 2023, 2024).

Area Organization: For the area organization, the maturity model provides a rating for the grade of MBSE and DA integration into the companies' organization. For each action element the grading goes from *"…is not integrated into the organization"* (Level 0) to *"… is fully integrated into the company and its organizational structure."* (Level 5). MBSE is a method that needs wide and deep acceptance in a company since its benefits will not show directly but in long term. DDMBSE takes this characteristic also, as described by Tissen et al. (2023, 2024).

Area Data-driven system model: As a central artifact in DDMBSE, the data-driven system model also needs to be looked at. Since DDMBSE after Tissen et al. (2023, 2024) postulates a fully autonomous and linked system model, a system model needs to be available and necessary information must be visible for the user. So, the development stage of the system model and its visualization level are important to be looked at, here included by the action elements.

Area IT & Tools: Both MBSE and DA (and therefore also DDMBSE) rely on a well-functioning and connected IT infrastructure together with the use of software tools from different domains (Tissen et al., 2023, 2024). As an important factor the maturity of DDMBSE tools (and similar MBSE and DA tools) needs to be looked at, as well as the level of available interfaces within the company. This also results into the IT infrastructure adaptability, going from *no IT infrastructure* to *fully integrated.*

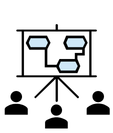
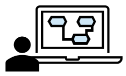
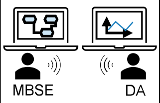
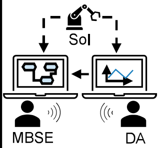
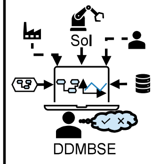
Action Element Group	Action Element	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5
Icon							
Naming		SE	MBSE	MBSE	MBSE and DA	MBSE with DA	DDMBSE
Competencies	MBSE Competencies	The user has no MBSE competencies.	Basic knowledge in the area of MBSE is present. The modeling tools used are known.	Basic knowledge in the area of MBSE is present. The modeling tools are known and have already been used in smaller projects.	MBSE has been successfully applied in projects.	MBSE knowledge is at an expert level. The applied methods and tools are used across all levels.	MBSE knowledge is at an expert level and is applied at the highest level in all projects.
	Data Analytics Competencies	The user has no Data Analytics competencies.	Basic knowledge in the area of Data Analytics is present.	Basic knowledge in the area of Data Analytics is present and has been applied in smaller projects.	Basic knowledge in the area of Data Analytics is present and has been used in several projects.	Data Analytics knowledge is at an expert level and used across multiple projects.	Data Analytics knowledge is at an expert level and is applied at the highest level in all projects.
	Integration of MBSE and DA	MBSE and DA are not connected.	MBSE and DA are connected in individual cases.	MBSE and DA are connected and have been used together in several projects.	MBSE and DA are connected and are regularly used together in various projects.	MBSE and DA are fully integrated and used in a coordinated way in all projects.	MBSE and DA are fully integrated and used in a coordinated way across all projects and organizational levels.
Organization	MBSE Integration	MBSE is not integrated into the organization.	MBSE is integrated into the first areas of the organization.	MBSE is integrated into the first projects of the organization.	MBSE is integrated into the company and applied in several areas.	MBSE is widely integrated into the company.	MBSE is fully integrated into the company and its organizational structure.
	DA Integration	DA is not integrated into the organization.	DA is integrated into the first areas of the organization.	DA is integrated into the first projects of the organization.	DA is integrated into the company and applied in several areas.	DA is widely integrated into the company.	DA is fully integrated into the company and its organizational structure.
Data-driven System Model	Development Stage of the System Model	There is no system model present.	An initial system model (e.g., digital, using modeling tools) is present.	The first system model is created in a modeling tool.	The system model is present in a modeling tool and is regularly maintained and updated.	The system model is present in a modeling tool and is regularly maintained and updated.	The system model is present in a modeling tool, is regularly maintained and updated, and is used across all projects.
	Visualization of the System Model	No visualization.	Initial visualization using modeling tools is present.	Initial visualization using modeling tools is created and used in projects.	Visualization of the system model is present and regularly used in projects.	Visualization of the system model is present, regularly used in projects, and allows for data analytics.	Visualization of the system model is present, regularly used in projects, allows for data analytics, and is tailored to specific needs.
IT & Tools	Tool Maturity in DDMBSE	No application of MBSE and/or DA tools.	Workshop materials and Brown Paper are used.	Modeling tools and DA tools are used.	Modeling tools and DA tools are used, and one tool is applied.	Modeling tools and DA tools are used and combined in projects.	Modeling tools and DA tools are used and integrated into the tool landscape.
	Technical and Ontological Interfaces	There are no standard interfaces present.	First ontological interfaces are present, but technical interfaces are in use.	Ontological interfaces are defined and technical interfaces are in use.	Ontological and technical interfaces are used.	Ontological and technical interfaces are fully integrated and in use.	Ontological and technical interfaces are fully integrated and in use.
	Adaptable IT Infrastructure	There is no adaptable IT infrastructure present.	Networked IT tools are tested.	IT tools are used and applied.	IT tools are used and applied across the organization.	IT tools are widely used and integrated into the organizational infrastructure.	IT tools are fully integrated into the organizational infrastructure and used comprehensively.
Data	Data Management	No data management is present.	Data and document transfer in models is present.	Initial manual approaches for data storage are in use.	Defined data storage and security measures are present.	Comprehensive data storage and security measures are in place, including data reviews.	Comprehensive data storage and security measures are in place, including data reviews and data analytics.
	Data Acquisition	No systematic data acquisition is present.	Sporadic, manual data acquisition from documents is present.	Manual data acquisition in individual projects with limited analysis is present.	Manual data acquisition is regularly performed across the lifecycle with complex analysis.	Advanced data acquisition methods are used, allowing for automated data analysis.	Fully integrated data acquisition with automated data analysis and usage.

Figure 4. The maturity model for DDMBSE

Area Data: Without data, DDMBSE cannot be performed (Tissen et al., 2023, 2024). Rating the companies' data management and data acquisition are essential. On the highest level, data management represents comprehensive data storage including a high degree of cyber security. The data acquisition is integrated and allows automated data analysis.

Action Element Group	Action Element	Recommendation for action				
		Level 0 → Level 1	Level 1 → Level 2	Level 2 → Level 3	Level 3 → Level 4	Level 4 → Level 5
Competencies	MBSE Competencies	• Conduct training and workshops on the basics of MBSE. • Provision of learning materials and MBSE resources…	• Introduction of simple modeling tools for MBSE. • Training programs to apply knowledge in practice. • …	• Advanced training programs for MBSE tools and methods. • Application of MBSE in pilot projects to gain experience…	• Assign MBSE experts for sup-port and knowledge transfer • Integration of MBSE into the project management processes…	• Continuous training and certification for MBSE. • Establish feedback loops to continuously improve MBSE applications and …
	Data Analytics Competencies	• Conduct training and workshops on the basics of DA. • Providing resources and learning materials for self-directed learning. • …	• Practical training sessions with a focus on the application of DA tools in small projects. • Mentoring by experienced data analysts to support the transfer (theory to practice)…	• Advanced training in specialized analytical methods & complex tools. • Establishment of inter-disciplinary teams to create synergies between different fields of knowledge…	• Assign DA experts for support and knowledge transfer • Investing in advanced analytics tools and technologies such as AI and machine learning. • …	• Fostering a data culture with continuous learning • Apply predictive and prescriptive analytics to make proactive decisions. • …
	Integration of MBSE and DA	• Define the strategic goals for MBSE and DA within the organization. • Training of staff in the basics of MBSE and DA. • …	• Identification of interfaces where MBSE and DA could complement each other. • Develop use cases that use either MBSE or DA to demonstrate their value…	• Selection of pilot projects suitable for the experimental linking of MBSE and DA. • Conducting inter-disciplinary workshops to develop common…	• Expand integration to more projects and embed them in fixed business processes. • Implementation of best practices from the pilot projects…	• Complete integration of MBSE and DA into all projects and business units. • Constant review and optimization of the combined processes…
Organisation	MBSE Integration	• Introduction of MBSE training for management and key personnel. • Establish a clear roadmap for implementing MBSE in the company. • …	• Launch of small pilot projects to deepen the understanding of MBSE and achieve initial successes. • Creation of case studies that show the benefits of MBSE…	• Scaling MBSE to multiple small projects and expanding the use cases. • Promotion of interdisciplinary cooperation through the involving different departments…	• Intensification of training and support offers for MBSE in order to achieve broader involvement in the company. • Anchoring MBSE in standard workflows and processes…	• Full integration of MBSE into all business processes and decision-making levels. • Build continuous improvement cycles to continuously optimize MBSE practices…
	DA Integration	• Initiating an awareness campaign to communicate the importance of data and its analysis. • Establishment of basic training in DA for employees to promote basic…	• Start of pilot projects in which DA techniques are tested for their practicability. • Apply DA in small projects to gain early usable results and insights. • …	• Scaling the DA application to multiple projects and departments. • Develop and implement company-wide guidelines for the use of DA. • …	• Integrate DA into the enterprise across the board through training programs and resource allocation. • Adapting IT infrastructure to support the collection and analysis of …	• Full integration of DA into the corporate structure, including strategic planning and operational execution. • Adopt continuous monitoring and predictive analytics to enable real-time …
Data-driven system model	Development stage of the system model	• Conducting workshops on the meaning and structure of system models. • Production of the first simple models to sharpen the understanding of the system…	• Selection and training in basic digital modeling tools. • Creation of first digital models to take advantage of digital transformation. • …	• Implementation of processes for regular review and updating of system models. • Integration of feedback from DA to refine and enrich the models…	• Development of aspect-specific dynamic models that focus on specific properties or behaviors. • Establish a link between models and real-time data …	• Fully integrate models with the IT infrastructure to enable continuous updates/data flow. • Applying ML and other AI techniques to make the models self-learning…
	Visualization of the system model	• Raising awareness of the importance of visual representations in workshops and trainings. • Purchase and provide basic visualization tools such as whiteboards…	• Introducing a digital modeling tool that meets the team's needs. • Training of staff in the use of the modeling tool to create digital models. • …	• Selection of an appropriate analysis tool capable of processing the data obtained from the modeling process. • Establish a workflow that synchronizes the use of both tools for …	• Implementation of interfaces or plugins that enable seamless inte-gration between modeling and analysis tools. • Develop processes for the parallel use of tools to ensure the data …	• Build an infrastructure that enables real-time data flows and instant updates of visualizations. • Integration of real-time data sources to instantly map dynamic system changes…
IT & Tools	Tool Maturity in DDMBSE	• Conducting informational workshops on the benefits and basics of MBSE and DA. • Purchase of materials (e.g brown paper) to visualize initial process flows …	• Selection and provision of suitable digital tools for MBSE and DA. • Training of employees in the use of these tools and transfer of the workshop results into …	• Implementation of processes that require the regular use of the tools in projects. • Create clear guidelines for data storage and processing in both tools…	• Development of interfaces or the use of middleware to exchange data between tools. • Build an inclusive data platform, to have a single point of access for data…	• Selecting or developing an integrated system that combines both MBSE and DA in one tool. • Integrate real-time data into the system model for dynamic …
	Technical and ontological interfaces	• Conducting seminars and workshops to raise awareness of the importance and foundations of ontologies. • Identification of the key concepts and relationships within the system…	• Definition of clear guidelines and standards for the creation and use of ontological interfaces. • Selection or development of tools capable of supporting ontological interfaces…	• Regularly review and fine-tune the ontologies to adapt them to new insights and requirements. • Develop best practices for the integration and management of technical interfaces…	• Expansion of ontologies to map more complex system relationships and dynamics. • Extension of technical interfaces to integrate a wider variety of data formats and sources…	• Development of a central interface management system for automatic adaptation to different data formats/sources • Leverage AI and ML to make interfaces intelligent, adaptive and …
	Adaptable IT infrastructure	• Evaluation of business requirements and definition of the company's IT needs. • Introducing a selection of enabling technologies and platforms that support common workflows. • …	• Decisions based on the results of pilot projects, on which tools to implement more broadly. • Creation of a plan for the gradual introduction of IT tools into daily work processes…	• Identify opportunities to connect IT tools to improve collaboration and data integration. • Development of a coherent IT strategy that provides for the expansion of the infrastructure …	• Expansion of the IT infra-structure to support inte-gration platforms. • Develop and implement security protocols to enable the integration of external infrastructures without …	• Implementation of advanced technologies (e.g. AI and ML) for real-time data analysis and optimization of IT infrastructure • Develop dynamic IT management systems…
Data	Data management	• Inventory of all data sources and types of data that exist within the company. • Train employees on how to handle data and introduce basic concepts of data modeling…	• Establish simple manual processes and policies for data organization and storage. • Create data directories and inventories to get an overview of existing data and its location…	• Develop and document company-wide processes for collecting, storing, and managing data. • Implementation of standards and guidelines to ensure data quality…	• Build a centralized data management system that allows for unified manage-ment and analysis of data. • Establish regular reviews and audits to monitor compliance with data quality standards…	• Integration of automated tools and systems that process and update data in real time. • Use business intelligence and data analytics to use data to make strategic decisions…
	Data acquisition	• Developing an awareness of the importance of data throughout the lifecycle. • Identify critical data points relevant to initial collection. • …	• Definition of key phases of the life cycle in which data is to be systematically collected. • Development of simple analysis methods for the evaluation …	• Extend data collection to all relevant lifecycle phases of the system. • Introduction of standardized forms and databases to better organize the data…	• Implementation of advanced analytical tools and methods • Building competencies in data analysis and interpretation …	• Automate data collection through the use of sensors and IoT technologies. • Integration of ML and AI to identify optimization potentials in real time…

Figure 5. Overview of the recommendation for actions based on the maturity model for DDMBSE (excerpt)

In order to apply the DDMBSE maturity model, it is necessary to record the actual and target states of the company. This is accomplished by the company evaluating the actual status within the individual fields of action. The desired target state is then recorded. It is important to note that the target state is typically higher than the actual state in relation to the individual levels. Once both steps have been completed, the necessary action steps for implementing the target status can be derived from the difference between the two. These **recommendations** are presented in a separate overview (see Fig. 5). Due to space limitations, only a partial representation of the visual illustration of the recommendations of the maturity model will be presented as an image. The recommendations for action are based on the transition from Level X to Level X+1. Thus, for instance, if an assessment of the actual status of a company is at Level 2, and the desired status is at Level 4, the recommendations from Level 2 to Level 3 and from Level 3 to Level 4 should be followed to reach the target status. The recommendations are presented in a general manner, providing a framework for the logical steps that must be taken to reach the next higher level. The recommendations do not specify how the actions should be carried out; rather, they outline the necessary actions. Given that DDMSBE is not currently a topic of extensive research, particularly from a strategic perspective, it would be inappropriate to attempt to provide a contemporary and up-to-date answer to the question of how the transition should be made.

5 Evaluation

In view of the description of the results in the previous chapter, it is now necessary to test the maturity model for DDMBSE in practice. The evaluation was conducted by applying the maturity model to two producing companies in context of a research project focusing on the application of sustainable engineering by applying DDMBSE. Both companies produce goods in the field of electronic components (Company 1) and consumer electronics (Company 2). An anonymized overview is provided in the following table (Table 1).

Table 1. Overview of the companies and representative for the evaluation (anonymized)

Name	Company 1	Company 2
Domain	Electronic components	Consumer electronics
Amount of employee	over 5.000	over 20.000
Representative A	Project coordinator	System architect
Representative B	Digital engineer	Systems engineer

The evaluation was conducted in distinct workshops, each spanning one to one and a half hours. In each workshop, two representatives (interviewees) from the company and the lead moderator were present. At the outset of each workshop, the moderator provided a concise overview of the topic of DDMBSE, presenting the definition of DDMBSE as outlined by Tissen et al. (2023). Subsequently, the structure of the maturity model as a whole was elucidated in order to afford the interviewees a comprehensive overview. In particular, the specific details of the maturity levels and the assessment groups were elucidated in greater depth. Building on this, each action element (AE) was subjected to a comprehensive examination in order to ascertain its actual status. Once all the AEs had been considered, the target status was evaluated. The two assessments were then integrated into a unified whole and applied to the corresponding counterpart in order to derive recommendations for action. The distinction between the actual and desired statuses is of significant consequence, as it enables the formulation of recommended actions. The discrepancy between the current and desired statuses provides insight into the specific actions that must be taken to achieve the desired status. This derivation was subsequently discussed with the interviewees. Finally, interviews were conducted with the representatives to ascertain their impressions of the maturity model for DDMBSE directly after the application as the most suitable form considering the number of people involved in the evaluation. By this, feedback can directly be considered.

A review of the data indicates that company 1 is at an early stage regarding both the use of model-based systems engineering (MBSE; AE 1) and data analysis (AE 2). However, the desire for greater maturity is also evident. Consequently, AE 3 and AE 6 are relatively low. In contrast, company 2 is more advanced in this regard, which is also evident from AE 1 and AE 2. For both companies, the objective is to integrate MBSE (Company 2) and DA (Company 1) extensively and deeply into the company (see Fig. 6 AE 4 and AE 5). This indicates that both domains represent crucial functions for the companies to bring successful products to the market in the future and to maintain competitiveness. A particularly noteworthy point emerges in AE 9 of the technical and ontological interfaces. Both companies rate their actual status as level 0 and emphasize that standardized interfaces are currently hardly supported by the tool providers (MBSE as well as DA). This indicates that there is currently no standardization or transparency of interfaces, which is therefore an essential point for the successful application of the DDMBSE in the future. In the context of the assessments of AE 10, AE 11, and AE 12, it can be observed that companies are already well advanced in their digitalization transformation. This, in turn, suggests that a significant proportion of digital artifacts and the corresponding data and information are managed in silos.

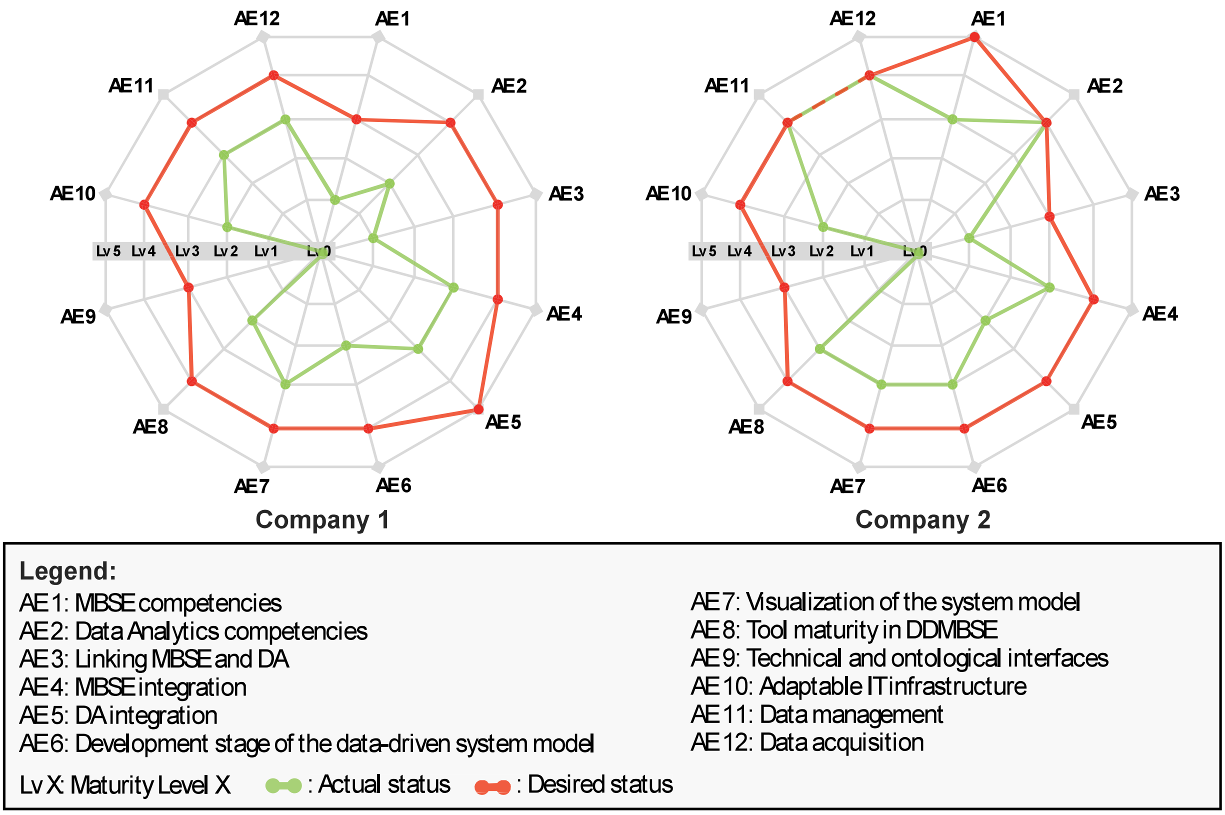


Figure 6. Application results for the maturity model for DDMBSE for two companies

The evaluation of the maturity model for the DDMBSE thus demonstrates its practical suitability, which also becomes evident in the interviews:

- *"I like the maturity model very well and it is easy. The images help to understand the levels."* (Representative A, Company 1)
- *"I have had the opportunity to observe and utilize several maturity models throughout the course of my professional career. The DDMBSE maturity model is readily accessible and intuitive to employ. I particularly appreciate the straightforward derivation of recommendations for action, which I have never encountered before."* (Representative B, Company 1)
- *"There are currently no general criticisms of the maturity model. Some terms need to be transferred to our own company because we use others for this purpose."* (Representative A, Company 2)
- *"The application of the maturity model is straightforward and intuitive. Nevertheless, it might be advisable to remove Level 0, which pertains to Systems Engineering, as MBSE would be a sufficient minimum requirement."* (Representative B, Company 2)

Although the general maturity model is relatively practicable due to its straightforward usability, it is clear that phase 6, "maintain," represents a future step that must be taken. Given the time-consuming nature of the deployment of the maturity model, it is advisable that companies initiate it in smaller circles, for instance, pilot projects. It is important to document the insights gained from this research to finish the development of the maturity model for DDMBSE. Nevertheless, the current version represents an initial step towards enabling companies to position themselves in the field of DDMBSE.

6 Conclusion and Future Research

Summary and contribution: This paper presents a **maturity model for data-driven model-based systems engineering (DDMBSE)**, accompanied by **recommendations for action** at each maturity level and action element. The **maturity model comprises six levels**, beginning with systems engineering (Level 0) and progressing to MBSE (Levels 1 and 2), MBSE and DA (Level 3), MBSE with DA (Level 4), and finally DDMBSE (Level 5). The twelve action elements are classified into five categories, which begin with competencies, organization, data-driven system model, IT and tools, and data. Each action element can be evaluated on each maturity level based on a clear description of each criterion. The maturity model sets itself apart from the existing maturity models from (MB)SE and DA. Users and companies can assess their actual and desired maturity levels in relation to DDMBSE in a straightforward manner. Furthermore, recommendations for actions to achieve the desired level of maturity are provided in a general manner. The recommendations can be derived by the differences between the desired and actual maturity levels in each action element, thereby providing users and companies with a plan to follow and act on. The maturity model for DDMBSE was subjected to an evaluation by two producing companies in the context of separate workshops. Each company was asked to rate their current and desired levels of maturity, and they were provided with recommendations for how to reach each level. The interviews conducted serve to illustrate the practical applicability of the maturity model and its user-friendly nature. The maturity model for DDMBSE provides companies with a framework for assessing their current position in the transition from (MB)SE to DDMBSE and represents one of the first support items in this research area. It opens the way for further methods to apply DDMBSE in a wide and deep aspect.

Limitations: The results are conveyed through the research methodology as outlined by Bruin et al. (2005) It should be noted that the application of an alternative research methodology may result in differing outcomes in terms of action elements, areas, and the underlying procedure. However, due to the high variety of maturity model design approaches, these aspects are very individual and subjective. Further testing of the maturity model, including a wide deployment and maintenance, may result in modifications to the presented version of the maturity model for DDMBSE. These modifications may include adjustments to individual criteria and descriptions. Nevertheless, due to the extensive process involved, the current version serves as an invaluable resource for implementing DDMBSE.

Future research: Further research is required to identify and address the limitations of the maturity model. As time progresses, this research will result in a more precise delineation of the areas, action elements, and recommendations. Moreover, the potential applications in an industrial context must be monitored, including the anticipated growth of DDMBSE over the next few years and the emergence of future technologies.

References

Bretz, L., 2021. Framework for the introduction of systems engineering and model-based systems engineering. Dissertation, University of Paderborn, Paderborn, Germany. DOI: 10.17619/UNIPB/1-1225.

Bruin, T., Freeze, R. D., Kulkarni, U., Rosemann, M., 2005. Understanding the Main Phases of Developing a Maturity Assessment Model. Australasian Conference on Information Systems (ACIS), Sydney, Australia.

Cornu, C., Chapurlat, V., Quiot, J., Irigoin, F., 2012. A maturity model for the deployment of Systems Engineering processes. IEEE International Systems Conference SysCon 2012, Vancouver, BC, Canada, pp. 1-6. DOI: 10.1109/SysCon.2012.6189535.

Cusick, K., 1997. The systems engineering capability maturity model: where to start? Proceedings of the IEEE 1997 National Aerospace and Electronics Conference. NAECON 1997, Dayton, OH, USA, pp. 410-416, DOI: 10.1109/NAECON.1997.618113.

Ilin, I., Borremans, A., Levina, A., Esser, M., 2022. Digital Transformation Maturity Model. In: Rudskoi, A., Akaev, A., Devezas, T. (eds) Digital Transformation and the World Economy. Studies on Entrepreneurship, Structural Change and Industrial Dynamics. Springer, pp. 221-235, DOI: 10.1007/978-3-030-89832-8_12.

INCOSE, 2021. Systems Engineering Vision 2035 – Engineering solutions for a better world. The International Council on Systems Engineering (INCOSE).

INCOSE, 2023. Systems Engineering Handbook – A guide for system life cycle processes and activities – Fifth edition. John Wiley & Sons Ltd., Hoboken, New Jersey, USA. ISBN: 978-1-119-81429-0.

Khoshgoftar, M., Osman, O., 2009. Comparison of maturity models. 2009 2nd IEEE International Conference on Computer Science and Information Technology, Beijing, China, pp. 297-301, DOI: 10.1109/ICCSIT.2009.5234402.

Król, K., Zdonek, D., 2020. Analytics Maturity Models: An Overview. Information 11, Vol. 3, p. 142, DOI: 10.3390/info11030142.

Martinez, I., Viles, E., Olaizola, I.G., 2021. A survey study of success factors in data science projects. 2021 IEEE International Conference on Big Data (Big Data), Orlando, FL, USA, DOI: 10.1109/BigData52589.2021.9671588.

Solemon, B., Sahibuddin, S., Ghani, A.A.A., 2012. A New Maturity Model for Requirements Engineering Process: An Overview. Journal of Software Engineering and Applications, Vol. 5, No. 5, DOI: 10.4236/jsea.2012.55040.

Statista, 2021. Volume of data/information created, captured, copied, and consumed worldwide from 2010 to 2020, with forecasts from 2021 to 2025 (in zettabytes). URL: https://www.statista.com/statistics/871513/worldwide-data-created/.

Statista, 2022. Spending on digital transformation technologies and services worldwide from 2017 to 2026 (in trillion U.S. dollars). URL: https://www.statista.com/statistics/870924/worldwide-digital-transformation-market-size/.

Tissen, D., Wiederkehr, I., Koldewey, C., Dumitrescu, R., 2023. Exploring data-driven model-based systems engineering: a systematic literature review, IEEE International Conference on Technology Management, Operations and Decisions (ICTMOD), Rabat, Marocco, DOI: 10.1109/ICTMOD59086.2023.10438129.

Tissen, D., Wiederkehr, I., Bernijazov, R., Koldewey, C., Dumitrescu, R., 2024. Spearhead data-driven model-based systems engineering: interview study on definition, preconditions, challenges, potentials, and use cases. NordDesign 2024, Reykjavik, Iceland (accepted, not presented yet).

Tränkler, H.R., O. Kanoun, O., 2007. Smart Systems and Devices: Innovative Key Modules for Engineering Application. Conference Smart Systems and Devices, Hammamet, Tunisia, pp. 3-12.

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