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A model-driven approach for the engineering of manufacturing execution systems in the food and beverage industry

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Scientific Contributions

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M. Sc.

The results and publications of this thesis were developed at the Technical University of Munich, Chair of Food Packaging Technology from November 2014 to March 2020.

Full Papers

The following peer-reviewed publications were generated in the period of this work and are related to the topic of the thesis (publications which are part of this thesis are indicated in bold).

The doctoral candidate is the main author of four out of the five publications presented in this thesis and shares in the fundamental and major part of conception, idea, and implementation of the approaches as well as the data analysis. The subsequent writing of the manuscripts was exclusively his product. In the second paper about the definition and extension of the modeling language, the doctoral candidate shared a co-authorship and contributed in requirements identification, structure definition, and practical application of the proposed modeling language.

1. **Xinyu Chen, Tobias Voigt, "*Implementation of the Manufacturing Execution System in the Food and Beverage Industry,*" Journal of Food Engineering, Volume 278, August 2020, 109932. DOI: 10.1016/j.jfoodeng.2020.109932**

2. **Benedikt Weißenberger, Stefan Flad, Xinyu Chen, Susanne Rösch, Tobias Voigt, Birgit Vogel-Heuser, *"Model driven engineering of manufacturing execution systems using a formal specification – Extension of the MES-ML for the generation of MES code*," 2015 ETFA, September 2015. DOI: 10.1109/ETFA.2015.7301430.**

3. **Xinyu Chen, Fabian Gemein, Stefan Flad, Tobias Voigt, "*Basis for the model-driven engineering of manufacturing execution systems: Modeling elements in the domain of beer brewing*," Computers in Industry, Volume 101, October 2018, Pages 127-137. DOI: 10.1016/j.compind.2018.07.005.**

4. **Xinyu Chen, Christoph Nophut, Tobias Voigt, "*Manufacturing Execution Systems for the Food and Beverage Industry: a model-driven Approach,*" Electronics, Volume 9, Issue 12, 2040, December 2020. DOI: 10.3390/electronics9122040.**

5. **Xinyu Chen, Christoph Nophut, Tobias Voigt, "*Model-driven Engineering of customizable Manufacturing Execution Systems for the Implementation in the Food and Beverage industry,"* Submitted at The International Journal of Advanced Manufacturing Technology, under review**

6. Xinyu Chen, Stefan Flad, Benedikt Marschall, Tobias Voigt, „Modellbasierte Entwicklungsmethode für MES," in Der Weihenstephaner 86 (03), 2018, pp. 115-118.

7. Susanne Rösch, Daniel Schütz, Benedikt Weißenberger, Xinyu Chen, Tobias Voigt, Birgit Vogel-Heuser, „Durchgängiges MES-Engineering als Grundlage für Industrie 4.0", VDI Kongress Automation, 2016, pp. 1-13.

8. Stefan Flad, Benedikt Weißenberger, Xinyu Chen, Susanne Rösch, Tobias Voigt, "Automatische Generierung von Fertigungs-Managementsystemen," in *Handbuch Industrie 4.0 Bd. 2*: Springer, 2017, pp. 349–368.

Conferences and oral presentations with the first authorship

1. Xinyu Chen (2019): Automatic generation of Manufacturing Execution Systems – what and how? Academic Exchange Conference at the Wuhan University of Technology. Wuhan, China, 29/03/2019.

2. Xinyu Chen (2018): Development of Modeling Elements for a model-driven Engineering of Manufacturing Execution Systems in the Domain of Beverage Filling. ISA@Montreal of International Society of Automation. Montreal, Canada, 17/10/2018.

3. Xinyu Chen (2015): Automatische Generierung von MES - Modellierung und Bibliothek. BrauBeviale Exhibition. Nürnberg, Germany, 12/11/2015

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Poster presentations with the first authorship

1. Xinyu Chen (2016): AutoMES - Automatische Generierung von Manufacturing Execution Systems. KMU Innovative. Hannover, Germany, 10/10/2016.

2. Xinyu Chen (2014): Automatische Generierung von Fertigungsmanagementsystemen. KMU Innovative. Berlin, Germany, 17/11/2014.

Abbreviations

CIM: Computer Integrated Manufacturing

CPS: Cyber-Physical System

DCS: Distributed Control System

EC: European Commission

ERD: Entity-Relationship Diagrams

ERP: Enterprise Resource Planning

EU: European Union

FDA: U.S. Food and Drug Administration

IoT: Internet of Things

ISA: International Society of Automation

KPI: Key Performance Indicator

MAS: Multi-Agent systems

MBE: Model-based engineering

MDA: Model-driven Architecture

MDD: Model-driven development

MDE: Model-driven engineering

MES: Manufacturing Execution System

MESA: Manufacturing Enterprise Solutions Association

MES-ML: Manufacturing Execution System Modeling Language

MRP: Material Requirement Planning

MTO: Make-to-Order

MTS: Make-to-Stock

OEE: Overall Equipment Effectiveness

OMG: Object Management Group

PLC: Programmable Logic Controller

RFID: Radio-frequency identification

SCADA: Supervisory Control and Data Acquisition

SME: Small- and medium-sized Enterprises

SOA: Service-oriented Architecture

UML: Unified Modeling Language

WHO: World Health Organization

WS: Weihenstephaner Standards

XMI: Extensible Markup Language Metadata Interchange

Summary

Manufacturing Execution System (MES) refers to a process-oriented IT-solution for the management of manufacturing processes and acts as the middle layer between the shop floor and the enterprise level. By implementing an MES, the sectors in the food and beverage industry can achieve increased energy and production efficiency, elevated product safety and traceability, and enhanced transparency in their process and the complete supply chain. Due to the fragment in nature, few exchanges of experience regarding novel technologies, low-profit margins, and limited resources for new investment, the implementation of the MES is for the enterprises (more than 99 % are small and medium-sized) in the food and beverage industry not applicable. As the MES manages, processes, and delivers manufacturing information from and to different sources and systems, the loads for integration, programming, and customizing complicate its implementation. Model-driven Engineering (MDE) is the term used for developing software systems with the model as the primary artifacts to represent the systems in a high-level abstraction and to be transformed into other models and/or codes. The focus of the design and development of software systems has shifted from code-centric to model-centric approaches by MDE, which are capable of reducing the complexity, and subsequently, the costs for implementing MES since the transformation between models and the generation of final systems can be performed automatically. However, though some rudiments concerning the application of the model-driven approaches for the engineering of MES have been mentioned in existing literature, none of them can cover the respective process in the software engineering or meet the requirements from the food and beverage industry. This work aims to develop a feasible model-driven approach for the engineering of MES that practical and applicable for the food and beverage industry with low integrating, programming, and customizing efforts.

A model-driven approach with six phases (e.g., the analyzing, modeling, specifying, generating, applying, and improving phase) that cover the whole life-cycle of the MES engineering is presented in this work. In the analyzing phase, an analysis is conducted on the actual production state, available data sources, required MES functions, and expected MES reports. Based on the results of the analyzing phase, the MES is modeled graphically with predefined modeling elements from domain-specific libraries at the modeling phase. The achieved MES model consists of four models that ensure that the modeling method in different application scenarios is compatible with each other, i.e., the plant model illustrating the technical systems of the plant and the data sets that can be collected from them, the process model describing the production process and providing information for process-related MES functions, the MES function model representing the required MES functions and the necessary data to realize the functions, the report model serving as the communication interface between the MES and the end-user. Following the modeling phase, the information existing in the graphical models is transformed in the specifying phase into a format that can be utilized by the software. As a platform to contain the information, the MES specification is defined using database tables with definite relationships. After that the information in the specification has been read, the MES with demanded functions is generated automatically in the generating phase by the fore-programmed MES generator, which consists of a front-end as the user interface to parameterize the MES functions, as well as a back-end for the data processing to realize the functions. In the applying phase, complying with the specific business processes, the MES is executed to meet the requirements from the end-user. To improve the MES dealing with further requirements, the improving phase accounts for defining new MES functions and integrating them into the current environment. To ensure the data consistency for the communication between the technical systems, the MES, and other software systems, the Weihenstephaner Standards, which are dominant communication standards in the food and beverage industry, have been introduced into this model-driven approach. The whole approach has been applied in a series of different use cases to prove its feasibility and practicality. Moreover, the application to two use cases with real production data, in the processing area and the packaging area, respectively, representing the two essential areas of the food and beverage industry, has indicated that the developed approach can also generate MES that should be customized to fulfill different requirements, which ensures the possibility and sustainability of the presented approach to be applied to other industries.

In summary, a model-driven approach for the MES engineering in the food and beverage industry is developed, and its feasibility and practicality have been proven by applying the approach in food and beverage processing and packaging areas. For subsequent studies, more MES functions for the process execution in real-time should be defined and implemented in the manufacturing enterprises, and the service-oriented architecture can also be integrated with the model-driven approach for modularizing the MES.

Zusammenfassung

Das Manufacturing Execution System (MES) ist eine prozessorientierte IT-Lösung, um die Fertigungsprozesse zu verwalten. Es dient als die mittlere Schicht zwischen der Automatisierungsebene und der Unternehmensführungsebene. Die Sektoren in der Lebensmittel- und Getränkeindustrie können von der Implementierung des MES profitieren, um die Energie- und Produktionseffizienz zu steigern, die Produktsicherheit und Rückverfolgbarkeit zu verbessern und die Transparenz in ihrem Prozess und der gesamten Lieferkette zu erhöhen. Aufgrund der fragmentierten Natur, des wenigen Erfahrungsaustauschs über neue Technologien, der geringen Gewinnspannen und der begrenzten Ressourcen für neue Investitionen ist die Implementierung des MES für die Hersteller in der Lebensmittel- und Getränkeindustrie nicht durchführbar, die sich hauptsächlich aus kleinen und mittleren Unternehmen zusammensetzt. Da das MES die Informationen aus der Fertigung von verschiedenen Quellen erfasst, bearbeitet und verwaltet, und auch an eine Reihe von Systemen liefert, wird die Komplexität der Implementierung von dem MES durch die Arbeit für die Integration, Programmierung und Individualisierung erhöht. Model-driven Engineering (MDE) ist ein Begriff für die Entwicklungsprozesse von Softwaresystemen, bei dem das Modell als primäre Artefakte verwendet wird, um die Systeme auf einer hohen Abstraktionsebene beschreiben und in andere Modelle und/oder Code zu transformieren. Der Schwerpunkt der Gestaltung und der Entwicklung von Softwaresystemen wurde durch das MDE vom codezentrierten zum modellzentrierten Ansatz verlagert, der das Potenzial hat, die Komplexität und dann die Kosten der Implementierung von MES zu reduzieren, da die Transformation zwischen den Modellen und die Generierung der endgültigen Systeme automatisch ausgeführt werden kann. Obwohl einige Ansätze zur Anwendung der modellgetriebenen Ansätze für die Entwicklung von MES in den Literaturen erwähnt wurden, kann kein einziger Ansatz jeden Prozess im Software-Engineering abdecken und darüber hinaus die Anforderungen aus der Lebensmittel- und Getränkeindustrie erfüllen. Das Ziel dieser Arbeit war es, einen praktikablen modellgetriebenen Ansatz für die Entwicklung von MES zu entwickeln, der mit geringem Integrations-, Programmierungs- und Anpassungsaufwand für die Lebensmittel- und Getränkeindustrie anwendbar ist.

Ein modellgetriebener Ansatz mit sechs Phasen, die den gesamten Lebenszyklus des MES-Engineerings abdecken, wurde in der Arbeit präsentiert, nämlich die Analysephase, die

Modellierungsphase, die Spezifizierungsphase, die Generierungsphase, die Anwendungsphase und die Verbesserungsphase. In der Analysephase werden der tatsächliche Produktionszustand, die verfügbaren Datenquellen, die erforderlichen MES-Funktionen und die gewünschten MES-Berichte analysiert. Basiert auf den Ergebnissen der Analysephase wird das MES in der Modellierungsphase mit vordefinierten Modellierungselementen aus domänenspezifischen Bibliotheken grafisch modelliert. Das MES-Modell besteht aus vier Tochtermodellen, die die Kompatibilität der Modellierungsmethode für verschiedene Anwendungsszenarien gewährleisten, d.h. das Anlagenmodell, das die technischen Systeme der Anlage und die daraus erfassbaren Datensätze abbildet; das Prozessmodell, das den Produktionsprozess beschreibt und Informationen für prozessbezogene MES-Funktionen liefert; das MES-Funktionsmodell, das die erforderlichen MES-Funktionen und die erforderlichen Daten zu ihrer Realisierung darstellt; das Berichtsmodell, das als Kommunikationsschnittstelle zwischen dem MES und dem Endbenutzer dient. Nach der Modellierungsphase werden die Informationen in den grafischen Modellen in ein software-verwendbares Format transformiert, was in der Spezifizierungsphase geschehen ist. Als Plattform zur Aufnahme der Informationen wird die MES-Spezifikation unter Verwendung von Datenbanktabellen mit eindeutigen Beziehungen definiert. Nachdem die Informationen in der Spezifikation gelesen wurden, wird das MES mit den angeforderten Funktionen in der Generierungsphase automatisch durch den vorprogrammierten MES-Generator generiert, der aus einem Front-End als Benutzerschnittstelle für die Parametrierung der MES-Funktionen und einem Back-End für die Datenverarbeitung zur Realisierung der Funktionen besteht. In der Anwendungsphase wird das MES nach den spezifischen Geschäftsprozessen ausgeführt, damit die Anforderungen des Endbenutzers erfüllt werden können. Um das MES zu verbessern, damit sich das MES mit weiteren Anforderungen erweitert und aktualisiert werden kann, ist die Verbesserungsphase für die Definition neuer MES-Funktionen und deren Integration in die aktuelle Umgebung verantwortlich. Die Weihenstephaner Standards, die in der Lebensmittel- und Getränkeindustrie dominierende Kommunikationsstandards sind, wurden in diesen modellgetriebenen Ansatzeingeführt, um die Datenkonsistenz für die Kommunikation zwischen den technischen Systemen, dem MES und anderen Softwaresystemen sicherzustellen. Der gesamte Ansatz wurde auf eine Reihe verschiedener Anwendungsfälle angewandt, um seine Durchführbarkeit und Praxistauglichkeit zu validieren. Darüber hinaus wurde der Ansatz auf zwei Anwendungsfälle mit realen Produktionsdaten implementiert, jeweils im Prozessbereich und im Verpackungsbereich, die die beiden essentiellen Bereiche der Lebensmittel- und Getränkeindustrie repräsentieren. Die Anwendungsfälle haben gezeigt, dass der vorgestellte Ansatz auch das MES generieren kann, das an unterschiedliche Anforderungen angepasst werden muss, was die Möglichkeit und Nachhaltigkeit des vorgestelllten Ansatzes für die Anwendung in anderen Branchen gewährleistet.

Zusammenfassend wurde ein modellgetriebener Ansatz für das MES-Engineering in der Lebensmittel- und Getränkeindustrie entwickelt, dessen Durchführbarkeit und Praxistauglichkeit durch die Anwendung auf die Bereiche in Lebensmittel- und Getränkeverarbeitung und -verpackung nachgewiesen wurden. Für zukünftige Studien sollten weitere MES-Funktionen für die Prozessausführung in Echtzeit definiert und in den Fertigungsunternehmen implementiert werden, in dem die serviceorientierte Architektur mit diesem modellgetriebenen Ansatz zur Modularisierung des MES integriert werden kann.

Contents

Acknowledgments II

Scientific Contributions III

Abbreviations VI

Summary VIII

Zusammenfassung X

Contents XIII

1 Introduction 1

1.1 Development and definition of the MES 3

1.2 The food and beverage industry and the implementation of MES 8

1.3 Model-driven engineering 11

1.4 Motivation and objective 14

2 Results – Thesis Publications 18

2.1 Publication I – Literature study for state of the art 18

2.2 Publication II – Development of the modeling language 33

2.3 Publication III – Modeling phase of the model-driven approach 42

2.4 Publication IV – Transformation phase and generation phase of the model-driven approach 54

2.5 Publication V – Further development and validation of the model-driven approach: 76

3 Discussion and conclusion ... 97

3.1 R1: Development of a feasible model-driven approach ... 97

3.2 R2: Definition of modeling elements for the food and beverage industry ... 99

3.3 R3: Support of a standard information model ... 103

3.4 R4: Support of a generic specification of the MES ... 106

3.5 R5: Dynamic generation of the MES ... 108

3.6 Final remarks and outlook ... 109

4 References ... 111

Appendix I – Modeling elements in process model library ... 120

Appendix II – Modeling elements for basic functions in MES function model library ... 126

Appendix III – Modeling elements in report model library ... 133

1 Introduction

The increasingly competitive environment in the manufacturing sectors leads to the application of computer-aided management systems in enterprises. Manufacturing Execution System (MES) is a process-oriented manufacturing system to facilitate manufacturers in improving product quality, increasing production efficiency, reducing production costs, minimizing lead time, and optimizing machine availability. It is connected directly to the process on the shop-floor for collecting, managing, processing, and delivering the information in real-time, serves as a middle layer between the production process on the shop floor and the business process on the Enterprise Resource Planning (ERP) level. On the one hand, MES implements gross production plans from enterprise systems into a detailed operative plan to the production areas and reacts to the actual state of the process. On the other hand, the MES processes the data at a high level and provides important key performance indicators (KPIs) to the company for making commercial decisions and improving the performance of the production. Some studies through the applications of MES indicated that the MES could provide manufacturing enterprises with impressive benefits of any manufacturing software, such as an average 45 % reduction in manufacturing cycle time, 32 % improvement of productivity, 57 % reduction in energy consumption, and significant improvement of the flexibility to respond to customer demands [1–4].

The food and beverage industry is a sector with special characteristics in the manufacturing industry: i) its production processes usually consist of divergent processes combined with convergent processes, as the splitting and mixing of lots are common activities; ii) production yields are uncertain, as the raw materials and semi-manufactured products often have dynamic characteristics changing over time; iii) recipes are variable and multi-level, e.g., different materials can lead to similar products; recycling of products or semi-finished products is typical in the food processing; iv) final products can be perishable and have a limited shelf-life [5,6]. The products of the food and beverage industry are meant for human consumption, which is facing more strict regulations from the domestic government and the global organizations outside of the country. The low profit-margins force the manufacturers in reducing energy consumption, saving materials and resources, and improving the efficiency so that their products can be priced reasonably with consideration of the production cost [7]. The demand from the consumers on variety and personality increases the complexity of the food and beverage production to be flexible against the unpredictable changes in the market. The food and beverage retailers' wish to optimize logistical management and reduce the inventory cost resulted in the transform of the production strategy from make-to-stock to make-to-order.

The application of MES, which contributes to achieving process transparency, efficiency improvement, on-time performance, and compliance with production plans, can benefit the food and beverage manufacturers in improving their production processes and competitiveness. However, the implementation of the MES was not widespread in the food and beverage industry, and the MES functionalities were still realized by manual documentation and calculation, or stand-alone software systems. In the following sections, the development and the definition of the MES, the particular characteristics of the food and beverage industry, the benefits that the MES can bring to the food and beverage industry, and the application of the model-driven concept to the software engineering are presented.

1.1 Development and definition of the MES

The application of software systems in the manufacturing industry to automate the financial area is the beginning of the development of manufacturing management software systems since the 1960s. With the change of the manufacturing strategy from the minimization of cost to production forecasting and precise process control, the Material Requirement Planning (MRP) systems and the MRP II were developed in the late 1970s and 1980s to improve the meeting of delivery, production scheduling, reaction to volume/product changes, and cost estimation [8,9]. In the late 1970s, the main challenges faced by the manufacturers are design and manufacturing lead time, inventory turnover period, production equipment preparation time, employee productivity, product quality, product improvement [10]. Resolving only a part of them and ignoring other issues did not lead to overall benefit improvement, the manufacturing enterprises needed a holistic solution. In 1973, the concept of Computer Integrated Manufacturing (CIM) was firstly coined by Harrington [11], but until the early 1980s, CIM was not a commonly known term [12]. At the end of the 1980s, IBM introduced a CIM framework to integrate information across the enterprise, including the areas of marketing, research and engineering, production business planning, plant operation, finance accounting, and administration [13,14]. The development roadmap of manufacturing systems was drawn from MRP to MRP II to CIM, and further to Enterprise Resource Planning (ERP). The ERP aimed at achieving effective management of the entire supply chain integrating the functionalities such as accounting, manufacturing, and inventory to improve business performance and rapid response of the enterprise. However, the ERP focuses on the business operations to manage the specified work within the existing time constraints at the planning level and production timelines for particular products on a daily, weekly or monthly basis [15], which cannot fulfill the granularity and speed required for the shop floor activities, i.e., in real-time. At this background, the development of real-time data collection software applications has gained attention, which becomes the MES today. The definition of MES was firstly mentioned by AMR Research in 1992, and the Manufacturing Enterprise Solutions Association (MESA) was also established in the same year.

The MESA defines the MES as: “The MES delivers information that enables the optimization of production activities from order launch to finished goods. Using current and accurate data, the MES guides, initiates, responds to, and reports on plant activities as they occur. The resulting rapid response to changing conditions, coupled with a focus on reducing non-value-added activities, drives effective plant operations and processes. The MES improves the return on operational assets as well as on-time delivery, inventory turns, gross margin, and cash flow performance. The MES provides mission-critical information about production activities across the enterprise and supply chain via bi-directional communications" [16]. To fulfill the requirements from different manufacturing environments, twelve MES functionalities were defined [17]:

- Resource allocation and control: managing resources directly associated with control and manufacturing. The resources include machines, tools, labor skills, materials, other equipment, documents, and other entities that are required for work to start and to be completed.
- Dispatching production: managing the flow of production in the form of jobs, orders, batches, lots, and work orders, by dispatching production to specific equipment and personnel.
- Data collection and acquisition: obtaining the operational production and parametric data that are associated with the production equipment and production processes;
- Quality management: providing real-time measurements collected from manufacturing and analysis in order to assure proper product quality control and to identify problems requiring attention;
- Process management: monitoring production and either automatically corrects or provides decision support to operators for correcting and improving in-process functions;
- Production tracking: providing the status of production and the disposition of work;
- Performance analysis: providing up-to-the-minute reporting of actual manufacturing operations results along with comparisons to past history and expected results;
- Operations and detailed scheduling: providing sequential and timely processing of operations based on priorities, attributes, characteristics, and production rules associated with specific production equipment and specific product characteristics;
- Document control: controlling records and forms that are maintained with the production unit;
- Labor management: providing the status of personnel including time and attendance reporting, certification tracking, and the ability to track indirect functions;
- Maintenance management: maintaining equipment and tools;

- Transport, storage and tracking of materials: managing and tracking the transport and storage of materials, in-process products and end products, and transfers between and within plants.

The International Society of Automation (ISA) has published the ISA-95 standard to solve the integration issues between different software systems in the manufacturing industry [18–22]. According to the ISA-95 standard, four control levels were defined in an enterprise [18,23]:

- Level 0 and 1: the actual physical processes and its sensing and actuation
- Level 2: manufacturing processes, especially Supervisory Control And Data Acquisition (SCADA), Programmable Logic Controller (PLC) and Distributed Control System (DCS)
- Level 3: systems which manage the workflow of batch, continuous or discrete production operations, the MES
- Level 4: business planning and logistics systems that manage business-related activities of production

Classically, the automation pyramid was used to describe the different levels in the industrial automation, and the MES as the production management level is located between the automation level and the enterprise planning level [24]. This pyramid model has been chosen because of the detailing grad of information on the different levels due to the amount of data and frequency of acquisition and transportation and the time horizon for data processing and decision making. Figure 1 presents the hierarchical location of MES together with the MES functions [25] and the decreasing data amount and the increasing time horizon from bottom to top in the automation pyramid [26].

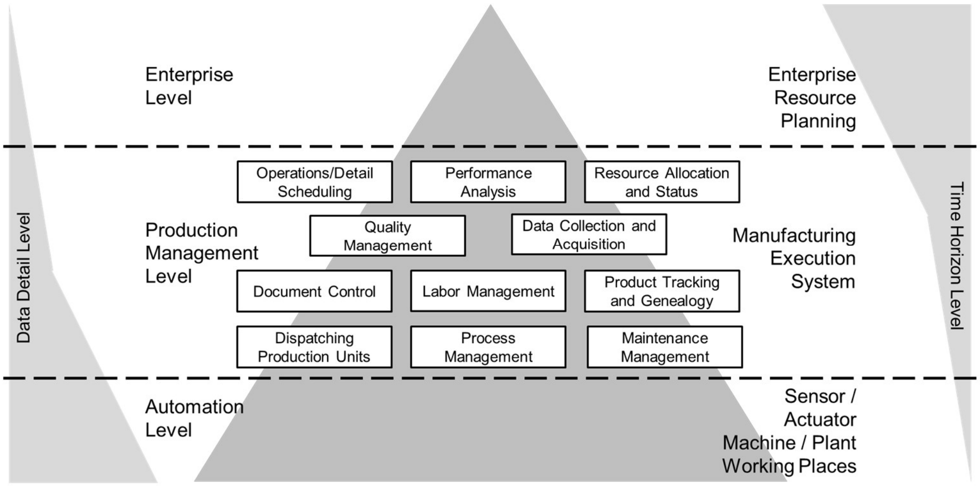

Figure 1: Location of the MES in the automation pyramid [25,26]

With the development of automation technology, three drivers can be indicated, which have changed the production organization, i.e., more intelligent field devices with enormous computational power implementing functions like maintenance support and asset management; extension in device communication to industrial Ethernets derivatives reducing the variation of industrial digital communication systems; more intelligent field bus components that capable of running their own PLCs to allow decentralized automation [27]. These changes make the MES to a powerful information center to increase efficiency and transparency in production. In this background, Vogel-Heuser et al. have introduced a new automation architecture named automation diabolo, which consists of two cones (shown in Figure 2) [27]. The lower cone that located directly above the production process represents the field and control elements, the upper cone that framed on the top by the enterprise resource planning represents the production management and production organization, and between the two cones is the information model serving as the connection level for the communication [28].

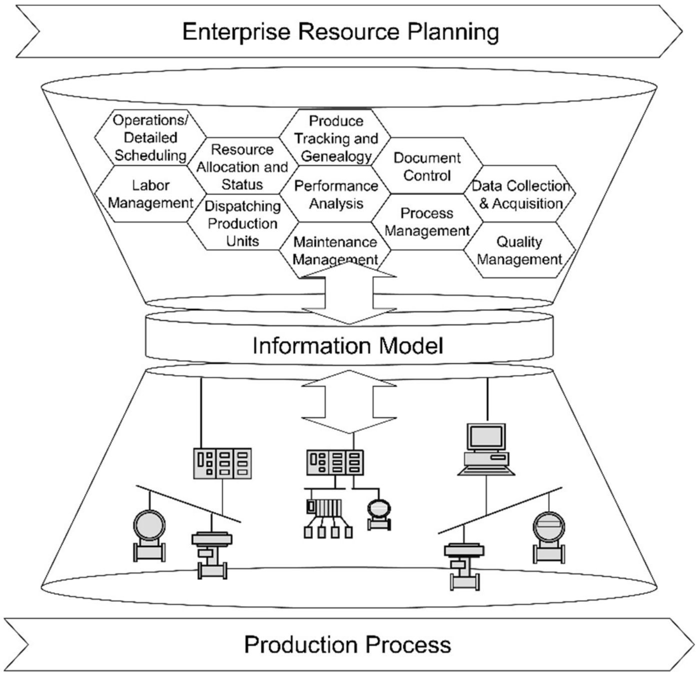

Figure 2: Automation diabolo as the new model for industrial automation [27]

Nowadays, with the publication of the concept of Industry 4.0 from the German government [29], terms like the Internet of Things (IoT), Cyber-Physical System (CPS), and Smart Factory are becoming high topicality. The technology of the IoT established the infrastructure enabling the interconnection of different types of devices to exchange data through the internet. CPS emphasizes the real-time dynamic information cycling and feedback process between the physical world and the information world. It consists of computation, communication, and control components combined with the physical processes of different domains to monitor and change the production applications autonomously, intelligently, dynamically, and systematically [30]. Based on the IoT and CPS, the manufacturing processes in a Smart Factory that are able to efficiently and profitably produce customized and small-lot products can be realized [31]. To implement the manufacturing strategy according to Industry 4.0, three key features should be considered: horizontal integration through value networks, vertical integration, and networked manufacturing systems; end-to-end digital integration of engineering across the entire value chain [32]. The MES that located in the center of the industrial automation is indispensable for the vertical integration from shop-floor level to ERP level, the horizontal integration of continuous and compatible communication and cooperation between different systems on the production management level, and the delivery of information over the manufacturing enterprises and the production plant [33].

1.2 The food and beverage industry and the implementation of MES

The manufacturing processes in the food and beverage industry are an integration of the various components of the food supply chain. It comprises all actors and activities from primary production, food processing, distribution, retailing, and, finally, consumption by consumers [34]. As the final products of the food and beverage industry are for human consumption, high quality and safety standards must be met in the whole life-cycle of the products [35]. On the one hand, the manufacturing enterprises must comply with the strict regulations from the domestic and global organizations, such as U.S. Food and Drug Administration (FDA), European Commission (EC), and World Health Organization (WHO). On the other hand, with the emergence of food incidents and scandals [36–39], consumers are becoming more sensitive to the information about the origins of raw material, the processing activities and methods, the safety and hygiene levels, and environmental issues such as greenhouse gas emissions of the enterprises and the treatment of wastewater [40]. Therefore, the safety and traceability of the food and beverage products must be ensured.

Compared to other considerations from the consumers to determine the food choice, the price emerged as the primary influence [41]. The European food and beverage sector has consumed the most energy in the manufacturing industry, equivalent to 26 % of the EU's final consumption in 2013, and 28 % of this consumption comes directly from industrial processing [42]. The rising energy price, new environmental regulations with associated CO_2 emission costs, and the growth of the awareness from consumers on the eco-efficient products are forcing the manufacturers in the food and beverage industry to reduce the energy consumption [43,44]. Furthermore, the food packaging machinery remains under-utilized [45], and the food and beverage industry needs efficiency-improving production methods to control the price of their products within a reasonable range [46]. Therefore, because of the low-profit margins in most food and beverage sectors, the awareness to reduce the energy consumption and to improve the production efficiency is growing [47].

The changed consumer behavior with increasing demand on new product features and personalization [48,49] and the retailer's restructuring of the supply chain to reduce the inventory pressure [50] has resulted in the movement of production strategy in the food and beverage industry from Make-to-Stock (MTS) to Make-to-Order (MTO) so that more flexibility can be gained [51]. To satisfy the wishes from the market and remain competitive, the volume and density of product variety increase over the product life span [52]. For the manufacturers in the food and beverage industry, to decide the production policy and the production plan for different types of products, effective scheduling, and fine planning method must be developed.

As introduced in Section 1.1, the MES can help sectors in the food and beverage industry to comply with the regulations from the government and organizations, the high-level demand from consumers and requirements from themselves for the product manufacturing with high quality, low cost and minimum the lead time [53]. The MES is connected directly to the shop-floor and supports the understanding of the energy consumption and availability of material resources in the process. The energy-saving potential can be clarified by the support from the MES, and it helps the sectors to manage and reduce energy consumption [54]. Besides that, MES that integrates the information systems in the horizontal and vertical dimensions can collect, process, and collaborate the data to ensure food safety and traceability by linking the information regarding the product and process characteristics in the supply chain and product life cycle [55,56]. The application of lean principles in manufacturing sectors can be supported by MES to provide useful real-time production information and to validate the lean decision-making processes for better production efficiency [57]. The MES is the basis for scheduling in the process industry, typically in the food and beverage industry [58] and can be integrated with the other technologies, such as radio-frequency identification (RFID), multi-agent systems (MAS) and holonic manufacturing, to schedule the production order in real-time and make more precise scheduling for short-series production [59–61].

Due to the software heterogeneity in the manufacturing environment, the adoption of communication interfaces among different software systems to ensure the smooth flow of information limited the implementation, integration, and maintenance of the MES [62]. Moreover, as the MES is directly connected to the operations on the shop-floor and the production processes vary from one enterprise to another, the MES must be adapted to the specific production process with much customizing and programming effort, which is cost-intensive and error-prone [63]. Conventionally, for the engineering of an MES project, the following seven stages must be accomplished, as shown in Table 1 [64]:

Table 1: Standard project structure plan for engineering MES [64]

Aim						
The feasible MES project	The approvable MES project	The MES project that can be contracted out to tender	The MES project that can be implemented	The functioning MES	The operational MES	The assessed and settled MES project
Project engineering						
1. Stage Basic determination	2. Stage Preplanning	3. Stage Basic planning	4. Stage Realisationplannin g	5. Stage Implementation	6. Stage Commissioning	7. Stage Project completion
– Agree main project targets with customer – Determine project scope and content – Rough cost estimation	– Compile specification: Analyse business processes and determine MES	– Compile MES tender – Comparison of MES bids – Evaluation and drafting of recommendation – Determine project costs and apply for project approval	– Generate orders – Map MES in detail	– Create user software – Conduct FAT – Basic system training – Installation of hardware / system software and integration into network – Installation of application software – Testing of application software – Application training for key users	– Application training for all users – Commissioning – Revise documentation	– Compile final report – Draft project accounting

Because of the complexity of information integration and the high engineering costs for customizing and programming of the MES projects, the large companies are able to afford it while the small- and medium-sized enterprises (SMEs) do not have the resources to complete the MES projects [65]. The food and beverage sector, as the largest manufacturing sector in the European Union (EU), represents 15% of the total manufacturing turnover, 14% of the total number of companies, and 15% of total employment [66], there are 294000 companies in the European food and beverage industry in 2018 and 99.1% of them are SMEs, which have less than 250 employees [67]. The fragment in nature, the few communication about advancements, the low-profit margins, and the limited financial flexibility in the food and beverage industry resulted in few implementations of the MES [68]. Instead of a centralized MES, the food and beverage manufacturers are still using cheap but unreliable solutions to provide partial MES functionality, e.g., manual calculation of the key performance indicators and production scheduling in spreadsheet programs [69].

1.3 Model-driven engineering

Model is a simplified representation of a system [70]. They are widely used in the development of software for communication between co-workers, analyzing the problem, and documenting the system. However, the detailed design of today's software system is still code-centric [71], which may have reached the point of exhaustion because of the pressure to reduce the cost and time for the software engineering [72]. Opposed to the code-centric development paradigm, the term model-driven engineering (MDE) presents the model-centric development processes, which can reduce the complexity of software system engineering and the cost for programming effort, as the final implementation is generated automatically with the transformation of models. With MDE, the terms of model-based engineering (MBE), model-driven development (MDD), and model-driven architecture (MDA) also appear together. The MBE is an engineering process in which the models play an essential role, although they are not the key artifacts of the development [73]. In contrast, MDD treats models as the primary artifact of the development process to represent the system in different levels of abstraction, and the implementation is automatically generated from the models [73]. In addition to MDD, MDE comprises all the other tasks of the software engineering process, such as testing and maintenance, which is considered as the superset of MDD [74]. MDA was firstly proposed by Object Management Group (OMG) in 2000. In the newest version of "MDA guide" that published by OMG, "MDA provides an approach for deriving value from models and architecture in support of the full life cycle of physical, organizational and IT systems" and "enables us to deal with complexity and derive value from models and modeling is defining the structure, semantics, and notations of models using industry standards" [75], which is a specific kind of MDD. The relationship of MBE, MDE, MDD, and MDA is shown in Figure 3.

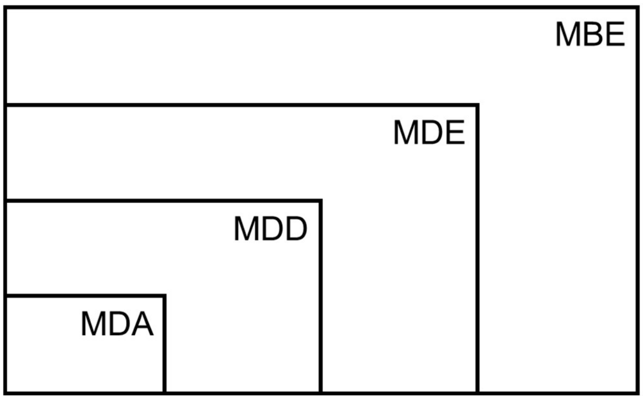

Figure 3: Relationship of MBE, MDE, MDD, and MDA

The benefits from applying MDE can be summarized as follows: increasing productivity by maximizing compatibility between systems by reusing standardized models; simplifying the design process by recurring design patterns; promoting communications of co-workers by standardizing terminology and best practices; improving the systems by changing the models without further programming effort [76,77]. MDE has been applied in different scenarios. To remove the gap between Web design and the final implementation, the MDA principles of automatic generation of software systems based on model transformation has been used during the development of Web application [78]. The usability and benefits of MDA to generate distributed real-time and embedded applications have also been proven in [79]. The implementation of methods and tools for the development of multi-agent systems can be supported by a model-driven development process with agent-based models [80]. There are also rudiments for the application of the MDE to the engineering of the high-level production system in the manufacturing enterprises. The model-driven approach with the MDA framework was applied by [81] to generate the ERP system. A prototype has been implemented to prove the applicability of MDE to the engineering ERP systems, which need to be customized related to specific application scenarios. The MDA was also introduced for the development of the MES in the machine processing industry by [82], in which the MES was modeled with Unified Modeling Language (UML) and transformed into Extensible Markup Language Metadata Interchange (XMI) as intermedia for the code generation. However, because of the limitation of the standardized general-purpose modeling language, namely the limited availability of modeling experience for exchange and analysis in every specific application scenario [83], the portability of this approach to other industries cannot be clarified. The modeling of the MES involves disciplinary information from co-workers, such as machine operators, employees, managers, and executives, with different viewpoints on the same production process in the manufacturing enterprise [84]. In the most successful implementation of MDE, small and non-standardized modeling languages must be developed for the domain-specific modeling [85]. To integrate the different viewpoints [86], with the analysis of the modeling requirements and comparison of the existing modeling notations, a formal specification framework for the MES was proposed in [87–89], which has divided the MES specification model into three parts, technical system (plant) model, production process model, and MES function model. With this division, it is possible to integrate the different views and domains in the specification process of MES.

Although researches about the application of MDE to implement MES in the manufacturing enterprise can be found, which has the potential to reduce the customization and programming effort and further the implementation cost to benefit the SMEs However, because of the specific characteristics of the production process and requirements on the MES (Section 1.2), a feasible MDE approach for the engineering of the MES in the food and beverage industry was not established.

1.4 Motivation and objective

In summary, the model-driven concept can be a solution to simplify MES implementation, in which the MES can be modeled at an abstract level for the efficient communication between co-workers, subsequently, be transformed and generated automatically without considering the details for programming and customizing efforts for the integration and adoption of the MES to the related business and production process. With a model-driven engineering approach, the sectors in the food and beverage industry, in which SMEs take a share of 99% of the total enterprises with limited flexibility to be invested in the MES projects, can exploit the implementation of MES (e.g., the increase in the energy and production efficiency, the enhancement of the safety and traceability of the product, refining the manufacturing processes in the shop floor, and the improvement of the transparency of the whole supply chain).

The objective of this work is to develop a model-driven approach for the engineering of the MES, which can reduce the programming and customizing effort in an MES project for the food and beverage industry. The requirements that should be satisfied by this approach are defined as:

- Requirement 1 (R1): Development of a feasible model-driven approach

  The model-driven approach should be designed in a way that it covers the necessary phases to carry the information in the established MES model, during the model transformation, and then for the MES generation. Furthermore, the approach should ensure the sustainability of the generated MES so that new demands on the MES can be fulfilled. Furthermore, to be feasible in different domains of the food and beverage industry, the easy exchange of domain-specific information is necessary for the mentioned models. Accordingly, the approach should adopt a suitable modeling language that supports the division of the MES model into independent sub-models.

- Requirement 2 (R2): Definition of modeling elements for the food and beverage industry

  The modeling elements as components of the MES model should be predefined. On one hand, they should be known to the later steps after modeling so that the MES can be generated automatically. On the other hand, the reuse of the predefined modeling elements can hinder the modeling effort. The generated MES should apply to enterprises in the food and beverage industry. For this reason, the MES functions relevant to the food and beverage manufacturing enterprises should be correctly represented (e.g., production efficiency evaluation, energy management, production scheduling, and predictive maintenance).

- Requirement 3 (R3): Support of a standard information model

  To avoid the effort to redefine the information interface between the shop floor and MES for every specific application and to integrate the MES with other software systems in the enterprise, the developed approach should adhere to a standard information model for consistent communication in the vertical and horizontal direction. Moreover, the portability of the predefined modeling elements reused in various application scenarios can also be ensured using the standard information model, since the data flow for exchange and processing within and without the MES remain uniform.

- Requirement 4 (R4): Support of a generic specification of the MES

  It is common in an MES to have to implement MES functions with different focuses or platforms to meet the demands. The specification covers the information transformed from the models and serves as the bridge between the modeling phase and the generating phase in the model-driven approach. It should be generic so that different types of MES functions can be adopted into the specification. Considering the relatively limited adoption of emerging technologies by enterprises in the food and beverage industry, the specification should also comply with the commonly used technology by those manufacturing enterprises.

- Requirement 5 (R5): Dynamic generation of the MES

  The modeling elements in this model-driven approach should not be defined for specific application scenarios but be exploited to compose distinct MES functions satisfying a range of demands. Thus, in terms of the flexible sequence and information flow among modeling elements, the MES should still be generated automatically and dynamically, which also requires the flexible transformation of models and generation of the final MES.

This thesis is structured as follows:

I. Literature study for state of the art:

Implementation of the Manufacturing Execution System in the Food and Beverage Industry

II. Development of the modeling language:

Model driven engineering of manufacturing execution systems using a formal specification – Extension of the MES-ML for the generation of MES code

III. Modeling phase of the model-driven approach:

Basis for the Mode-Driven Engineering of Manufacturing Execution Systems: Modeling Elements in the Domain of Beer Brewing

IV. Transformation phase and generation phase of the model-driven approach:

Manufacturing Execution Systems for the Food and Beverage Industry: a model-driven Approach

V. Further development and validation of the model-driven approach:

Model-driven generation of customizable Manufacturing Execution Systems for the implementation in the food and beverage industry

To explore the research area of MES implementation in the food and beverage industry, a literature review (Publication I) has been made. In this review article, two different viewpoints have been considered, namely the characteristics of the food and beverage manufacturing processes and the development of the MES, to analyze the barriers, the requirements, and the possible solutions for the feasible and efficient MES implementation in the food and beverage industry. As a result, the standardization of the information model, the service-oriented architecture (SOA), and the model-driven engineering have been considered as the valuable research direction to face the challenges and fulfill the requirements. To be suitable for the model-driven MES engineering, the modeling language, Manufacturing Execution Systems – Modelling Language (MES-ML), has been extended in Publication II. With this extension, the MES can be modeled with four components, the plant model, the process model, the MES function model, and the report model. Using the concept of the SOA, reusable basic functions have been defined as the smallest elements to compose the final MES functions in a wide range. In Publication III, a model-driven approach with three steps, i.e. modeling, specifying, and generating, has been proposed. In this approach, the standardized information model, Weihenstephaner Standards, has been integrated to define modeling elements that relevant to the food and beverage industry, which can compose the MES functions for the management of energy consumption and evaluation of the production efficiency. As this research has focused on the modeling, and the further steps have not been clarified with more details, a more concrete model-driven approach with five phases has been proposed in Publication IV, i.e., the analyzing phase that analyzes the actual state of the targeted process and defines the demands on the MES, the modeling phase that models the components of the MES with a suitable modeling language, the specifying phase that transforms the information from the models into the format that the software can utilize, the generating phase that creates a user interface and establishes the inner-connections among the components of the MES, and the application phase that configures the MES according to the specific business processes. In this research, the further steps that mentioned in Publication III have been clarified. With the use case in a fictitious brewhouse for the MES function of energy management, the feasibility of the whole approach has been proven. However, it lacks the verification of the presented approach with real production data and demands from the manufacturers in the food and beverage industry. Therefore, in Publication V, based on the interviews with the manufacturers in the food and beverage industry, the approach has been extended with an improving phase for adopting the generated MES to the new demands from the manufacturing processes, and two use cases either in the processing and packaging areas in the food and beverage industry with real production data have completed the verification of the presented approach with a more convincing result.

2 Results – Thesis Publications

2.1 Publication I – Literature study for state of the art

Implementation of the Manufacturing Execution System in the Food and Beverage Industry

Xinyu Chen; Tobias Voigt

Page 18 – 32

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To support the manufacturers in the food and beverage industry to face the challenges, e.g., rigorous regulations from domestic government and global organizations, increasing demand on product diversity from the consumers, changing production strategies to reduce the inventory of the retailers, and own requirements to reduce the energy consumption and enhance the production efficiency, the implementation of modern IT solutions is indispensable. The Manufacturing Execution System (MES), the middle layer between the production process on the shop floor and the business process on the enterprise level, guides the execution of rough production plans into detailed operations on one hand, and provides key performance indicators for making commercial decisions on the other hand. The implementation of the MES enables the improvement of the process transparency and the information exchange in real-time. However, the implementation of the MES is not widespread in the food and beverage industry.

In this study, with the literature review, the requirements of the food and beverage manufacturing processes are analyzed in three aspects, i.e., safety and traceability, energy and production efficiency, and flexibility and scheduling. In consideration of the requirements, the support from the MES is discussed. To answer the questions, why the MES implementation is limited in the food and beverage industry, and how those hindrances can be overcome, the barriers and solutions for the implementation of the MES are presented.

Contributions of the doctoral candidate – Conceptualization, Methodology, Investigation, Resources, Writing - Original Draft, Writing - Review & Editing

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Implementation of the Manufacturing Execution System in the food and beverage industry

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ABSTRACT

The Manufacturing Execution System (MES) is a production management system serving as the information center in the enterprise to improve manufacturing transparency. It is the middle layer connecting the manufacturing process on the shop floor and the business process on the Enterprise Resource Planning (ERP) level. On the one hand, the MES guides the execution of rough production plans into detailed operations on the shop floor. On the other hand, it provides the firm with critical key performance indicators (KPIs), enabling commercial decisions. The support from the MES, such as production fine planning, performance analysis, and product tracing, can help manufacturers to be efficient and gain more competitiveness in the global market. However, in the food and beverage industry, which faces strict regulations, growing competitiveness, customer demand changing, and suffer from low-profit margins, the implementation of the MES did not become widespread. This article intends to present the particular characteristics of the food and beverage manufacturing process, analyze the potential benefits and barriers of the MES implementation in the food and beverage industry through literature review. The solutions to solve the MES implementation issues and the research areas that need to be explored in order to meet the MES requirements from the food and beverage industry are also discussed in this article.

1. Introduction

In the 1970s, computer-aided software applications had already caught the attention of manufacturers. In order to improve the competitiveness of the enterprises, the efficiency of the production lines, and to comply with the regulations from (domestic) government and global organizations (outside the country), Manufacturing Execution System (MES) has been developed since the mid-1990s. They are process-oriented manufacturing systems for collecting and managing the information from the manufacturing processes. On the one hand, the MES implements gross production plans from enterprise systems into a detailed operational plan to the production areas. On the other hand, it provides critical key performance indicators (KPIs) to the company for making commercial decisions and improving production performance. In the classical automation pyramid of industrial automation, the MES layer is located between the Supervisory Control and Data Acquisition (SCADA) layer and the Enterprise Resource Planning (ERP) layer, which manages the information from the manufacturing process, provides reports to the higher management level, and reacts to changes and disturbances in real-time (Mersch et al., 2010).

The food and beverage industry, whose final products are consumed by human beings, should be facing more rigorous and meticulous regulations, as the quality and safety must be ensured in the product supply chain between different manufacturing sectors and in the product life cycle within the individual enterprise (Grunert, 2005; Henson and Caswell, 1999). Also, the products should be traceable to provide information such as food attributes, country of origin, and genetic engineering (Bosona and Gebresenbet, 2013). Contamination should also be identified when there are consumer complaints (Opara and Mazaud, 2001). Due to the low-profit margins in most sectors, the need for improving production efficiency, reducing energy consumption and saving resources has resulted in a drive for updating the production management software systems (Osterroth et al., 2017).

The MES, as an information center in industrial automation, contributes to achieving process transparency, efficiency improvement, on-time performance, and compliance with production plans. The benefits that are brought from the implementation of the MES can be summarized (Kletti, 2015): i) increase in quality, MES enables the inspection

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during production, permanent monitoring of important production data, and availability of work instructions in digital form; ii) reduction of the lead time, MES provides transparency over the complete order sequence, better synchronization of the operations of a production order, and support of internal material transport; iii) increase in personnel productivity, MES can help to avoid manual provision of information at the workplace, manual data acquisition, evaluation, and redundant planning effort; iv) reduction of energy consumption not only for individual machine but also the whole production line by identifying of the peak loads and avoiding considerable penalty costs with the MES. However, although MES was already being used in many manufacturing industries, its implementation in the food and beverage industry was not widespread, the MES functionalities were still realized by manual documentation and calculation, or stand-alone software systems.

This paper intends to present the characteristics of the food and beverage manufacturing process to identify major benefits, barriers, possible solutions, and future research areas of the MES implementation in the food and beverage industry. The paper is structured as follows. Section 2 introduces the research background containing the development, definition, and functionalities of the MES and the characteristics and requirements of the manufacturing process in the food and beverage industry. Section 3 presents the research questions and methodology for the literature review process. The facts and researches to fulfill the requirements from the food and beverage industry, the benefits that can be brought from the MES, the barriers and solutions for the implementation of the MES in the food and beverage industry are presented in Section 4. Section 5 presents the final concluding remarks and further research directions.

2. Research background

This section provides background knowledge to the MES and the manufacturing process in the food and beverage industry. The development, definition, and functionalities of the MES and the characteristics and requirements of the food and beverage industry are presented.

2.1. Development of the MES

In the 1960s, manufacturing organizations started applying software solutions to automate their financial area, as the primary competitive factor was cost, which resulted in product-focused manufacturing strategies based on high-volume production, cost minimization, and assuming stable economic conditions. In the late 1970s, the sectors in manufacturing industries were focusing on marketing and led to the adoption of target-market strategies concentrating on better production integration and planning (Jacobs, 2007). The Material Requirement Planning (MRP) system, which integrates forecasting, master scheduling, and procurement, was introduced to ensure the fulfillment of the demand by releasing a set of production/supplying orders for each item of the bill of materials that allows synchronizing the internal and external logistics flows (Orlicki, 1975). Due to the competitive pressure from the global market, the manufacturing strategy in the 1980s shifted to detailed process control, world-class manufacturing, and reduction of overhead costs. Against this background, the MRP evolved and became the MRP II, which provided three major features: material planning, material control, and production order definition (Jacobs, 2007; Sum and Yang, 1993). In 1973, the concept of computer integrated manufacturing was firstly proposed (Harrington, 1973). At the end of the 1980s, IBM introduced a new computer-integrated manufacturing framework to integrate information across the enterprise. It implies a systematic approach to support a manufacturing enterprise and includes the major functional business areas, i.e., Marketing, Research and Engineering, Production Business Planning, Plant Operations, Finance Accounting, and Administration (Harris, 1985; Meudt et al., 2017). With reference to "across the enterprise," the migration path from early MRP to MRP II to computer integrated manufacturing, and further to Enterprise Resource Planning (ERP) had been laid (Jacobs, 2007). The ERPs are systems aimed at integrating organizational functions for better customer support and planning, which have excelled in providing better forecasting and planning, inventory management, and accounting functionalities (Muhammad et al., 2010). However, the ERP applications cannot manage the operations on the shop floor, as these applications lacked the granularity and speed required for the shop floor activities. The transactional data in the ERP applications are recorded and reported on a weekly, monthly or daily basis, while plant management requires the recording, reporting, and reacting of every single transaction on the floor instantaneously, i.e., in real-time (Schleipen et al., 2011). This inability of the ERP/MRP systems accelerates the development for real-time data collection software applications, which went on to become the MES that we have today. The term of MES was firstly used in 1992 by AMR Research, and in the same year MESA (Manufacturing Enterprise Solutions Association) came into existence. The emergence of the MES presents the development of a critical interface between MRP II systems and the shop floor with device control systems (Rondeau and Litteral, 2001). The most essential contribution of the MES is that it combined the manufacturing process with a value delivery system focused on meeting customer requirements and demand (Marks, 1997).

2.2. Definition and functionalities of the MES

The MESA, a global organization focusing on driving business results from manufacturing information, has proposed a formal definition of the MES that describes the core task of the MES in the manufacturing enterprise: "The MES delivers information that enables the optimization of production activities from order launch to finished goods. Using current and accurate data, the MES guides, initiates, responds to, and reports on plant activities as they occur. The resulting rapid response to changing conditions, coupled with a focus on reducing non-value-added activities, drives effective plant operations and processes. The MES improves the return on operational assets as well as on-time delivery, inventory turns, gross margin, and cash flow performance. The MES provides mission-critical information about production activities across the enterprise and supply chain via bi-directional communications" (MESA, 1997). To fulfill the requirements from different manufacturing environments, twelve MES functionalities were defined (IEC, 2013):

- Resource allocation and control: managing resources directly associated with control and manufacturing. The resources include machines, tools, labor skills, materials, other equipment, documents, and other entities that are required for work to start and to be completed.
- Dispatching production: managing the flow of production in the form of jobs, orders, batches, lots, and work orders, by dispatching production to specific equipment and personnel.
- Data collection and acquisition: obtaining the operational production and parametric data that are associated with the production equipment and production processes;
- Quality management: providing real-time measurements collected from manufacturing and analysis in order to assure proper product quality control and to identify problems requiring attention;
- Process management: monitoring production and either automatically corrects or provides decision support to operators for correcting and improving in-process functions;
- Production tracking: providing the status of production and the disposition of work;
- Performance analysis: providing up-to-the-minute reporting of actual manufacturing operations results along with comparisons to past history and expected results;
- Operations and detailed scheduling: providing sequential and timely processing of operations based on priorities, attributes,

characteristics, and production rules associated with specific production equipment and specific product characteristics;
- Document control: controlling records and forms that are maintained with the production unit;
- Labor management: providing the status of personnel including time and attendance reporting, certification tracking, and the ability to track indirect functions;
- Maintenance management: maintaining equipment and tools;
- Transport, storage and tracking of materials: managing and tracking the transport and storage of materials, in-process products and end products, and transfers between and within plants.

To establish meaningful data on the real benefits of the MES for manufacturing and financial managers of manufacturing companies, the MESA has conducted two survey analysis about the benefits that can be brought by the MES in 1993 and 1996 with the MESA members in different industries. The results of the two surveys have shown that the MES can help to reduce 40% of the manufacturing cycle time, 55% of the data entry time, 25% of the Work in Progress, 27% of the lead time, 19% of the product defects and 56% of the paperwork between shifts in average (MESA, 1997). An industrial analysis reporting the improvement of the manufacturing process by using the MES was made in 2004. Based on the responses from the companies that were winners and finalists of the Industry Week Best Plants Award between 1998 and 2002, improvement of the production plants were observed and evaluated in a period of three years. Compared with the plants that didn't use the MES, greater reductions in production cost (34%), energy consumption (57%), and cycle time (37%) can be measured on the plants using the MES (Fraser, 2004; Strategic Direction, 2004).

As more and more software systems were used in the manufacturing industry, the integration of these systems was becoming an issue that needed to be solved. From 2000 to 2013, the International Society of Automation (ISA) published five parts of the ISA-95 standard for the integration of enterprise control (ISA, 2000, 2001, 2012, 2013a, 2013b). Four control levels were defined in the ISA-95 standard (Fig. 1):

- level 0 and 1, the actual physical processes and its sensing and actuation;
- level 2, manufacturing processes, especially SCADA, Programmable Logic Controller (PLC) and Distributed Control System (DCS);
- level 3, systems which manage the workflow of batch, continuous or discrete production operations, the MES;
- level 4: business planning and logistics systems that manage business-related activities of production (Verdouw et al., 2015).

The benefits that the ISA-95 can bring are: i) decreasing costs and complexity of the integration of business logistics systems and manufacturing systems, ii) enabling comparisons between best practices for the operation of manufacturing, iii) facilitating discussions about it by creating a common vocabulary and framework, and iv) reducing costs and complexity of the integration of systems that operate manufacturing systems (ISA, 2000). The major contribution of the ISA-95 standard is the clarification of key interactions between different components of an MES system and their interfaces with other systems in the enterprise. In the absence of an MES system, the developed solutions may not be able to follow the changing needs of the industry, and may even be unable to respond to the problem effectively, e.g., a periodical quality problem may be correctly interpreted if it can be mapped to maintenance operations (Saenz de Ugarte et al., 2009). Based on the ISA-95, the International Electrotechnical Commission (IEC) has published the international standard IEC 62264 for the enterprise control system integration (IEC, 2013a, 2013b, 2016a, 2016b, 2016c).

Today, topics such as Industry 4.0, the Internet of Things (IoT), and the Cyber-Physical System (CPS), have gained attention. Due to the development of information technology, the changes to the life cycle of production plants including their engineering, and the pressure to increase efficiency through standardization and modularization, Vogel-Heuser et al. (2013a) proposed a new information model for industrial automation that serves as the backbone for information integration in the heterogeneous industrial automation environment (Fig. 2).

The new model can be seen as a double cone or diabolo model, which is framed at the bottom by the manufacturing process and at the top by the business process: the lower cone represents the field and control, and the upper cone represents the process management and organization levels, in which the MES functions are implemented (Vogel-Heuser et al., 2013a, 2013b). For manufacturing enterprises, the MES is becoming an indispensable layer to implement the logical decentralization of the systems, plants, products, resources in the manufacturing processes, the vertical integration between the entities in the business process and on the shop floor, the connectivity within the shop floor to identify the localization of materials or containers and to reduce the complexity of communication, and cloud computing and advanced analysis (Almada-Lobo, 2016).

2.3. Characteristics of the food and beverage manufacturing process

The manufacturing process in the food and beverage industry can be categorized into three different types: batch process manufacturing, continuous process manufacturing, and discrete parts manufacturing to handle three main process stages, i.e., processing, mixing, and packaging:

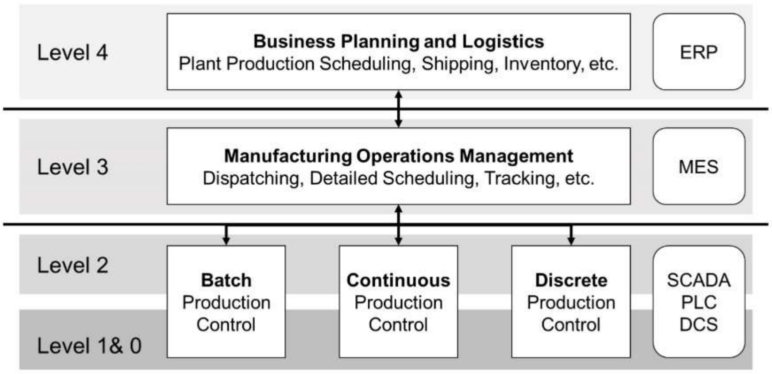

Fig. 1. Levels and position of MES defined in the ISA-95 standard (ISA, 2000).

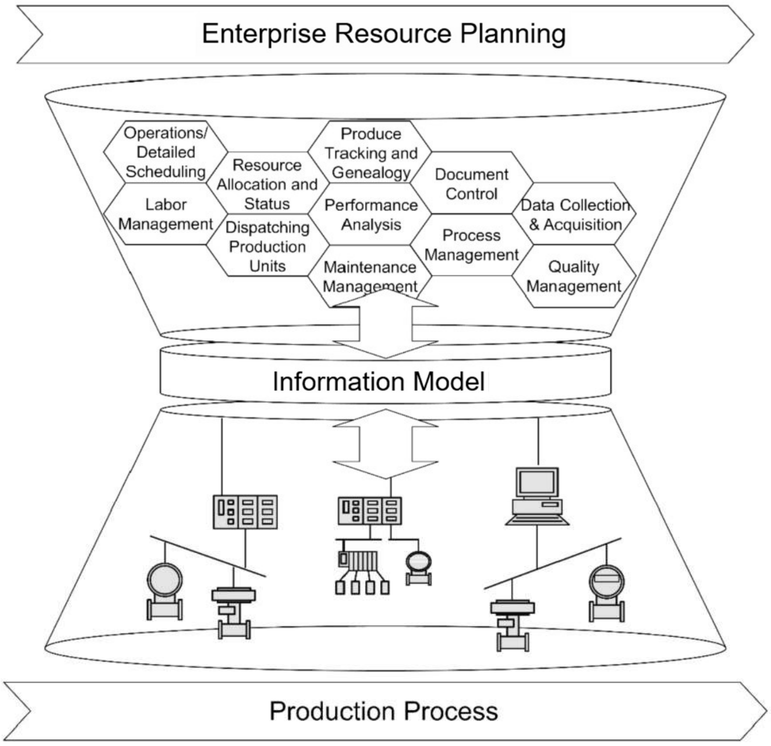

Fig. 2. The diabolo as the new model for industrial automation (Vogel-Heuser et al., 2013a).

- Batch process: production of finite quantities of material by subjecting quantities of input materials, e.g., the baking process from dough to the final bread
- Continuous process: continuous flow of material through processing equipment, e.g., operation of raw milk into skimmed milk and cream
- Discrete process: specified quantity of parts moves as a unit between workstations, e.g., filling of beverage on the filling line

Characteristics of the processes in the food and beverage industry can be described as: manufacturing processes usually consist of divergent processes combined with convergent processes, as the splitting and mixing of lots are common activities; production yields are uncertain, as the raw materials and semi-manufactured products often have dynamic characteristics changing over time; recipes are variable and multi-level, e.g., different materials can lead to similar products; recycling of products or semi-finished products is common in the food processing (den Ouden et al., 1996; Hvolby and Trienekens, 1999); as the safety and quality of final products are influenced by the environmental hygiene and sanitation, mixed transportation, storage condition, personal hygiene, and safety and quality of semi-finished products and additives, prerequisite programs (PRPs) that comprise principles, procedures, and means for safe food production are considered as the fundamental practices and conditions to be implemented (Mortimore and Warren, 2014; WHO, 1998); final products can be perishable and have a limited shelf-life, the use of data on products and processes in various management processes is necessary for such as production planning, order management for purchasing and sales, warehouse management, detailed manufacturing execution, and freight management (Trienekens, 1999).

2.4. Requirements on the process in the food and beverage industry

The food and beverage sector, as the largest manufacturing sector in the European Union (EU), represents 15.2% of the total manufacturing turnover, 15% of the employment in the EU manufacturing industry, and 13.8% of EU household consumption expenditure (FoodDrinkEurope, 2018). As the final product of the food and beverage industry is for human consumption, compared to other manufacturing industries, it has higher requirements on its processes. The manufacturing processes in the food and beverage industry are an integration of the various components of the food supply chain. It comprises all actors and activities from primary production, food processing, distribution, retailing, and finally, consumption by consumers (ECSIP, 2016). In this sense, the safety and traceability of the food and beverage products must be ensured.

The European Food Information Council (EUFIC) has summarized the factors influencing the preference of consumers' choice for food and beverage: biological determinants including hunger, appetite and taste; economic determinants, such as cost, income and availability; physical determinants of access, education, skills and time; social determinants such as culture, family, peers and meal patterns; psychological determinants that may include mood, stress, etc.; attitudes, beliefs and knowledge about food (EUFIC, 2005). DiSantis et al. (2013) have pointed out that among the different factors, the price remains the most crucial factor determining food choice. Because of the low-profit margins in most food and beverage sectors, to control the cost of production, the awareness to reduce energy consumption and improve production efficiency is growing (Olsmats and Kaivo-Oja, 2014).

Food and beverage industry experiences growing logistical demands from the customers (van Pieter Donk, 2000), growing variety of products, and intense competition in the global market (Matthews et al., 2006). Due to the dynamic and competitive nature of the food and beverage sector, conventional products may lose their commercial viability and new products are continually introduced in an unpredictable way (Gargouri et al., 2002). The volume and density of product variety increase over the product life span (Erens, 1996). It is often difficult for the manufacturers to decide which products to make to order and which products to stock. To satisfy the customer's wishes and to stay flexible against the market changes while keeping the production cost at a reasonable level without losing its efficiency, the manufacturing processes should be regulated with an effective scheduling strategy.

3. Research questions and methodology

As previously stated, though the MES can help the manufacturers to improve the transparency of the manufacturing process, the implementation in the food and beverage industry was rarely to be found. Combined with the analysis of the characteristics and requirements of the food and beverage industry, the main objective of this work is to answer three research questions:

i. Why the food and beverage manufacturers need support from the MES;
ii. What are the barriers for the implementation of the MES in the food and beverage industry;
iii. Which technologies can improve the implementation process of the MES for the food and beverage industry

The literature review process was performed using ScienceDirect as a scientific database firstly. This database was chosen as it contains a range of scholarly peer-reviewed publications from foundational science to new and novel researches. In order to determine the basic framework, academic papers in this database were filtered through the combination of the keywords that included in the title, abstract or author-specified keywords, i.e., "food" AND "Manufacturing Execution System", which was considered as the basic filter for further refining. However, only four search results can be found in the database (Table 1).

Because of the limited search results for academic research, another database, the FSTA (Food Science and Technology Abstracts) was used to expand the scope of the literature review, which includes scientific and technological research and information relating to food, beverages, and nutrition. In the FSTA database, the keyword "Manufacturing Execution System" was used. As a result, twenty-seven articles were found. Most of them were industrial magazines to report the technological information and two out of the results were scientific articles focusing on the production optimization with the support of the MES (Table 2).

Based on the fact that only a few scientific researches have been done

Table 1
Literature filtered by using the keywords of „food" AND „Manufacturing Execution System" in database ScienceDirect.

Nr.	Year of publication	Journal	Title
1	2018	Computers in Industry	Basis for the model-driven engineering of manufacturing execution systems: Modeling elements in the domain of beer brewing
2	2005	CIRP Annals	Holonic Manufacturing Execution Systems
3	2012	Engineering Applications of Artificial Intelligence	Real-world production scheduling for the food industry: An integrated approach
4	2013	Journal of Food Engineering	Diagnostic model for assessing traceability system performance in fish processing plants

Table 2
Literature search results in the FSTA database using the keyword "Manufacturing Execution System".

Nr.	Year of publication	Journal	Title
1	2015	Cereal & Food Industry	Research on MES system and production optimization technology in grain processing industry
2	2015	Cereal & Feed Industry	Internal logistics technology based on RFID in wheat processing enterprise

in the area of the MES implementation in the food and beverage industry, the framework and research direction of this work were established. After the research background was introduced, along with the literature review process, the research to fulfill the requirements of the food and beverage industry, and the benefits that can be brought to the manufacturing industry by the implementation of the MES were discussed, though some researches and experience were not learned specifically from the food and beverage industry due to the limited research amount. Following that, the barriers to the implementation of the MES in the food and beverage industry were analyzed. Lastly, the possible solutions to simplify the implementation process of the MES in the food and beverage industry were presented (Fig. 3).

4. Literature review

4.1. Facts and researches in the food and beverage industry

Based on requirements presented in Section 2.4, the research in the food and beverage industry has been assigned into three main categories, i.e., safety and traceability, energy and production efficiency, and flexibility and scheduling.

4.1.1. Safety and traceability

The products from the food and beverage industry meant for human consumption must meet high quality and safety standards. With the emergence of food incidents and scandals, such as dioxin-contaminated production, phthalate-tainted foodstuffs, the addition of anhydride to starch products (Tsai et al., 2016; Rieger et al., 2016; Peng et al., 2017; Chen et al., 2013), consumers have become more critical and wish to be informed about the origins and processes of food procurement, safety levels, production methods, hygiene, use of genetically modified feed, application of pesticides, and other environmental issues like food miles and carbon footprints (Trienekens, 2009). Scharff (2012) reported that the illnesses and deaths related to food safety issues account for a $77 billion burden on the U.S. economy every year. To comply with the increasingly strict regulations, the food and beverage manufacturers have to apply principles to improve and ensure the safety of the manufacturing process, such as Good Hygiene Practices (GHP), Good Manufacturing Practices (GMP), and hazard analysis and critical control points (HACCP) (Ababio and Lovatt, 2015; de Oliveira et al., 2016). To provide safe food to the consumers, the set of requirements in GHP has been defined to prevent contamination of food in the aspects of primary production, establishment design and facilities, control of operations, maintenance and sanitation, personal hygiene, transportation, product information and consumer awareness, and establishment of training programs (FAO, 2006). The GMP ensures that ingredients, products, and packaging materials are handled safely and food products are processed in a suitable environment. It contains all the policies and procedures required to meet the production standards and related activities to implement and monitor them. Once the GHP and GMP (PRPs) are in place, the HACCP system can be implemented to control hazards that may affect food safety (Sun and Ockerman, 2005). The Food Safety Modernization Act (FSMA) that became effective in 2011 has changed the present food safety focus from a reactive to a preventive approach, i.e., the sectors should concentrate on preventive controls rather than

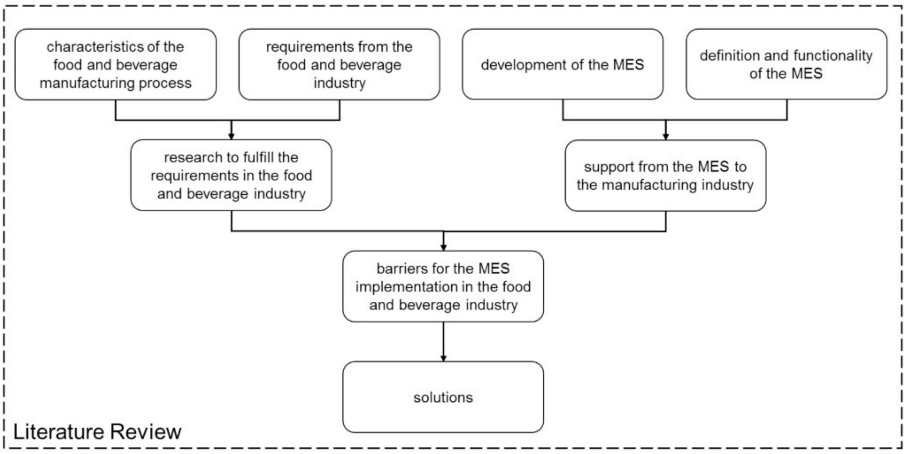

Fig. 3. Framework of the literature review process.

simply react to food safety events (Grover et al., 2016). In order to ensure food safety, a number of researches have been made. Alfian et al. (2017) proposed a Radio-Frequency Identification (RFID) and wireless sensor network based e-pedigree system for documentation of the product location, temperature, and humidity during the storage and transportation to satisfy the growing consumer awareness of food quality and safety. Based on the RFID technology, Lorite et al. (2017) have introduced a critical temperature indicator to monitor the temperature profile to enhance food safety and quality in the supply chain. Refrigeration is considered as an important role in reducing the rate of growth of pathogens organisms and slowing down the spoilage process. Gwanpua et al. (2015) developed the FRISBEE software tool to optimize the quality of refrigerated food, energy use, and global warming impact of refrigeration technologies along the European cold chain. The nanotechnology can also be applied to improve food safety (Berekaa, 2015), e.g., food preservation (Hamad et al., 2018), food packaging materials with barrier effects (Pathakoti et al., 2017), and detection of contamination (He and Hwang, 2016).

To comply with the regulation, limit contamination risk, and reassure consumers facing food safety crises, the food sectors tried to trace their products along the whole supply chain. A traceability system is applied to identify the involved actors and relevant flows which characterize the material and processing operations that contribute to the production of the final items. van Rijswijk and Frewer (2008) reported that major consumers perceive that the traceability is interlinked to food quality and safety. The research of Clemens (2015) indicates that Japanese consumers believe that those food products that can be traced according to the producer names are safer than the comparable ones without such traceability. Thakur and Hurburgh (2009) developed a framework for implementing a traceability system in the U.S. bulk grain supply chain including the consideration of internal and external chain traceability so that the internal operations related to the products are traceable to obtain food safety management systems certification and the information exchange between actors on the supply chain. An optimization model for traceability systems that integrates traceability initiatives with operation factors was proposed by Wang et al. (2009) so that the desired product quality and minimum impact of product recalls can be achieved. Abad et al. (2009) proposed an RFID tag integrated real-time traceability system and cold chain monitoring for final products. More application of RFID technologies used in the food traceability and safety systems can be found in (Hong et al., 2011; Parreño-Marchante et al., 2014; Barge et al., 2019; Tian, 2016).

4.1.2. *Energy and production efficiency*

Electricity and thermal energy (including fuel and steam energy) are the two main energy forms used in the food and beverage manufacturing processes. Taking the energy consumption in the brewery as an example, 70% of the electricity is consumed by refrigeration, packaging, and compressed air, while the brewing process dominates the use of thermal energy at 45% to heating up the mash tun and whirlpool during the production of wort (Brewers Association, 2015). Muller et al. (2007) have identified the potential energy-saving opportunities in the food industry and proposed a method to track them, which has clarified the energy-saving priorities and the energy requirements of consumers during the food processing. Osterroth et al. (2017) proposed a simulation model associated with the machine status on the bottling line to predict and further reduce the electricity use of the machines in the manufacturing processes. Law et al. (2013) pointed out that 11.4 TWh of recoverable waste heat is emitted to the environment per year via waste streams in process industries, and 2.8 TWh waste heat is from the food and beverage manufacturing industry. Recovery of this waste heat can contribute to reducing emissions and production costs significantly. Aneke et al. (2012) presented the potential of recovering waste heat based on the food processing application of a chip manufacturing plant and discussed the different recovering potential of low-temperature waste heat (for preheating) and high-temperature waste heat (for evaporation). A knowledge-based system for low-grade waste heat recovery in the process industry to reduce greenhouse gas emissions and plant utility costs was presented in (Law et al., 2016). Maxime et al. (2006) developed the Eco-Efficiency indicators (EEIs) to measure the energy use, emission of greenhouse gases, water use, generation of solid organic residue and generation of packaging waste so that a framework can be built for a sustainable production system helping the regulators and sectors in implementing cleaner production initiatives to save cost and enhance competitiveness.

The food and beverage industries are facing increased regulations from international and national organizations, such as the World Health Organization (WHO), Food and Drug Administration (FDA), and European Commission (EC). Compliance with these regulations results in increased costs of process improvements in other areas. Advanced management principles and systems are applied to food and beverage processing, which bring rewards in terms of reducing costs and increasing the overall efficiency of the processing system (Mahalik and Nambiar, 2010). Weinekötter (2009) reported that the processing and packaging machinery in the food and pharmaceutical industry remain underutilized. It leads to shorter production runs and frequent changeovers. Overall Equipment Effectiveness (OEE) is a key performance indicator used in manufacturing systems for controlling and monitoring the productivity of technical equipment (Huang et al., 2002). The OEE is the multiplication of its three components, availability, performance efficiency, and quality rate. A world-class OEE is generally considered to be better than 85%, in which 90% for availability, 95% for performance, and 99.9% for quality rate. Tsarouhas (2013) has calculated the OEE in the beverage industry with a case study on a production line of alcoholic mixed drinks with an average OEE of 73% multiplied from availability of 89%, performance of 86%, and quality rate of 96%, in which activities to improve the performance efficiency and quality rate should be optimized. In order to improve the efficiency of production plants in the food and beverage industry, modern maintenance strategies should be implemented (Baglee and Knowles, 2013). Kennedy et al. (2013) applied the lean principles in a UK food manufacturing company. The result of their research has shown that the deployment of lean tools can improve production efficiency, product quality, and lower production costs by reducing waste and adding value. The concept of Total Productive Maintenance (TPM) was introduced in the food industry for increasing productivity, improving product quality, and reducing the production cost of the line (Tsarouhas, 2007). More information about the energy and production efficiency in the food and beverage industry can be found in (Evans et al., 2014; Müller et al., 2014; Therkelsen et al., 2014; Ali et al., 2009; Ivester, 2008; Lehtinen and Torkko, 2005).

4.1.3. Flexibility and scheduling

Make-to-Stock (MTS) and Make-to-Order (MTO) are two production strategies in the manufacturing industry (Rajagopalan, 2002). To lower the production cost and limit the number of set-ups, the MTS policy has dominated in food processing companies for a long time. However, the production policy has to tend to MTO gradually. The reasons can be summarized by two main factors: consumer behavior with increasing demand on new products, more choices over product features and personalization (Salvador et al., 2002; Meulenberg and Viaene, 1998); retailers' restructuring the supply chain to achieve a reduction in inventories, faster replenishment, shortening of cycle times and private labels (van Donk, 2001). MTO is the strategy that is suitable to produce high variety of customer-specific products with characteristics of low volume, small batches, and long-time windows for delivery. This strategy has moved the focus of production on order execution and order-dependent performance (Soman et al., 2004). van Donk and van der Vaart (2004) pointed out that the manufacturers can gain flexibility from MTO strategy to fulfill the requirements of the customers. Alfnes et al. (2000) analyzed the market challenges faced by food companies in Norway: the declining of high-volume foods with predictable demand, the increasing of low-volume foods with unpredictable demand, fiercer international competition, and increasing demand for private labels from retailers. Based on the results, they have identified the emerging need for the food industry, i.e., mass-customization, high flexibility, and quick responsiveness.

Due to the growing logistical demands on performance and special orders from the customers, e.g., personalized products or products for export, the need from sectors in food and beverage industry for flexibility is increasing, while the production efficiency and quick response to order change should be ensured by rational scheduling activities (Meulenberg and Viaene, 1998; Nakhla, 1995; Jakeman, 1994). The complexity of the manufacturing process in the food and beverage industry due to the mixed batch, continuous, and discrete processes, variety of product types, heterogeneous set-ups, etc., leads to the difficulty of establishing optimal scheduling algorithms. Akkerman and van Donk (2009) confirmed the necessity of the scheduling in the food processing industry and analyzed scheduling issues decomposition of the structure of the manufacturing process from the task of the scheduler. On the one hand, the decomposition approach provides opportunities for a good understanding of the process to improve the decision-making in scheduling. On the other hand, this approach supports the scheduler to execute the scheduling tasks and clarifies the relationships between the production tasks of the process and the decision-making tasks of the scheduler. Touil et al. (2016) developed a mixed integer linear programming model to solve the production scheduling problems in the multistage, multiproduct milk processing industry. This model has been evaluated suitable to create optimal scheduling plan with a computational application with small instance. Baldo et al. (2014) indicated that due to the long lead time required for the fermentation and maturation processes in the brewing process and the beer can remain in tanks waiting for being bottled, the scheduling in the brewery industry is facing the challenge to synchronize the two stages. They proposed an approach based on the relax-and-fix heuristic and fix-and-optimize strategies to solve this scheduling problem. More researches contributed to the scheduling issues in the food and beverage industry can be found in (Kopanos et al., 2011; Claassen et al., 2016; Simpson and Abakarov, 2009; Chatavithee et al., 2015).

4.2. Support from the MES to the food and beverage industry

Facing the above-mentioned requirements from regulations and consumers, the trend of technologies and their applications, the sustainability-related increase of energy and production efficiency, the decrease of production waste, limitation of greenhouse gas emissions, the transparency to ensure food safety traceability in the whole supply chain, and the production flexibility and scheduling must be improved. To do this, information systems must be implemented, aiming to retrieve and provide information to consumers as well as decision-makers in the food and beverage industry (Wognum et al., 2011). According to the definition and the functionalities introduced in Section 2.2, the MES can help sectors in the food and beverage industry to comply with the regulations from the government and organizations, the high-level demand from consumers, and requirements from the manufacturers themselves for the product manufacturing with high quality, low cost and minimum the lead time (Zhong et al., 2008). An interview with six breweries and five MES providers was conducted in Germany in 2016 to identify the supply and demand situation from different viewpoints (Bär, 2017). On the side of the end-users from the breweries, they indicated that the MES could help them the most in the improvement of production efficiency and product traceability. Four of six breweries considered the MES is necessary to manage energy use in production. Three of them confirmed that MES benefitted maintenance, corporate strategy, and quality control. For the MES providers, the reason why their customers should apply the MES can be summarized as follows: product traceability, improvement of production efficiency, and quality control (full vote); energy management, corporate strategy (four of five); organization and state-of-the-art (one of five).

4.2.1. Safety and traceability

To ensure food safety and traceability, the application of information systems on the food supply chain is considered as the solution to link the information regarding product and process characteristics together in every part of the chain (Trienekens and Beulens, 2001). Since compliance to food safety regulation is increasingly becoming mandatory in global value chains, the development, implementation, and maintaining of the food safety management system (FSMS) is necessary for the food and beverage sectors. In this sense, adequate information should be available for planning, execution, monitoring functions from the manufacturing process (Trienekens and Zuurbier, 2008). As a key factor for the successful implementation of FSMS, the support from the MES cannot be absent, which serves as an information center delivering critical information from the manufacturing processes to the proper co-systems. The interest in coupling data from more than one control or management system is increasing to ensure traceability, as its development can be spurred by improving the efficiency of data collection, plant control, and quality assurance (Moe, 1998). As the MES is connected with the process on the shop floor, it can help to fill the information gap of the traceability in process, where the physical identification is not possible to be made. By integrating the process information in the traceability in the food production process, the problems related to inappropriate processing can be identified quickly to limit the recall of the affected batches, which requires real-time monitoring and data processing supported by the MES (Klafft et al., 2006). The requirements in GHP and the programs of HACCP can be achieved and implemented efficiently with the functionalities of the MES by systematically documenting and tracing food sources and production routines, reasonable arrangement of the food storage and transport, generation of practical schedules for maintenance and sanitation, and providing transparent production information of the whole product life cycle (ASABE, 2006; Bos et al., 2010).

4.2.2. Energy and production efficiency

Bunse et al. (2011) indicated that the MES could help to manage and to reduce energy consumption in the manufacturing processes, as MES is directly connected to the shop floor level and supports the sectors to understand the consumption of energy resources in the process globally. The evaluation and assessment of potential energy-saving investments can be clarified by the implementation of the MES. As the MES enables the automated data collection with evaluation, the error-prone calculation of the OEE based on paper forms or spreadsheet programs can be replaced. The automated evaluation also helps the group of companies to establish a standardized OEE benchmark to compare the internal production efficiency with each other. Besides the basic reference measure for analyzing and comparing the utilization of resources at the plant, the OEE can help the sectors to identify potential areas of improvement and support lean initiatives (Sohal et al., 2010), such as upgrading operation management, replacement of technical parts, training programs for operators, etc. The application of lean principles in manufacturing sectors can also be supported by MES. It can provide useful real-time information such as the use of materials, processing times, and machine breakdowns to trigger, feed, or validate the lean decision-making processes to better the production efficiency (Cottyn et al., 2011). Palanisamy and Siddiqui (2013) proposed a method integrating the Single Minute Exchange of Die (SMED) principle in MES to reduce the changeover time, which increased the planning and production efficiency.

4.2.3. Flexibility and scheduling

Zhong et al. (2011) introduced an RFID integrated MES that can schedule the production order in real-time. They pointed out, through the usage of data mining technologies together with the RFID data, the MES is able to perform more precise scheduling for production on the shop floor. Cupek et al. (2016) indicated that detailed scheduling requires the link to the order execution that integrated into MES and proposed an agent-based MES for the scheduling of short-series production. A number of researches (van Brussel et al., 1998; Babiceanu and Chen, 2006; Valckenaers and van Brussel, 2005; Colombo et al., 2006) that focused on the development and application of holonic architecture for MES treated scheduling function as a holon that must communicate with other holons to compose the whole MES realizing real-time reactive scheduling. Wauters et al. (2012) indicated the MES is the basis for scheduling in the process industry, typically the food and beverage industry, and proposed a scheduling approach integrated with MES, which separate the scheduling task as several subtasks for information acquisition, route calculation and decision making in the food industry.

4.2.4. Industry 4.0

The benefits that the modern technologies bring to the food and beverage industry, such as cyber-physical systems, digital factory, Industry 4.0, and IoT (Vogel-Heuser et al., 2013a, 2013b), are inseparable from MES, as it is the essential information processing and providing layer between the ERP system for business processes and control systems for manufacturing processes in the new industrial automation environment. Rüßmann et al. (2015) reported that the next generation of digital industrial technology, known as Industry 4.0, can increase manufacturing productivity and drive revenue and employment growth. Furthermore, the optimization of the transparency in the whole product life cycle, the flexibilization of manufacturing processes through self-configuring and self-organizing production facilities, the efficient planning of the maintenance interval of key production machinery, and the innovative production such as personal customizable products, are also considered as benefits that Industry 4.0 brought along for manufacturing industries (Pötter et al., 2017). Arica and Powell (2017) analyzed the technologies coming up with Industry 4.0 and confirmed the sustainability of the MES in the developing manufacturing industry.

4.3. Implementation of the MES in the food and beverage industry

In this section, the barriers for the implementation of the MES in the food and beverage industry and the solutions are presented.

4.3.1. Barriers

The MES executes and controls production orders from ERP. This top-down structure is difficult to integrate with different production forms, which favors a bottom-up production strategy, such as just-in-time production, pull production, and inverse manufacturing (Artiba and Elmaghraby, 1996). Because of the software heterogeneity in the manufacturing environment, to ensure a smooth information flow within the enterprise, the adoption of communication interfaces among different software systems is the primary reason limiting the implementation, integration, and maintenance of the MES (Liu et al., 2002; Westerlund, 1996). For the large companies which are able to afford an MES project, they don't have the necessary time to complete it: on the one hand, the integration of the MES to the existed IT systems, such as ERP, Labor Information Management System (LIMS), and Production Planning System (PPS), is an ongoing activity that continues long (Koch, 2001); on the other hand, as an MES project involves co-workers from different departments of the company, it is hard to find time to i) organize meetings to define the requirements on the desired MES, ii) coordinate the tasks that should be done by each department, iii) compare MES providers with rational price, and iv) stop regular production to test the MES functionality. In contrast, though the small- and medium-sized enterprises (SMEs) have the flexibility in terms of time, they don't have the resources to complete the MES projects (Mensah and Julien, 2011). As the manufacturing process and the related production plants vary from one enterprise to another, the MES, which is closely connected to the operations on the shop floor, must be adopted with a lot of programming and customizing effort, which is cost-intensive and error-prone (Drath, 2008). Besides that, there are few rudiments of MES solutions designed particularly for the food and beverage manufacturing processes. Of the 285,000 companies in the European food and beverage industry, more than 99% of them are considered SMEs with less than 250 employees (FoodDrinkEurope, 2018). However, SMEs in the food and beverage industry are in an awkward position since this industry is fragmented in nature, and the adaptation to information technology is rather slow, as competitors rarely inform each other of advancements to improve their products and production efficiency. In addition, due to the size of the company, the low margin of the products, and the low financial flexibility that comes with it, SMEs often cannot afford to invest in expertise in the area of production and resource efficiency as well as in renewable energy integration (Meyers et al., 2016). In this sense, though the MES can help manufacturing sectors in many ways to improve their product quality, production efficiency, product safety and traceability, and supply chain transparency (Zhong et al., 2017; Menezes et al., 2018), the implementation of the MES in food and beverage industry is not widespread because of high engineering costs, the complexity of information integration - especially in the area of programming and customizing - and the high heterogeneity of manufacturing processes. Instead of a centralized MES, the food and beverage manufacturers are still using cheap but unreliable solutions to provide partial MES functionality.

4.3.2. Solutions

In this section, based on the analysis of the barriers for the implementation of the MES in the food and beverage industry, three solutions are presented.

4.3.2.1. Standardization of the information model. Large pools of data from customers and manufacturing enterprises are recorded, communicated, aggregated, stored, and analyzed (McAfee et al., 2012). The data and information are scattered across the food, health, and agriculture sectors in the food and beverage supply chain. Marvin et al. (2017) indicated that interoperability standards should be applied to the food and beverage industry. Walton and Marucheck (1997) analyzed the use of electronic data interchange, which is the computer-to-computer transmission of standardized business transactions, for supply chain coordination in the food and beverage industry. Also, in the automation diabolo, a standardized product-related information model coordinates the work of different systems, allowing the design cycle to be modularized into two automation layers (Khedher et al., 2011). The standardized information model ensures data consistency for the communication of integrated software systems within the enterprise.

A standard information model widely used in the food and beverage industry is called "Weihenstephan Standards" (WS). The WS specify a universal communication interface for connecting different machines and process-control systems to a higher-ranking MES. They also define the data that must be available for acquisition. With this information model, the processing of the data from machines and processes can be standardized for the necessary MES functions (Kather and Voigt, 2010). The principles for calculating KPIs and energy consumption, as well as for tracing batches to prepare clear production reports, were also defined in this information model. The development of WS began in 2005, and so far the WS cover the information model primarily in four application areas: WS Food for the meat processing industry; WS Bake for the baking industry; WS Brew for the brewing industry; WS Pack for the packaging and filling area of the food and beverage industry. The working group of WS is developing the WS further for more application areas in the food and beverage industry.

4.3.2.2. Service-oriented architecture. The technology named Service-Oriented Architecture (SOA) can be a solution to solve the integration issues for the implementation of the MES. It makes a high coherence in integration system architecture and solves the problem of using uniform standards and tools in the system integration process (Xiao et al., 2008). SOA is an architecture paradigm of information technology from the area of distributed systems used to structure and utilize services provided by the IT system. A service is a software component that can be accessed by a service provider to achieve the desired end results for a service consumer, and both provider and consumer are roles played by software agents on behalf of their owners (He, 2003). The principal characteristics of SOA can be summarized as loose coupling enable the maintaining and guaranteeing of service data and state consistency; implementation neutrality ensures the independence of the programming language and implementation of each service, as the description of interface matters most; reusability, the services may be individually useful or integrated and/or composed to provide higher-level services; flexible configurability for dynamic change of the system (Huhns and Singh, 2005; Srinivasan and Treadwell, 2005). SOA prescribes the form of the reusable components, which established a good base for knowledge-based integration and a service-based loose coupling integration technique. The only disadvantage of the SOA solution is that it would require the complete rewriting of all the current applications in the enterprise (Erl, 2006). However, nowadays many pieces of research and main contributions for information integration have been found that are based on the SOA concept. Komoda (2006) has reported that the SOA has been applied to the industrial systems on the business level of the enterprises. For the manufacturing systems that require real-time functionalities, the SOA has also been successfully applied, e.g., for the business and logistics system and the semiconductor processing equipment. Spiess et al., 2009; Cannata et al. (2008) pointed out that the advances made in the areas of embedded systems, computing, and networking are leading to an infrastructure composed of millions of heterogeneous devices, which should be interconnected to provide and consume information available on the network and cooperate in the manufacturing enterprise. They have proposed an SOA-based approach named SOCRADES Integration Architecture to integrate the information flow among different devices. Each device can offer its functionality as a standard service, and at the same time discover and invoke new functionality from other services on demand. Chen et al. (2006) indicated that the requirement from customers on sophisticated design and the short production cycle force enterprises to create a multi-disciplinary group, or even a multi-disciplinary group across the enterprises to work together in an effective way. They built a collaborative manufacturing system on an SOA-based platform to enable the synchronous cooperation support of message-based technologies among the manufacturing enterprises. Morariu and Borangiu (2012) proposed a manufacturing integration framework based on the SOA technology, which matches the processes on the shop floor with business processes to shorten the time to market by increasing manufacturing process flexibility in the manufacturing enterprise. For the development of a batch process management system, Virta et al. (2010) have proposed an approach based on SOA for the integration of the MES with Process Control Systems (PCS) on the shop floor. This approach contributed to simplify the data exchange and design process of the management system. Chazalet and Lalanda (2007) have proposed an approach for services-oriented applications to achieve a seamless integration from sensors distributed in the real world up to IT systems supporting various business activities. More SOA-related research and contributions for integrating information in a manufacturing enterprise can be found in (Jiang et al., 2007; Ma and LI, 2005; Savio and Karnouskos, 2008; De SouzaLuciana Moreira et al., 2008).

4.3.2.3. Model-driven engineering. As the MES is directly connected to the operations on the shop floor and the manufacturing processes vary from one enterprise to another, the MES must be adopted specifically with high customizing and programming effort. Conventionally, to implement an MES solution within a manufacturing enterprise, seven phases are necessary (NAMUR, 2006; Sauer and Ebel, 2007):

- Basic evaluation phase: coordinating the objectives of the MES project with the enterprise, defining the project scope and content, estimating the rough costs of the project.
- Pre-planning phase: creating the specification for the business process within the enterprise, defining the concept and requirements of the MES solution.
- Basic planning phase: calling for tenders of the desired MES solution; comparing the different offers; evaluation and preparation of the recommendation; obtaining the approval for the MES project; allocating the project to the MES provider.
- Detailed design phase: placing the order to the MES provider, designing the MES with details.
- Realization phase: creating the application software; preparing the data systems; training of the basic systems; installing the software and hardware; integrating the network; installing the application software; verification of the application software: training of the application for key users.
- Operation phase: training of the application for all users; commissioning of the MES solution; revising the documentation.
- Running up phase: drafting the final report and the project settlement.

To reduce the engineering and implementation effort of the MES, the model-driven concept was introduced. A model is a simplification of a system that can answer questions in place of the actual system (Bézivin and Gerbé, 2001). Although models are widely used in software development, they are mainly used for communication between co-workers in a project, analyzing the problem, and documenting the system, while the detailed design is code-centric (Mohagheghi and Aagedal, 2007). With the growing pressure to reduce the cost and time for the engineering of the software systems, the current development paradigm, which is based on object-orientation, may have reached the point of exhaustion (Greenfield and Short, 2003). The term opposed to code-centric, namely Model-driven Engineering (MDE), is used for development processes that are model-centric. The prime artifacts in MDE are models representing the system at different levels of abstraction and transformed into other models and/or code (Bézivin, 2004). The benefits from applying MDE can be summarized as follows: increasing productivity by maximizing compatibility between systems by reusing standardized models; simplifying the design process by recurring design patterns; promoting communications of co-workers by standardizing terminology and best practices; improving the systems by changing the models without further programming effort (Basha et al., 2012; Vanderdonckt, 2008). Al Mosawi et al. (2006) proposed an enterprise application architecture based on the Object Management Group's (OMG) Model-Driven Architecture (MDA) to integrate and harmonize the isolated business applications, processes, and functions in an enterprise. MDE was also used to develop applications on mobile devices to reduce technical complexity and development costs, as the independent models can be used for the engineering of cross-platform applications (Umuhoza and Brambilla, 2016). Hästbacka et al. (2011) introduced a model-driven approach to the development of industrial process control applications to gain more engineering productivity. Damo and Becker (2018) applied the MDE to the generation of automation applications for the petrochemical industry, which allows the representation of industrial plants with different and interchangeable object-oriented models and provides the means to perform automatic code generation from a plant specification for different software platforms. More information about the application of MDE in various industries can be found elsewhere (Thompson et al., 2014; Ardagna et al., 2012; Ding and Klein, 2010; Steffen et al., 2006; Balasubramanian et al., 2006).

4.3.2.3.1. Model-driven approaches in the manufacturing industry. In the area of the engineering of high-level production systems in a manufacturing enterprise, the application of MDE can also be found. Dugerdil and Gaillard (2006) applied a model-driven approach for the implementation of the ERP system using the OMG's MDA framework with a computer independent model (CIM), a platform-independent model (PIM) and a platform-specific model (PSM). An extended UML profile was defined to model the business process at the level of ERP for CIM. The transformation rules from CIM into PIM were represented by a high-level model of the generic process to be implemented in the ERP to propagate tagged values from the CIM to the PIM with specific states of each business process' tasks. Based on the result of the propagation, namely constraints described in Object Constraint Language (OCJ), the PIM is transformed into a PSM represented with Business Activity Diagram (BAD). A prototype has been implemented in an MDA toolkit to prove the applicability of the MDA framework to the customization of ERP. Furthermore, Mizuoka and Koga (2010) presented an approach for implementing the MDA development method in the MES, in which the latter is firstly modeled with Unified Modeling Language (UML) and transformed to Extensible Markup Language Metadata Interchange (XMI) as intermedia for code generation. This approach was applied to the machine parts processing industry, and the portability of this approach was not clarified. As the modeling of MES is strongly dependent on the target business process, this approach is difficult to transfer to the food and beverage industry. Besides that, the modeling of the MES requires interdisciplinary information from different disciplines, as the machine operators, employees, and executives have different views on the same manufacturing process in a manufacturing enterprise (Ricken and Vogel-Heuser, 2010). Whittle et al. (2013) pointed out that in the most successful implementation of MDE, domain-specific modeling paradigms are used, in which small and non-standardized modeling languages must be developed, although a set of standards has been presented to support the use of MDE, such as the key modeling language in MDA, the UML (Selic, 2003). On the one hand, developing models that cover broad domains demand significant effort to capture knowledge from every specific domain, and on the other hand, the domain-specific languages (DSL) for narrow and well-understood domains can be developed within a short period. France and Rumpe (2007) mentioned that the use of a standardized general-purpose modeling language that covers a wide range of abstractions for every different application scenarios could be problematic, as little modeling experience is available for exchange and analysis. They also discussed the challenges of the use of DSL, for (1) each DSL needs its own set of tools (editor, checker, analyzer, code generator) and (2) the problems of interoperability, the language version, and language migration must be considered while using DSL. This leads to challenges in defining the rules of transformation between models. A possible solution for this is the combination of general-purpose languages, domain-specific languages, and tools for automated model management, such as transformation, validation, comparison, etc. (Kolovos et al., 2013).

4.3.2.3.2. Application of model-driven concept in the food and beverage industry. Witsch and Vogel-Heuser (2011) presented a formal modeling language for the specification of MES, named MES Modeling Language (MES-ML). It has been evaluated to be suitable for the engineering of MES in interdisciplinary workshops, is easily understandable and efficient in communicating MES specification details. Based on the MES-ML, Weißenberger et al. (2015) have extended the MES-ML as the modeling language for the model-driven engineering of MES, including automatic code generation. Flad et al. (2017) have proposed a model-driven concept for the engineering of MES in the food and beverage industry. According to this concept, the engineering process can be divided into three steps: first, the components of an MES solution are modeled with suitable modeling language; second, the models are transformed into a specification that can be utilized by software applications, an MES generator; finally, an operational MES is generated automatically by the generator based on the specifications. However, the modeling elements that can be generally used in the food and beverage industry, the platform of the specification and generator, and the transformation mechanisms from models to specifications and further to the final MES solution were not clarified in this concept. Following this concept, Chen et al. (2018) proposed a model-driven approach in more detail, focusing on the definition of the modeling elements that represent the typical manufacturing processes and MES functions required in the food and beverage industry. The processes in a brewery have been chosen as the application target for this approach because the processing area and packaging area were included in the manufacturing process in the brewery, which represented the two typical areas in the food and beverage industry. This approach has been evaluated by the MES experts with food and beverage experience as a feasible solution to reduce the effort for the integrating, programming, and individualizing in the MES engineering process. The standardized information model WS was introduced in this approach and the MES functionality was composed by basic function elements that independent of each other and provide their processed information, which work as a "service" that defined in SOA. However, further developments of this approach must be completed to clarify the model transformation and the MES generation after the modeling phase. It may open an efficient way for implementing the MES in the food and beverage industry.

5. Conclusion

This article presents a literature review of the implementation of the MES in the food and beverage industry. Compared to other sectors, as the products of the food and beverage industry are intended for human consumption, the characteristics and requirements related to food safety, traceability, production efficiency, and energy consumption were presented in this article. The MES, which was developed as a data exchange and processing center to fill the information gap between the shop floor, control systems, and other enterprise business applications, can help the food and beverage manufacturers to improve the transparency of their processes, discover their potential to increase production efficiency and reduce energy consumption, provide enterprises with the KPIs for making business decisions. Based on further analysis, some reasons have been confirmed to explain why the implementation of the MES in the food and beverage is not widespread: on the one hand, this industry is composed primarily of SMEs producing various types of product, due to its complex manufacturing environment, poor exchange of know-how, and low financial flexibility, there are few resources for them to implement the MES; on the other hand, the effort needed for the information integration of the MES, the customizing and programming in the engineering process make the MES implementation to a complex project. In this sense, the possible solutions for the barriers standing in the way of the MES implementation were also discussed. It was also to be noted that the most MES providers are focusing on the management functionality based on data acquisition and processing for certain results, such as energy consumption or material/resource inventory, while the execution functionality, namely the fine planning, was not mentioned.

In order to implement the MES in a broader range and efficiently for the food and beverage industry, as the results of this work: i) a standardized information model to bridge the communication from shop floor to MES and further to ERP should be developed to cover the different requirements from the process area; ii) new engineering approaches with less programming and customizing effort should be developed for the whole life cycle of the MES solution so that the SMEs can also benefit from them; iii) as the time to market of the food and beverage products is becoming shorter, the real-time execution functionality of the MES, such as efficient resource planning according to machine performance and order delivery time, order re-planning against machine failures, and predictive maintenance for reducing machine downtime should be considered as a key feature of the MES for the food and beverage industry.

Although this work has delivered interesting results, there are some limitations that the authors are aware of: i) this work focused on the food and beverage industry in an abstractive level to present the characteristics and requirements from it, the specific manufacturing processes, e. g., meat production, dairy operation, and confectionery production, were not discussed in detail; ii) as limited academic research that has been found, the data to analyze the benefits quantitatively from the MES to the food and beverage industry were not able to be presented in this work. In the future, following directions can be considered as the main research focuses: i) more detailed analysis of the specific characteristics and requirements from each sector in the food and beverage industry; ii) a summary of the commons and differences of food and beverage sectors in terms of process characteristics and requirements as the basis to evaluate the benefits from the MES; iii) interview survey with manufacturers in the food and beverage industry to evaluate the manufacturing process before and after the implementation of the MES.

This work gave the readers an overview to the state of the MES implementation in the food and beverage industry. Combined with the analysis of the characteristics and requirements of the food and manufacturing processes, it addressed the benefits, barriers and solutions of the MES implementation, which can be considered as the drive to open the research and practice field in this area.

Declaration of competing interest

The authors declared that they have no conflicts of interest to this work.

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2.2 Publication II – Development of the modeling language

Model Driven Engineering of Manufacturing Execution Systems using a formal Specification Benedikt Weißenberger; Stefan Flad; Xinyu Chen; Susanne Rösch; Tobias Voigt; Birgit Vogel-Heuser *In IEEE 20th Conference on Emerging Technologies & Factory Automation (ETFA), September 2015* *DOI: 10.1109/ETFA.2015.7301430*	**Page 33 – 41**

For the interdisciplinary specification of the Manufacturing Execution System (MES), a modeling language has been developed, namely the MES Modeling Language (MES-ML). It was evaluated to be suitable for the engineering of MES in interdisciplinary workshops and easily comprehensible as well as efficient in communicating MES specification details. However, in the area of model-driven engineering of MES, there is no suitable modeling language that has been defined. This study presents the extension of the MES-ML so that this modeling language can provide a solid foundation for the model-driven approach including generic modeling of the MES components and automatic MES generation. In the extended MES-ML, the division of the complete MES model into separate models is a core concept for an independent modeling. To be suitable for the automatic generation of the final MES, requirements for each model have been presented in this study, thereby impacting the semantic and the structure of the metamodel of the modeling language. As a result, the technical systems can be described with six hierarchy levels in the plant model, i.e., factory, area, plant, line, machine, and aggregate; the process model consists of three hierarchy levels with increasing degree of detail, i.e., process, process stage, and process operation. The MES function can be divided into basic functions and MES functions. The MES function related report model is the communication interface between the end-users and the MES. Based on a use case to model the brewing process in a brewhouse, the requirements for the modeling language have been evaluated. It has been proven that the requirements are satisfied by the proposed extensions of the MES-ML, and the suitability of the extended MES-ML for the model-driven approach to the engineering of MES, including automatic code generation, has been confirmed.

Contributions of the doctoral candidate – Methodology, Validation, Writing – Original Draft, Resources

Model Driven Engineering of Manufacturing Execution Systems using a formal specification

Extension of the MES-ML for the generation of MES code

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***Abstract*— Industrial manufacturing processes are complex processes, where transparency of every process step is necessary to achieve a high level of quality and efficiency. In order to achieve this transparency, manufacturing execution systems (MES) are used. However, as these systems are very expensive, mainly due to individual programming effort, MES usage is oftentimes limited to larger companies. To ultimately reduce implementation costs for MES, the current research project AutoMES proposes a standardized, model-based approach to facilitate automatic generation of MES functions. This paper presents requirements on a suitable modeling language, as well as how these requirements are fulfilled by the modeling language used in the AutoMES project. The modeling language is an extension of the MES Modeling Language (MES-ML), a modeling language for the specification of MES. With the use of the extended MES-ML it is possible to generate a generic, machine-usable MES specification, suitable for code generation. To evaluate the proposed modeling language extensions, an industrial brewing process has been modeled and verified by MES engineers during the project AutoMES.**

Keywords*— *Manufacturing Execution Systems, Model-based software development, code generation, formal specifications, standards

I. Introduction

Manufacturing Execution Systems (MES) are process-oriented software systems used for vertical integration in factory automation [1]. They connect the enterprise layer with the automation layer and their usage can improve production efficiency and quality [2]. Due to their position between the automation layers, MES require very complex interfaces to surrounding systems. Compound this with the fact, that instead of a central MES, the IT systems landscape is mostly heterogeneous at present, especially in small and medium-sized enterprises (SMEs), current challenges regarding a flexible and economic production process cannot be met [3]. Yet, a lot of SMEs shy away from MES projects, mainly because of engineering costs and are still using cheap but error-prone solutions to provide some of the functionality of a MES, for example Key Performance Indicator (KPI) calculations and detailed production scheduling in spreadsheet programs. In automation system projects, which include MES projects, engineering costs are a major factor and need to be reduced [4]. This paper proposes the foundation for a model-based code generation approach for this challenge, in order to allow more SMEs to afford MES implementations at their sites. In case of MES, engineering costs are primarily caused by programming effort to customize the MES for the site where it is to be installed. Interfaces of legacy IT systems and programmable logic controllers (PLCs) have to be implemented and maintained for example. The focus here is not on how data is provided to the MES, for example by using OPC UA, but rather on how the MES handles the provided data.

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In the AutoMES project, a current research project aiming to automatically generate MES code, a method is proposed, which has the potential to reduce MES implementation costs by using a model based engineering approach for MES [5]. It defines three steps to generate MES. The first step is the creation of a comprehensive plant model containing a model of the technical system of the plant, a model of the production process, a functional model of the MES and interconnections between these models based on an extension of the MES Modeling Language (MES-ML) [6], a modeling language for the interdisciplinary specification of MES. The MES-ML has been evaluated to be suitable for the engineering of MES in interdisciplinary workshops, is easily comprehensible and efficient in communicating MES specification details [6]. It was also found, that using it can reduce MES engineering costs. The division of the model into separate models is a core concept of the MES-ML. Witsch et al. proved in multiple industrial modeling workshops and expert interviews with MES users and MES engineers that this division greatly enhances the interdisciplinary comprehensibility of models, reduces perceived model complexity and aids in identifying cross-system interactions [6][7]. While the MES-ML provides a solid foundation for the AutoMES method, it cannot fulfill all the requirements to be suitable for code generation, presented in section II. In the second step, based on these models a generic MES specification is created using a software tool which converts the mainly graphical models into a machine-usable database format. This generic MES specification may then be used in a third step to automatically generate the code of the MES. Fig. 1 shows an overview of how the three steps interact with each other. This paper focuses on the development of a domain specific modeling language suitable for the specification of MES and code generation, based on the MES-ML. MES-ML models, while being formally specified, are designed to be used as a human-readable substitute for text-based MES specifications. For the AutoMES method, additional requirements need to be fulfilled for the purpose of later code generation, thus the MES-ML had to be extended. The proposed extensions of the MES-ML were evaluated by modeling an industrial brewing process and brew house. The domain of food and beverage industry was chosen, because it combines continuous and discrete production processes, resulting in evaluation results transferable to other domains.

The paper is structured as follows. In the following section requirements on a modeling language for generating MES is presented. In the section state of the art, related work in the fields of MES engineering and specification is presented. Subsequently the extended MES-ML is presented in section IV. Section V shows an evaluation of the MES-ML using an example in the brewing industry. A summary and an outlook are given at the end of this paper.

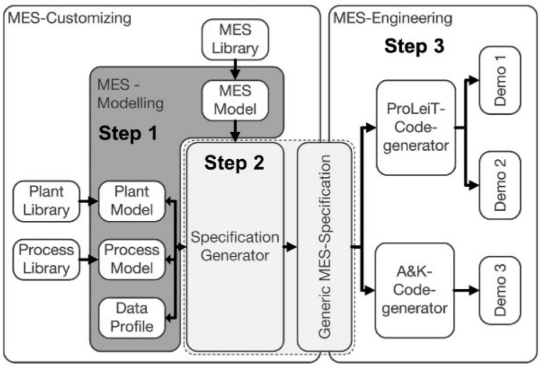

Fig. 1. Overview of the project AutoMES, based on [5]

II. Requirements On A Modeling Lanugage For Generating MES

The MES-ML provides the models necessary for specifying the technical system, the process and the MES model as needed for a model-based approach for generating MES. The requirements for bridging the gap of manually implementing the MES software based on the model to automatic code generation are analyzed and presented in the following.

In order to allow for later code generation it is necessary that rules can be found how models have to be interpreted. This is much easier, if a high degree of standardization is present in the model of the technical system. As such, a standard hierarchy of the plant model should be enforced. In order to minimize conflicts with existing plant descriptions in control systems that hierarchy should be inspired by ISA-95 [8], as it is the leading industry standard for describing plant hierarchies (Technical System Requirement 1 – TS1). In plant automation data or signals are used and specified on different hierarchy levels. An example where signals on an upper plant hierarchy level are needed is a sensor measuring the overall energy consumption of a whole production line without additional sensors from individual machines or aggregates. Therefore, the possibility to assign signals to all hierarchy levels of the plant model for accurately assigning data from the technical system to the correct hierarchy level is needed (TS2). One of the most time consuming and thus expensive steps in MES projects is the connection of existing IT systems, control systems, etc. to the MES. This is due to the fact that there is no standardized way to connect them. By defining a standardized set of signals and attaching semantic meaning to them, for example the signal called "WS_Cur_State" represents the state of a machine, this challenge can be conquered. As a result it is necessary to be able to define a standard set of signals, while still keeping enough freedom to allow for domain specific extensions of these standard signals (TS3). In addition, the more generalized MES and process tasks can be defined, the easier automatic code generation becomes. To be able to do so, ways are needed to model the tasks for as wide a range of signals as possible. A general function calculating the total sum of consumption values in a plant and providing this figure in an energy consumption report can be used whether the consumption values stem from energy consumption sensors or from steam consumption sensors for example. Therefore, to support a more generalized approach of MES function modeling a categorization of signals has to be made (TS4).

To be able to use the process model for code generation, process tasks have to be semantically defined. This can be achieved by modeling process tasks as independent of all other models as possible, enabling their usage in other MES projects. If a process task requires a specific signal from the technical system to function, for example, it should be possible to model this without knowing the exact technical system model. In addition to that, modeling of process tasks has to be consistent with current industry standards, such as the ISA-S88 for batch processes [9]. This allows for a standardized mapping between modeled process tasks and procedures stored in an underlying control system, e.g. a batch control system. The resulting first requirement for the model of the production process is to be able to model the production process as generalized as possible (Production Process Requirement 1 – P1). By fulfilling requirement P1, the model of the technical system and the process model are separated as much as possible. In order for the model to still contain the correct plant behavior, the assignment, which process task is performed by which element of the technical system at any given time, has to be modeled as well. As oftentimes the same process task can be performed by different elements of the technical system but the decision which element is performing the process task at any given time is made at runtime, there has to be a way to unambiguously define that assignment (P2). For this, it is insufficient to map process tasks to elements of the technical system, as the time at which this mapping is valid has to be considered as well.

In order to facilitate code generation, semantic meaning has to be assigned to MES tasks. Consequently, a standardized, semantically defined set of basic MES tasks is required and all other more complex MES tasks have to be a composition of this standardized set of basic MES tasks (MES Requirement 1 – M1). An example would be a standardized function providing the total sum of a consumption value over a given time frame. If these basic MES tasks are known to the code generator, it is possible do produce the corresponding MES code from the model. In order to be able to define these basic MES tasks and other more complex MES tasks, it is necessary to assign required input parameters as well as resulting output parameters, independent of the rest of the MES model. This enables the modeler do create libraries of basic functions that can be used in every MES project, independent of process model and technical system model. Thus, the MES model has to support the explicit modeling of these parameters (M2). After the MES tasks of a model are defined, it is necessary to connect them to show their interfaces and interactions. In order to do so, a number of possible connection sources have to be considered (M3). A parameter has to be connectable to either the in- or output of another MES task, a signal from the technical system or to an external in- or output source that is not known at modeling time but will be available at runtime, for example the input of a user. During the project AutoMES it was found that the vast majority of MES tasks that provide data to the user are reports, for example a status report for the control room or a KPI report for plant management. In order to generate these reports for the MES user, it is necessary to define their structure, content and the source of data contained in the report (M4).

TABLE I. MODELING REQUIREMENTS

Req.-No.	Requirement
Requirements for the model of the technical system	
TS1	Standardized plant model
TS2	Signals on every hierarchy level of the plant model
TS3	Expandable standardized set of signals
TS4	Categorized signals
Requirements for the model of the production process	
P1	Generalized process modeling conforming to standardized approach
P2	Unambiguous assignment of deployment links and possible deployments
Requirements for the model of the MES	
M1	Semantically defined MES tasks
M2	Explicit modeling of input and output parameters
M3	Modeling of data sources
M4	Modeling of reports

III. STATE OF THE ART

A common solution to reduce programming costs is code generation from software models. There are numerous solutions in different fields to automate programming tasks, for example the generation of controller classes from UML sequence diagrams [10]. In the field of MES however, there are currently no known applications of code generation, mainly because MES usually are individual implementations for different sites and very few parts are standardized. Another reason, that standard code generation methods are not easily transferable to MES are the unique requirements to MES modeling, as shown by Ricken et al. [11]. As a result, a modeling language for the specification of MES, the MES Modeling Language (MES-ML) has been proposed. It is a formal [7][13] modeling language for the specification of MES, based on the modeling language "Business Process Model and Notation" (BPMN) [12] and was specifically designed to conform with modeling language design guidelines as proposed in [14] and is used as base for the proposed method in this paper. The reason the MES-ML is used is that it has been found to be more suitable for the specification of MES than other modeling languages [11] such as SysML/UML based languages [15][16][17] and formal languages like Petrinets [18]. The MES-ML defines three basic models and an additional linking model [7]. The first base model of the MES-ML is the technical system model. It is a static hierarchical tree structure representing the technological structure of a plant. It can be used for existing plants, as well as during the engineering of a new plant. The second model in the MES-ML is the model of the production process. Its primary purpose is to model production business processes to make the visualization and specification of the interaction with the MES possible. The third base model of the MES-ML is the MES-Model. It contains all functional requirements for an MES in the context of surrounding IT-systems and the interactions with the production process and the technical system. The complete MES-ML metamodel can be found in [6].

While the MES-ML provides a solid base as a modeling language, e.g. the division into three basic models and formal description of MES functionality, the additional requirements from section II are not met. There are for example no standardized signals (TS3) and no semantically defined MES task (M1). It is also not possible to generate code from it. In order to meet the requirements and use it for code generation, the existing MES-ML metamodel has to be extended.

IV. EXTENDING THE MES-ML

While the MES-ML had to be extended, the majority of the core modeling concepts of the MES-ML are still valid, so unless otherwise noted, the standard MES-ML metamodel is used. For example, there is still a division into three basic models (technical system, MES model and model of the production process) and the linking model between the models.

A. Extending the Model of the Technical System

The model of the technical system is represented as a static hierarchical tree structure of the technological structure of a plant. The focus here is not on underlying systems, but on data provided to the MES. From the MES point of view, it is more important to know which signals are available and what they represent, rather than knowing the exact signal chain. The purpose of the model of the technical system remained the same as the standard MES-ML version of the model, but in order to fulfill requirements TS1-TS4 and for easier code generation later on it had to be reconstructed from scratch for the AutoMES method. The proposed metamodel for the model of the technical system can be seen in Fig. 2. To fulfill requirement TS1 and ensure a standardized overall plant structure, the model of the technical system has been constricted to a total of six hierarchical plant levels, as opposed to unlimited levels in standard MES-ML, plus the enterprise level. Only one enterprise may exist in one model, so cross-enterprise models are not supported. The six hierarchical plant

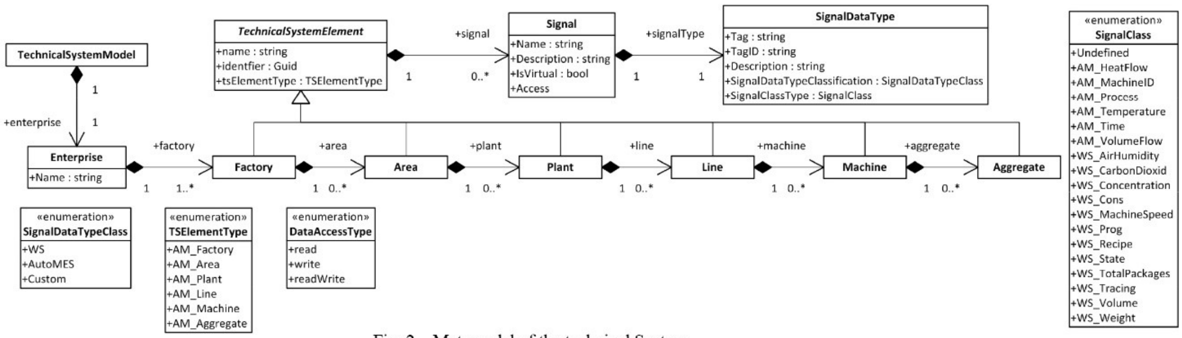

Fig. 2. Metamodel of the technical System

levels are in descending order: factory, area, plant, line, machine and aggregate and were inspired by the levels defined in ISA-S95 [8]. The lower five of the levels are optional but unlike standard MES-ML none may be skipped. Also no additional levels may be added. While this may occasionally lead to cases where artificial plant levels have to be modeled, later code generation is easier due to fewer possible variations in plant hierarchies. To fulfill requirement TS2, an accurate assignment of signals at every hierarchy level in the model of the technical system is needed. In the standard MES-ML signals can only be added at the lowest level (control modules). If a signal is present that applies to a whole production line, it is either necessary to add artificial entries for machines and aggregates for the signal to be added or the signal has to be assigned to an existing aggregate and the information, that the signal applies to the whole production line is lost. As a result, the metamodel of the MES-ML has been extended, so every hierarchy level may contain signals. To meet the third requirement for the model of the technical system, the existence of an expandable set of standardized signals (TS3), a modeling mechanism to standardize signals had to be found. The MES-ML assigns some general data to its signals (e.g. name, measurementUnit and scalingFactor), but the signals have to be defined individually for every MES-ML modeling project. There are no standardized signals and there is no semantic meaning attached to signals. In the AutoMES extensions of the MES-ML signals are assigned to a *SignalDataType*. Each *SignalDataType* represents the semantic definition of a signal. It is assigned to a signal standard via their *signalDataTypeClassification* attribute and it contains a unique *tagID* identifier and unique tag *name*. Coupled with a standardized signal listing this fulfills requirement TS3. As long as they define uniquely identifiable signals, every domain specific signal standard can be incorporated into an AutoMES model. As the first test application in the project AutoMES is a brewery (see section V), this has been proven by integrating the Weihenstephan Standard (WS) for food and packaging [19] into the AutoMES metamodel. The standard has been chosen, because it is widely established in the food and beverage industry and provided by most machines in this industry sector. Fig. 3 shows an excerpt of the WS metamodel containing only relevant information and an example of a status datapoint according to the Weihenstephan Standard. It is uniquely identifiable by its tag ID 00300 as well as its tag name "WS_Cur_State". Its semantic meaning is defined as the

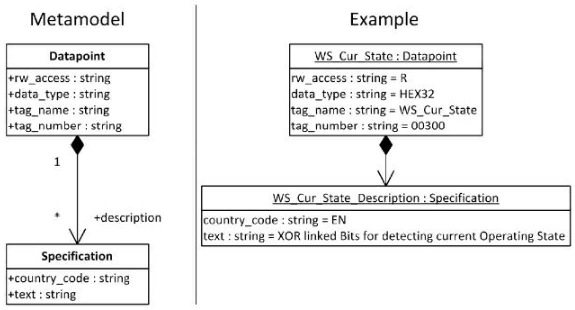

Fig. 3. Excerpt of the WS metamodel and modeling example

current operating state of a machine as defined in the Weihenstephan Standard [19]. It can be seen that this WS datapoint can be easily incorporated into the expanded MES-ML metamodel. The final requirement for the model of the technical system calls for a categorization of signals (TS4) to assist in generalized task modeling. As the MES-ML does not provide a mechanism to categorize signals, the MES-ML metamodel has been extended by adding a *signalClassType* attribute to *signalDataTypes*. An abbreviated list of possible *signalClasses* can be seen in Fig. 2 and is inspired by the categorization of datapoints in the Weihenstephan Standard. The Weihenstephan Standard categorizations by themselves are tailored towards the food and beverage industry, so they have been extended for general usage in different industries.

B. Extending the Model of the Production Process

The model of the production process of the MES-ML provides a lot of basic functionality that is still used in AutoMES models. In order to fulfill the requirements presented in section II, three slight modifications have been made to the metamodel of the process model. An excerpt of the metamodel containing those changes can be seen in Fig. 4.

To fulfill requirement P1 the standardized modeling of process tasks has to be possible. The major issue with generalized process modeling is that dependencies to the technical system have to be modeled without knowledge of the plant model of a specific plant. In standard MES-ML the dependency of a process task on a signal is done by using a proxy element of the technical system with a message flow to the process task, as can be seen in Fig. 5. This does not allow

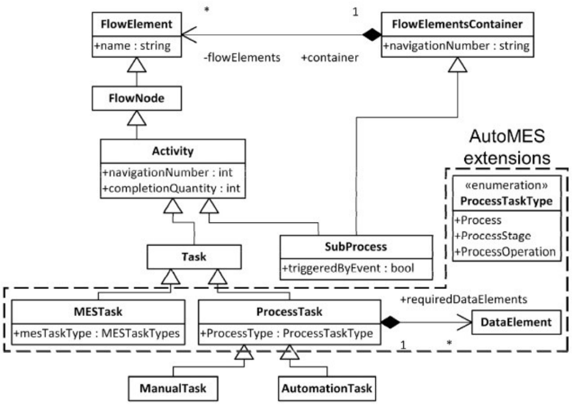

Fig. 4. Excerpt of the metamodel of the process model

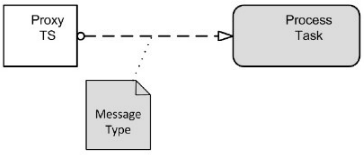

Fig. 5. Standard MES-ML assignment of required signal

the generalized modeling of the process task as only existing signals can be linked. To solve this issue, the MES-ML has been expanded to include a list of required signals for every process task. This list does not have a graphical representation to prevent cluttered diagrams. Paired with the definition of standardized signals (see section IV.A) it is then possible to model required signals independently of the technical systemand it is also possible to set required signal classes only such as a process task needing the signal of a temperature sensor, but at the time of modeling it is not yet known which aggregate will supply this signal. The second issue with generalized process modeling is that after code generation, the process tasks have to be known to the underlying control system. This mapping is oftentimes fixed and done in accordance with ISA-S88 [9]. In the MES-ML, process steps in the production process are modeled as process tasks. To achieve a better comprehensibility of the model, subprocess tasks, are used for vertical modularization and there is no limit on the maximum number of subprocess task levels. This will result in an inability to automatically assign process tasks to corresponding stored procedures in the MES or control system. Consequently, a limit of a total of three levels of process tasks was introduced to achieve a more standardized process model based on the process levels for batch processes defined in the ISA-S88. The extended MES-ML contains three levels of process tasks which are processes, process stages and process operations in descending order. The fourth level in the ISA-S88, process action, is not considered, because modeling it has been found to be too specifically tailored towards an individual plant, so a generalized approach is not viable. As a result, this will ensure that later on the mapping of modeled process tasks to stored procedures in the control system is consistent. For the control system of a batch process based on ISA-88 the assignment will be as follows: Processes are mapped to procedures, process stages are mapped to unit procedures and process operations are mapped to operations.

A resulting issue with generalized process modeling is that the information which element of the technical system performs which process task may be ambiguous. The MES-ML includes deployment links to model which elements of the technical system are used to perform a process task. While this approach unambiguously defines the relationship between technical system element and process task, the assignment information has to be known at modeling time. In industrial plants, this is oftentimes a runtime decision so an assignment at modeling time cannot be made. As a result the meaning of deployment links in the extended MES-ML has been changed to that of a list of elements of the technical system that are capable of performing a certain process task and may be chosen at runtime.

This allows for a more generalized modeling of the process tasks to fulfill requirement P1. An example would be if milk in a dairy is pumped into tanks for further processing. The process task is always the same but it can be performed by different tanks. In the standard MES-ML, the process task would have to be modeled for each tank separately, with the AutoMES extensions it needs to be modeled only once. The drawback of this method is that the deployment might be ambiguous. To rectify that and fulfill requirement P2, additional signals in the technical system were defined: AM_Cur_Process, AM_Cur_ProcessStage and AM_Cur_ProcessOperation. They contain the information which process task an element of the technical system has performed at any given time. If an element of the technical system is linked to a process task the corresponding signal is mandatory and has to be provided by the element of the technical system. The deployment links are also limited loosely based on ISA-S88 restrictions. Only plants can be linked to processes, only machines to process stages and only aggregates can be linked to process operations. As a result, process tasks can be modeled in a very generic way, yet the deployment information will be available to the MES at runtime.

C. Extending the MES-Model

None of the modeling concepts of the MES-ML for the MES model have been removed but some extensions had to be made in order to support better standardization of MES tasks and fulfill the requirements in section II. An excerpt of the extended metamodel can be seen in Fig. 6.

In order to be useful for code generation, MES tasks have to be semantically defined. The MES-ML assigns MES tasks a descriptive name but nothing else. While that is enough for human-readable MES specifications, to be interpreted by code generators, additional information is needed. To supply the necessary information, in the extended MES-ML a division into three types of MES tasks has been established: basic functions, MES functions and report functions. Basic functions are the most atomic functions present in the model. They serve as the base for all other MES tasks and their semantic meaning is defined in a library of AutoMES basic functions. For code generation purposes all other functions can be translated into an interconnected collection of basic functions. MES function

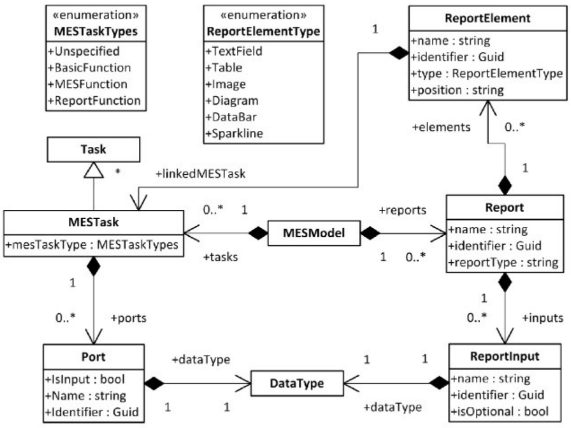

Fig. 6. Excerpt of the metamodel of the MES model

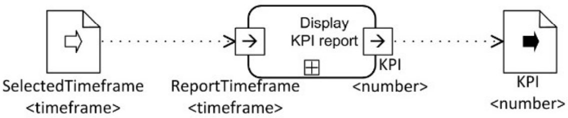

Fig. 7. Example of a report function with user in- and output

serve as an organizational unit for basic functions and other MES functions. They can be composed from basic functions and other MES functions but recursive use of MES functions is not permitted. They can use input from other MES tasks, from the production process or the technical system but not from other sources, e.g. user input. Report functions are specialized MES tasks that are used for tasks that require input that is only available from external sources at runtime. An example would be a MES user wanting to look at a KPI report for a certain timeframe. At modeling time the selected timeframe is not known to the MES, so instead a user input of type timeframe has to be modeled instead. Fig. 7 shows this example.

As a result, basic functions have to be defined independently of the overall MES model they will be used in. This leads to the input and output parameters having to be modeled explicitly. The MES-ML does not contain explicit modeling syntax to depict input and output parameter for MES tasks. While it is possible to add incoming and outgoing message or data flows to MES tasks, it is not possible to do so without connecting them to a source. This results in an inability to model generalized MES tasks without a complete MES model. Also for later consistency checks it is not possible to check for missing in- or outputs as they can only be defined when connected. A modeling language that does support explicit in- and output is the Systems Modeling Language (SysML) [16]. It contains a concept for the definition of ports that contain information about input and outputs of blocks. As an extension to the MES-ML, the SysML port concept has been used as an inspiration and has been added to the MES-ML metamodel. MES tasks can now be assigned input and output parameters with the possibility to assign them a name and data type. They can be assigned in a very generic way, for example only requiring data from a line or requiring a signal of a certain signal class, or be precisely specified to require an exactly defined signal.

With the addition of ports, it is very important to consider all the various possible data sources a MES can use as an input as described in section II. The MES-ML removed the explicit syntax elements for input and output data objects from the BPMN metamodel and instead uses directed message or data flows to convey that information. While that is suitable for MES models where these connections can be readily made, it does not account for data sources that are only available at runtime. As the MES-ML does not include the MES user in its model, user inputs cannot be explicitly be modeled. As a result, explicit input and output data objects from the BPMN have been reintroduced to the extended MES-ML. They are assigned a data type, which allows the matching of user in- and output to the in- and outputs of other MES tasks. Fig. 7 shows an example how and where they are used.

Now that outputs to the user can be modeled with the use of output data objects, they deserve a closer look. As described in section II, these outputs oftentimes come in the form of reports. They aggregate information and present them to the user in a concise format. They are not considered in the MES-ML at all. It is possible to model user interaction with MES tasks such as "show report to user", but they are neither semantically defined, nor are the reports themselves defined. In order to enable report modeling, the MES-ML has been extended to include reports. Fig. 6 shows the metamodel of reports. The extended MES-ML allows the creation of reports in a standardized, generic way, so the report structure and content that the MES shows to its user can be modeled. The actual data included in reports will be provided by the MES later on. Reports consist of the name of the report, a classification for the categorization of reports, report inputs and report elements. Report inputs are inputs that are required to get the correct data for the report, for example a selected user timeframe for the report. These inputs may have an assigned datatype and are identified by their name. Report elements are elements in the report that display information in a certain way. They have a type, e.g. number, table or data bar and are connected to a report function which provides the corresponding output.

V. Evaluation in the Domain of Beer Brewing

To evaluate the extended MES-ML it is planned to model three food production lines during the AutoMES project. The first evaluation has been finished by modelling a typical brew house, the brewing process and the MES function energy management. The results of this evaluation are presented here.

A. Domain Beer Brewing

In the brew house, wort is made from the ingredients malted barley, water and hops (Fig. 8). The first process step is mashing, where water and malt are mixed and heated up to specific temperature levels to extract substances like sugar. The lautering process separates the liquid phase (wort) from the grains in the lautertun. After that the wort is boiled with hops in a wort kettle for sterilization and isomerization of the hops. The solid particles (like hops and protein) that arise from the boiling will be separated in the whirlpool. After that the

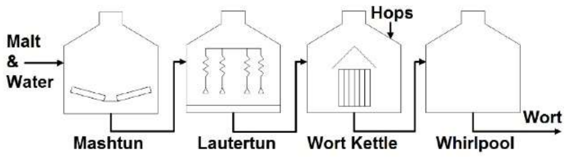

Fig. 8. Overview beer brewing process

wort is ready for fermentation and storing [20]. For the purpose of energy management, the processes mashing and boiling are the most important ones, as they have the highest energy consumption. Another factor in the overall energy consumption of the brewing process are different types of beer. A consumption report may look like Fig. 9. In this report the information about the steam consumption of the brewing process is shown to the brewer. It shows the steam consumption in total, as well as per process step for a specific product.

Batch	Steam consumption [kWh]		
	Mashing	*Boiling*	*Total*
Lager	2.220	5.535	7.755
Wheat beer	2.704	4.872	7.576
Indian Pale Ale	2.523	5.392	7.915

Fig. 9. Examplary consumption report

B. Modelling of the brewing process

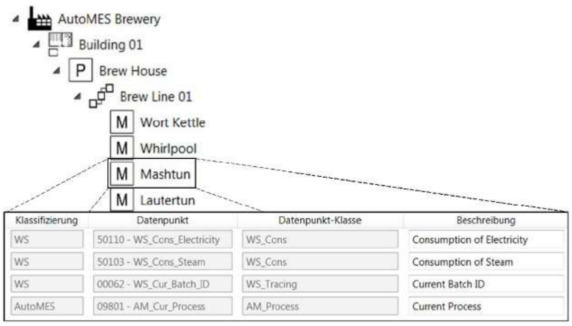

Fig. 10. Model of the technical system of a brew house

The model of the technical system of the brewery that was used as a modeling example is shown in Fig. 10. The brewery is divided into the hierarchy levels defined in section IV.A and its brew house consists of a mashtun, a lautertun, a wort kettle and a whirl pool. Also shown in Fig. 10 are the signals of the mashtun. For the calculation of the energy consumption for different beer types, the signals for consumption of energy, such as steam and electricity as well as the information about the process and the batch are needed. The excerpt of the process model in Fig. 11, shows the detailed view of the wort production. It contains the four process stages mashing,

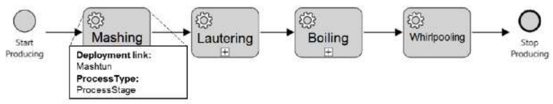

Fig. 11. Detailed view of the process wort production

lautering, boiling and whirlpooling, performed in sequential order. Each of the processes can be assigned to machines in the model of the technical system. The example shows the deployment link between the process stage mashing and the Mashtun. Fig. 12 shows the an excerpt of the MES model containing a report function called "Steam Consumption Calculation for Batch" that displays the total consumption of a batch to the user. In this example the user of the MES selects the Batch ID 009, on which the calculation is based.

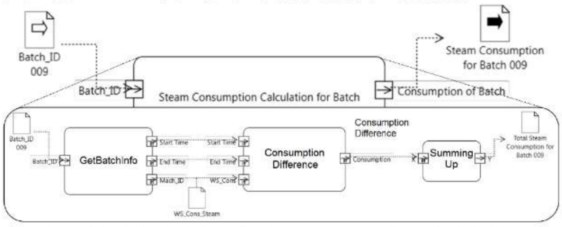

Fig. 12. Model of the MES function "steam consumption calculation"

The report function is composed from different basic functions, shown in the lower part of Fig. 12. In this case the basic function "GetBatchInfo" identifies machines and time period in which the batch was executed. These outputs will be used by the basic function "Consumption Difference". This function uses the start and end time of the batch per machine and the steam consumption signal of the machines to calculate the different machine consumptions. The "Summing Up" basic function sums up the different consumptions and delivers it to the user. This example shows how extended MES-ML models can be modeled. The modelling of process tasks and MES tasks is done in a generalized way, so they can be reused in later MES projects. They are not constricted to the domain of food and beverage, but for other domains, signal meta data has to be included as the Weihenstephan Standard is not universally accepted there. This can be accomplished by either expanding the Weihenstephan Standard or other industry standards have to be imported into the AutoMES metamodel.

C. Evaluation of the Model

To evaluate the AutoMES method, the models presented in this section were created using the AutoMES modeling tool, a graphical model editor which supports the creation of AutoMES models, as well as the generation of a generic MES specification from AutoMES models. The created models were evaluated in a first step by MES vendors and engineers. As currently direct code generation from the models is not available, this was done by manually using the data provided by the models to create a generic MES specification which was then used to parameterize a MES of one of the project partners in the project AutoMES. It was shown, that such a parameterization is feasible and feedback from the MES vendors and engineers indicates that the method is successful in saving time even without automatic code generation because all information is available from a single source, the AutoMES modeling tool. As shown in TABLE II. the majority of the requirements presented in section II were achieved, but not all of them could be fully evaluated yet. The technical system is standardized, signals can be added at every hierarchy level and signals can be standardized and categorized based on the

Weihenstephan Standard. The process model can be modeled independently from the other models but it is still possible to deploy on elements of the technical system. The MES tasks in the MES-model of the evaluation study are entirely composed of basic functions and can be connected through ports. In- and outputs to external sources can be modeled with the help of BPMN inputs and outputs. Only requirement M4 (Modelling of reports) could not be evaluated yet. The extended metamodel supports it already, but the AutoMES modeling tool used for evaluation does not fully support it yet.

TABLE II. EVALUATION OF REQUIREMENTS

Req.-No.	Evaluation Result
Evaluation Requirements for the model of the technical system	
TS1	Model is standardized by defined hirarchy levels
TS2	Signals can be added on every hierarchy level
TS3	Weihenstephan Standard provides a standardized set of signals. It is expandable by adding signalDataTypes
TS4	The Weihenstephan Standard provides basic signal classification. Some categorizations were adjusted
Requirements for the model of the production process	
P1	Modeling of the brewing process was successful
P2	Processes can be deployed on elements of the technical system
Requirements for the model of the MES	
M1	MES tasks can be defined, but have be composed by using basic MES tasks avaiable from an AutoMES task library, containing semantic data for basic tasks and MES tasks.
M2	Input and output parameters can be modeled with ports
M3	Functions can be connect to each other and to external sources like user inputs
M4	Concepts of report modelling are developed, evaluation is currently in progress

VI. CONCLUSION AND OUTLOOK

This paper presents requirements for a modeling language that can be used for the automatic generation of MES. These requirements are fulfilled by the proposed extensions of the MES-ML. Its suitability for the task has been shown by using an industrial brew house as a modeling example and has been approved by MES engineers. In future work it is planned to further refine the modeling language and prove its applicability to a wider range of industries. In addition to that, consistency checks for the MES model are considered as a way to assist the modeler in its work and to improve model quality. Also, as the next step in the project AutoMES the first iteration of code generators are currently under development. As soon as they are finished, the installation of automatically generated MES at industrial sites of project partners in different industries are targeted. These reference implementations will then be used to evaluate the proposed method in relation to individual programming effort for manual MES engineering projects.

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2.3 Publication III – Modeling phase of the model-driven approach

Basis for the model-driven engineering of manufacturing execution systems: Modeling elements in the domain of beer brewing

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Page 42 – 53

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To develop a model-driven approach, the basis, namely the modeling language and modeling elements, should be defined rigorously. This study is dealing with the definition of modeling elements in the domain of beer brewing for model-driven engineering of MES. According to the metamodel of extended MES-ML, the MES model can be divided into four sub-models, i.e., the plant model in a tree diagram that illustrates the technical systems, the process model with three hierarchies that describes the production processes, the MES model composed of basic functions that represent the required MES functions, and the report model connecting the three models that shows the results. Dependent on the result of requirements analysis, the modeling elements are defined to realize two main MES functions: management of energy consumption and analysis of production efficiency. The modeling elements are assigned to domain-specific libraries so that they can be reused concerning the application scenarios.

A use case of the defined modeling elements applied to a traditional brewhouse has shown the usability of the defined modeling elements to represent the relevant MES functions in the food and beverage industry. The use case has also been evaluated by experts with the implementation experience of the MES in the food and beverage industry following five criteria, i.e., profitability, comprehensibility, simplicity, completeness, and sustainability. It was confirmed that the defined modeling elements had sufficiently underpinned the model-driven approach with later steps for automatic transformation, specification, and generation.

Contributions of the doctoral candidate – Conceptualization, Methodology, Validation, Investigation, Resources, Writing - Original Draft

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Basis for the model-driven engineering of manufacturing execution systems: Modeling elements in the domain of beer brewing

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ABSTRACT

Manufacturing execution systems (MES) are process-oriented IT solutions that collect and manage information from manufacturing processes to improve transparency. Owing to the considerable programming effort required for the implementation of custom systems for specific production processes, investing in MES is not an option for many food and beverage manufacturers. Model-driven engineering (MDE) is one solution for reducing the implementation costs involved in custom systems. However, a concrete MDE approach that fulfills the requirements of the food and beverage industry has not yet been established for MES. With this background, this paper introduces an MDE approach for MES and focuses on the first step in implementing this approach by defining the modeling elements of MES functions that enable the automatic transformation from models into an operational MES. The modeling elements are defined for the four components of an MES solution: the plant model illustrating the technical systems, the process model describing the production processes, the MES function model representing the required MES functions and the report model showing the results of MES functions. A use case in the domain of beer brewing is presented to evaluate the proposed approach. This use case demonstrates the feasibility and suitability of predefined modeling elements in the modeling phase for automatic MES generation.

1. Introduction

Manufacturing execution systems (MES) connect the automation layer and enterprise layer in industrial processes [1,2]. On one hand, they are IT systems that manage and analyze information in the manufacturing process and guide the implementation of rough production plans from enterprise systems into detailed operations. On the other hand, MES provide the firm with important key performance indicators (KPIs), such as specific energy consumption and machine efficiency data that enable commercial decisions and improve the performance of the manufacturing process. The food and beverage industry must meet particular challenges in quality insurance and cost control [3], and MES could improve the transparency and efficiency of food-production processes. Most sectors of the food and beverage industry comprise small and medium-sized enterprises (SMEs). Owing to high installation costs, SMEs tend to use a variety of IT systems instead of a central MES. This fact, combined with the wide range of functions that control production processes on the shop floor and their need for communication with higher-level systems, can increase the complexity of MES implementation. An example is the communication between the MES and enterprise resource planning (ERP) systems, which organize, define, and standardize the internal business processes in all departments of a company. ERP systems need summary information from the shop floor, which is provided by the MES [4]. The engineering and programming effort involved in customizing individual MES solutions is the major cost factor in MES projects [5]. Despite significant advances in programming languages and support for integrated development environments, the development of such a complex software system by using current code-centric technologies requires a herculean effort. Model-driven engineering (MDE) focuses primarily on software engineering by using models to improve software productivity [6]. After modeling complex systems as abstract representations, developers rely on computer-based technologies to transform models into operational systems [7,8]. MDE offers three main benefits: it increases productivity by maximizing compatibility between systems by reusing standardized models; it simplifies the design process with recurring design patterns; it promotes communication between individuals and teams working on the system by standardizing terminology and best practices [9]. But, a concrete model-driven approach for engineering of MES to fulfill the requirements from the food and beverage industry is not yet established. This paper presents an approach for automatic generation of MES according to the concept of model-driven engineering and its focus

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is on the first step by defining modeling elements, which is considered as the basis for this approach.

This paper is structured as follows. Section 2 presents the requirements on a model-driven approach for MES. Section 3 shows the related works in the field of management systems in the food and beverage industry and MES engineering. Section 4 describes the model-driven approach for MES in detail to indicate the purpose of defining the modeling elements ahead of time; this section also describes the information model, modeling language, and its metamodel used in this approach. Section 5 shows a use case on the utilization of the predefined modeling elements in the domain of beer brewing. Section 6 evaluates the use case according to the requirements presented in Section 2 and presents the results of interviews with MES experts regarding to the predefined modeling elements as well as the presented approach. Section 7 draws the conclusions and outlines future works.

2. Requirements

This section defines the requirements that shall be fulfilled by an approach to automatically transform predefined models into an operational MES.

1) Requirement 1 (R1): Representation of relevant MES functions:
The MES software shall be suitable for food and beverage SMEs. Hence, the software must be able to correctly represent the MES functions commonly used by these enterprises. The relevant MES functions include job scheduling, predictive maintenance, auditing, and process control. To be calculated, they require KPIs, such as the overall equipment effectiveness (OEE) or the energy consumption of a range of machines.
2) Requirement 2 (R2): Development and application of a model-driven engineering approach of MES:
The model-driven approach should be able to deploy universally applicable models for the plants, processes, functions, and reports for SMEs. Furthermore, to be feasible in different domains of the food and beverage industry, the easy exchange of domain-specific information is necessary for these models. Therefore, the approach should use four metamodels: a plant model illustrating the technical systems, a process model describing the production processes, an MES function model representing the required MES functions, and a report model that shows the results of MES functions, along with corresponding domain-specific libraries.
3) Requirement 3 (R3): Support of a consistent communication standard:
For easy implementation, the presented approach shall ensure conformity between the software solution and the physical machines used in the food and beverage industry. The software should adhere to a communication standard that is supported by enterprises and machines in the food and beverage domain. The portability of predefined models can also be ensured by using a standardized communication interface because the information basis for data exchange and processing remains uniform.
4) Requirement 4 (R4): Dynamic generation from models to MES solution:
The modeling elements in this model-driven approach are not defined for specific application scenarios but can be used to compose distinct MES functions that fulfill various requirements. Thus, regarding the flexible sequence and information flow among elements, the MES solution modeled by those elements should be generated automatically and dynamically. This dynamic modeling also requires the flexible transformation of models to specifications.

3. State of the art

3.1. Food manufacturing industry

The food and beverage industry is an industry with specific manufacturing requirements. Its products meant for human consumption must meet high quality and safety standards [3]. Food manufacturers are obligated to ensure the safety of their products at every step during processing. They must also be able to determine the source of any quality or safety problem and ensure the traceability of the products throughout the entire production chain. Several technologies have been applied to minimize the chance of the production and distribution of any unsafe or low-quality items in the food supply chain. These include information technology for management systems, digital technology for product identification, and geospatial technologies for tracking [10]. The application of wireless sensors for food logistics and supply-chain management processes has been studied for the agriculture and food industry [11,12]. Owing to food scandals and incidents, consumers increasingly demand high-quality food with integrity, as well as safety guarantees and transparent production processes [10,13–15]. To fulfill regulatory requirements, the food and beverage industry has begun to implement food-safety management systems [3,16]. Lan et al. [17] developed a structure for a supply-chain management system that combines government, industry, and society to improve food safety in China.

Energy efficiency is of increasing concern for food and beverage manufacturers because energy prices are rising, strict environmental regulations carry associated costs for CO_2 emissions, and customers demand “green” products [18]. For example, to meet the EU CO_2 emission goals by 2020 and to reduce energy consumption, factors such as process integration, process intensification, and energy efficiency have been studied as important indicators [19]. Biglia et al. [20] introduced a software tool to optimize energy performance by modeling and simulating the energy consumption of a system. However, given that they focused on reducing the energy consumption of individual production units, they did not develop a holistic framework for increasing production-line energy efficiency and generating real-time energy reports.

The manufacturing industry is in a period of rapid change owing to shorter product life cycles, decreased delivery times, and increased customization levels [21]. As a fast moving consumer goods industry [22], the food manufacturing sector has shifted toward a production strategy that combines make-to-stock and make-to-order approaches. This has increased the complexity of the manufacturing process, and control systems such as MES and ERP could help manage these processes and increase efficiency [23]. Cupek et al. [24] proposed an agent-based MES architecture to handle short-series production scheduling. Considering the limited size of companies in the food and beverage industry and their low financial flexibility, companies have installed a heterogeneous constellation of IT systems for ERP to meet regulatory standards. A central MES for communication between the shop floor and ERP has not yet been applied because interfacing with such a range of technologies is challenging [5,25]. Customizing an MES for a specific manufacturing process is the main cost driver when engineering an MES. Many MDE approaches, including code generation, are implemented in automation technology to design cost-effective IT systems with low programming effort [26]. In the current research, an implementation of MDE is studied for the improvement of energy management and production efficiency in the food and beverage industry.

3.2. Information model for MES

Large pools of data are recorded, communicated, aggregated, stored, and analyzed from consumers and within the manufacturing process [27]. Big data continues to reveal unexpected sources of value.

Given that the data and information relevant to the food and beverage industry are scattered across the food, health, and agriculture sectors, big data approaches are seldom used because data sets are difficult to standardize. Marvin et al. [28] indicated that interoperability standards for the collection, storage, transfer, and analysis of data are needed to apply big data approaches in the food and beverage industry. Speaking of standards for data, Hill et al. [29] analyzed the use of electronic data interchange, which is the computer-to-computer transmission of standardized business transactions, for supply-chain coordination in the food and beverage industry. Within a manufacturing enterprise, Vogel-Heuser et al. [1] introduced an architecture called the "automation diabolo" for use as global information architecture for industrial automation. This architecture consists of two cones: the lower cone represents the field and control levels, and the upper cone represents the process management and organization levels in which MES functions are implemented. To achieve vertical and horizontal integration between the two cones and between the devices and entities in each cone, an information model is inserted in the middle of the automation diabolo. A standardized product-related information model coordinates the work of different systems [30], thus allowing the design cycle to be modularized into two automation layers. A standardized information model for communication between shop floor and MES is implemented in the approach presented in the current paper such that the MES functions can be reused in any manufacturing scenario that allows this type of information model.

3.3. MDE of MES

MDE is a software-development methodology that uses abstraction to systematically utilize models as primary artifacts during the software engineering process [31]. These models must be defined precisely according to the specific modeling language [32]. The motivation behind MDE is to move the focus of software engineering from coding to solution modeling by introducing automated code generation [33]. MDE has already been used to engineer production systems. Examples include engineering an ERP system by applying a model-driven architecture [34] framework based on a high-level model of business processes [35]. However, the concept of MDE is seldom applied to MES design because MESs generally have to be customized to meet the customers' demands with few standardized components. When modeling an MES, diverse interests and requirements must also be met. For example, a management professional has a different view of the technical and business process than a machine operator [36]. Mizuoka and Koga [37] introduced a method to generate MES automatically on the basis of model-driven architecture with models described in XML metadata interchange. This language was extended from UML. They focused on the machine parts processing industry, which have different requirements for MES than the food and beverage industry. A concept for the MDE of MES for the food and beverage industry was proposed in 2014 [38]. In this concept, the design process was separated into three steps: first, the required MES functions, manufacturing plant and processes, and reports are specified; second, the models are transformed into a specification that can be read by a generator; finally, this generator creates an operational MES on the basis of the given specifications. However, the modeling elements that provide the basis for MES modeling and for the whole concept were not defined in that paper. In the current paper, a more concrete approach is introduced, and modeling elements that meet the requirements of the food and beverage industry are defined.

4. An model-driven approach for MES

Although this paper focuses on the modeling phase, we begin with an overview of the model-driven approach to emphasize the importance of defining modeling elements ahead of time. Following Flad et al. [38], a more concrete approach for MDE is illustrated in Fig. 1.

Three steps precede the automated generation of MES. The first step creates universally applicable models on the basis of predefined domain-specific libraries. In this step, four models are needed to describe the whole MES. First, a model of the technical systems of the plant and the data that can be collected from them is needed. Second, a process model describes the production processes and provides information for process-related MES functions. Third, an MES function model represents the required MES functions and the necessary data to realize them. Fourth, the report model serves as a bridge to the other three models by establishing mapping functions in all the models. This report model also determines the layout of the final report. The MES function model is independent from the plant model and process model. Although the required data to realize the MES functions are modeled in the MES function model, their sources are not determined. In other words, for any plant model and process model that can provide the necessary data, the appropriate MES functions can be used directly with the mapping function of the report model. Furthermore, in order to ensure the generality of the MES function models, no definite formula is defined at the moment of modeling, as the manufacturers and the MES providers can have their own methods to analyze the acquired data or implement the MES functions. The MES function model presents which data sources should be available to realize the specific MES function, but does not contain information about how the data should be processed. The concrete method for data processing is formalized in the generation phase later, at the instance, when the MES functions must be implemented. Libraries for different domains must be built in this approach to provide the basis for later steps. These are assemblies of modeling elements for each model, i.e. the plant library, process library, MES function library, and report library. With the libraries, the modeling effort can be reduced and the reusability of modeling elements is ensured also [9,39]. In the second step, a specification generator transforms the information in graphical models into a format of specifications that the software can utilize, namely, a generic MES specification. This specification is generic because it is not supposed to focus only on specific MES functionalities but instead focuses on mixed functionalities from different implementation possibilities [40]. Given the correlation among different models, tables in a data base are chosen as the platform for specifications. The specification includes the information in each model, along with the links among the four models. The MES generator used in the third step consists of two parts, a toolbox and a connection finder. In the toolbox, the predefined modeling elements for MES functions are implemented as specific procedures in code. The aim of the connection finder is to reproduce the correlations among modeling elements based on the specification in the second step to decide which procedures must be invoked from the toolbox to realize the required MES functions. Therefore, the modeling elements must be predefined and implemented in the generator before the MES solution can be created. After that the required procedures in toolbox are invoked with the modeled order in the first step by the connection finder, a working software solution for the MES can be automatically generated by the MES generator.

To ensure a seamless communication among predefined modeling elements, a standardized information model should be used. An information model widely used in the food and beverage industry called the "Weihenstephan Standards" (WS) is integrated into this approach. The WS specifies a universal communication interface for connecting different machines and process-control systems to a higher-ranking MES. They also define the data that must be available for acquisition. With this standardized information model, the processing of the data from machines and processes can be defined consistently for the necessary MES functions [41]. The principles for calculating KPIs and energy consumption, as well as for tracing batches to prepare clear production reports, can also be defined according to this information model.

A suitable modeling language must be used to make this approach feasible and operational. The MES modeling language (MES-ML) is a

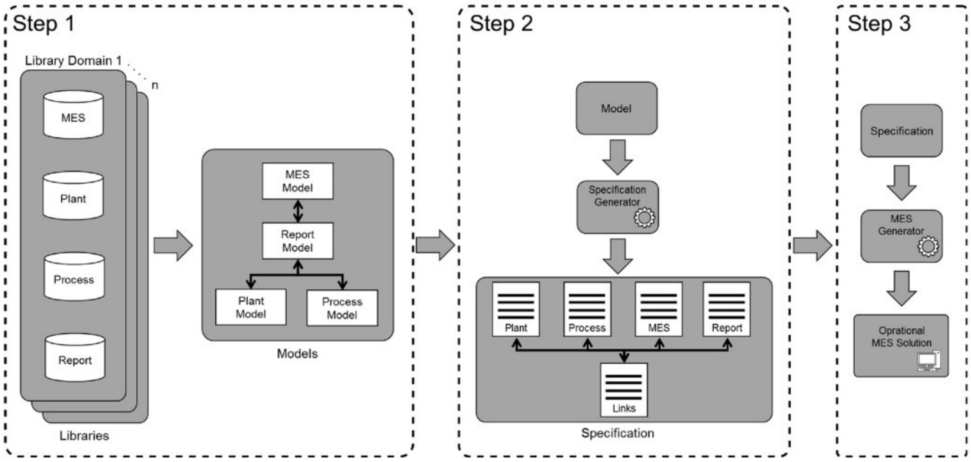


Fig. 1. Overview of approach for automatic generation of MES.

language for the interdisciplinary specification of MES and has proven to be suitable for the engineering of MES [42,43]. Considering that the original MES-ML was not designed for automated MES generation, it was extended by Weißenberger et al. [5]. This metamodel divides MES into four models presented above, namely, the plant model, process model, MES function model, and report model. After extension, the MES-ML was proven suitable for the creation of machine-readable MES specifications from graphical notations and for the subsequent automated generation of MES. The metamodel of the extended MES-ML are presented as follows:

4.1. Plant metamodel

To allow the automated generation of an MES, the metamodel of the modeling language MES-ML for technical systems is defined [5]: Its hierarchy is inspired by the leading industry standard ISA-95 [44] to minimize conflicts with existing plant descriptions. Signals for data collection can be assigned to all hierarchy levels in which signals are needed. The standard signal set in the WS is used as the communication interface between the plant and MES. The signals are categorized according to their characteristics. Its metamodel of the extended MES-ML for describing the technical system is presented in Fig. 2.

4.2. Process metamodel

For the automatic generation of an MES, the following prerequisites are fulfilled by defining the process metamodel [5]: Generalized process modeling was ensured by the dependency of the process model, i.e. the process can be modeled without knowledge of the specific plant model. At the moment of modeling, the process model does not need an existing signal from any specific element in the plant model to be linked, it is realized by a list of required signals for every process task that can be offered by the plant model. A total of three levels of process tasks (processes, process stages, and process operations) are introduced to achieve a more standardized model based on the levels of batch processes defined in ISA-S88 [45]. To each type of process tasks, process data elements can be assigned: AM_Process for processes, AM_ProcessStage for process stages and AM_ProcessOperation for process operations. They contain the information when a process task has been performed, which can help to complete the process related calculation and analyze, for example electricity consumption of a specific process task. The process metamodel is presented in the Fig. 3.

4.3. MES function metamodel

The MES tasks are defined and divided into basic functions and MES functions in the extended MES-ML [5]. Basic functions are the atomic

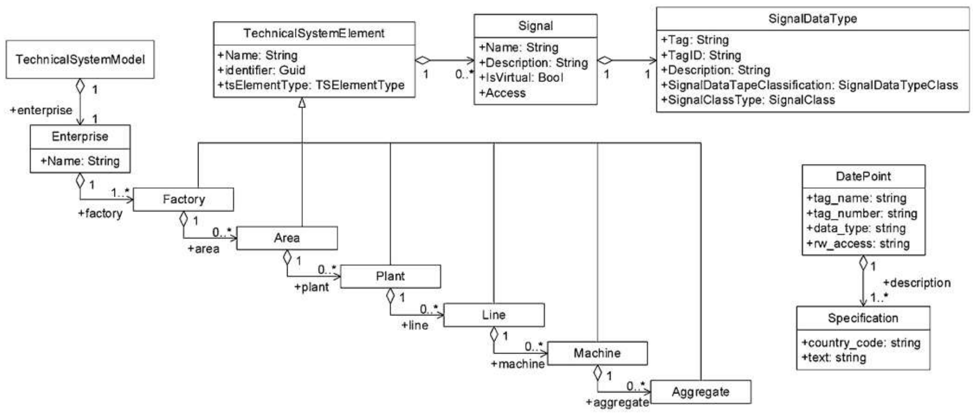


Fig. 2. Metamodel of technical systems in extended MES-ML [5].

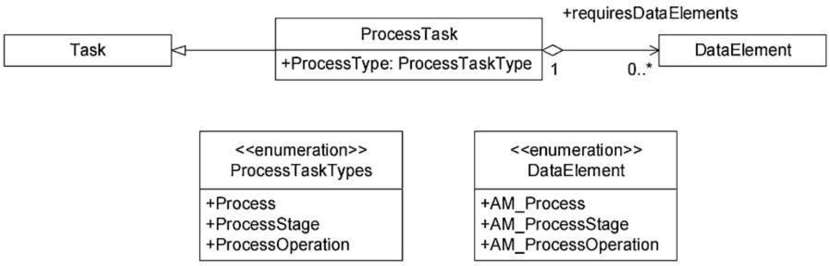


Fig. 3. Process metamodel in extended MES-ML [5].

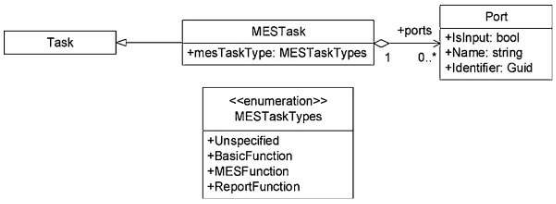


Fig. 4. MES metamodel in extended MES-ML [5].

functions of the model and serve as the base for all other MES tasks. Their semantics are predefined in the extended MES-ML. For the purpose of automatic MES generation, all other functions can be translated into an interconnected collection of basic functions. MES functions serve as the organizational unit for basic functions and other MES functions. The reasons to define the basic functions are, on the one hand side, that a wide range of MES functions can be modeled by using a limited number of basic functions; on the other hand, that the programming effort of the generator for MES solutions can be reduced. Given that the basic functions must be defined independently of the overall MES function model to be used generically, MES tasks can be assigned input and output parameters in a generic manner. The MES function metamodel in extended MES-ML is presented in Fig. 4.

4.4. Report metamodel

The output parameters of MES functions are results in the reports. Extended MES-ML allows the standardized, generic modeling of reports [5]. Report model has a report name and consists of report elements and the report inputs. Report inputs are required to obtain the correct data sources for the report, such as a user-selected timeframe or a specific production machine. They may have an assigned data type and are identified by name. Report elements display information in a certain manner. They have a type, such as number, table, or data bar. Each report elements is connected to a MES function that provides the corresponding output. The metamodel of reports is shown in Fig. 5.

5. Use case in the domain of beer brewing

In this section, the first step of above presented approach for automatically generating an operational MES solution on the basis of predefined domain-specific libraries will be applied in the use case of brew house of a brewery. Fig. 6 illustrates a traditional brewing process.

In the brew house, wort is made from malted barley, water, and hops. The first step is mashing, during which water and malt are mixed and heated to a series of specific temperatures for the decomposition of starch in malted barley. The lautering process separates the liquid phase (wort) from the grains in the lauter tun. The wort is then boiled with hops in a wort kettle for the sterilization of wort and isomerization of the hops. Solid particles such as hops and proteins generated in the boiling are then separated in the whirlpool. Thereafter, the wort is ready for fermentation and storage [5,46]. As discussed in the section 3, the analysis of energy consumption and KPIs for machine efficiency are the focus in this use case.

5.1. Libraries for beer brewing

5.1.1. Plant library

From the viewpoint of the technical systems in the brew house, the raw materials, malted barley, water, and hops, flow from the mash tun through the lauter tun and to the wort kettle, and then passing through the whirlpool to the heat exchanger. At the end of the heat exchanger, the cooled wort can be transported to a fermenting cellar to pitch the yeast. By incorporating these brewery-specific technical elements into the metamodel, the plant library can be developed. To collect data, the required data points that indicate the machine mode, program and state, the total produced good and bad products, and energy consumption are assigned to the elements in the plant library at the proper hierarchy level. These establish the foundation of MES functions for calculating OEE indicators and energy consumption. The predefined

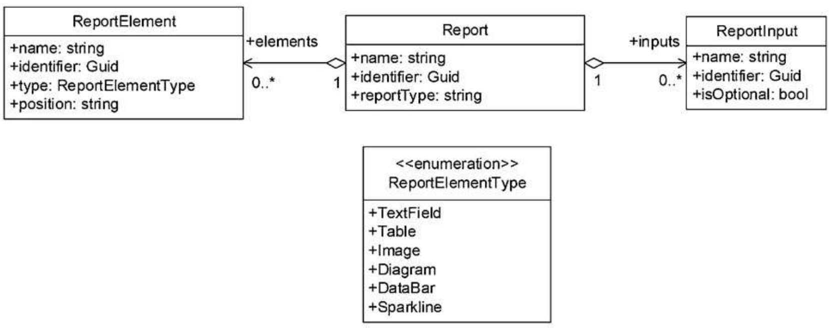


Fig. 5. Report metamodel in extended MES-ML [5].

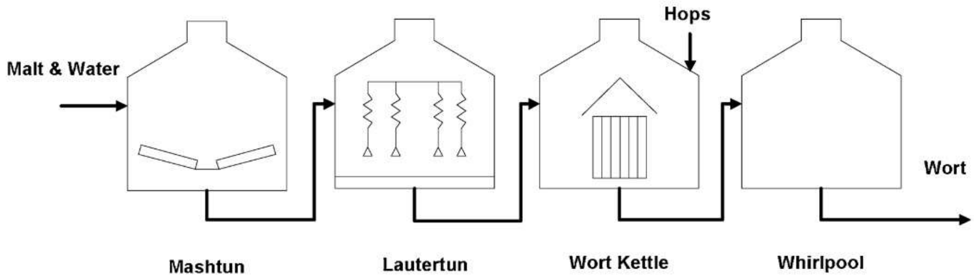


Fig. 6. Brewing process in a brew house [46].

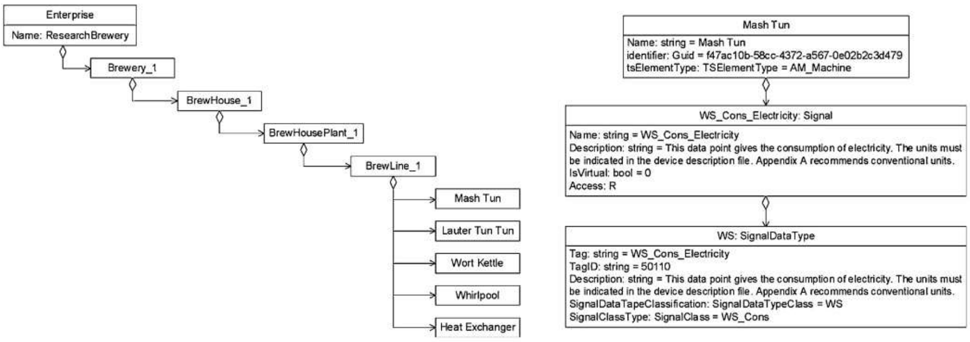


Fig. 7. Modeling elements in plant library with an example data point.

modeling elements in the plant library and an example of the data points that need to be collected to document the consumption of electricity (WS_Cons_Electricity) on the mash tun are shown in Fig. 7.

5.1.2. Process library

Wort is the final product of a brew house. The first process step in wort production is mashing, in which water and malt are mixed and heated to specific temperatures with defined rests to extract substances while protecting the vitality of the enzymes. In the second step, the liquid phase (wort) and solid phase (spent grains) are separated. The wort is then boiled with hops in a wort kettle for infusing the aroma from the hops and for sterilization of the wort. The particles that come from the hops and the congealed proteins are then separated by sedimentation in a whirlpool. In the last step, the wort is cooled down to the temperature for fermentation with a heat exchanger and is pumped into the fermentation cellar [46]. When modeling these steps, the process wort producing is modeled at the hierarchy level of process and consists of five subprocesses at the hierarchy level of process stage: mashing, lautering, wort boiling, sedimentation, and wort cooling. These subprocesses can be modeled in a greater detail at the hierarchy level of a process operation (heating, stirring, cooling, etc.). To obtain the start time and end time of each process element, the following data points were assigned to the process elements in related hierarchies: AM_Process, AM_ProcessStage, and AM_ProcessOperation. The resulting elements are listed in Table 1 with the instance models of the hierarchy level of processes.

5.1.3. MES function library

The Manufacturing Enterprise Solutions Association (MESA) has defined eleven MES functions in its whitepaper [47], for example operations and detail scheduling, quality management, performance analysis, etc. According to the classification for MES functions of MESA, the two MES functions in the use case can be categorized under performance analysis, which includes "measurements as resource utilization, resource availability, product unit cycle time, conformance to schedule and performance to standards". Another classification can be found in the German guideline for MES, the VDI 5600 [48], which has defined MES functions in ten categories, such as order management, detailed scheduling and process control, performance analysis and energy management. As the aim of MES functions for performance analysis is defined to "implement control loops with different cycle times in the production environment" for exerting the operational influences on the process with a short cycle time (hour, shift) and optimizing the process for appraising requirements with a long cycle time (weeks, months, years), while the aim of the MES function for energy management is defined to "plan, systematically record, monitor, control and ultimately reduce energy consumption in manufacturing companies", the energy management was considered as a separate category from the performance analysis in this paper. Consequently, in the MES function library, as the MES functions for analysis of energy consumption and KPIs for machine efficiency are the focus of this use case, according to their types and application purposes defined in the VDI 5600, two categories of basic functions are defined firstly. They are basic functions to calculate the energy consumption in a given period of time for a specific energy form (dependent on the data points) and basic functions to calculate the different indicators according to the time accounts defined by the OEE. As the mathematical operations can be used generally, the basic functions to perform basic mathematical operations, such as the sum or multiplication of two or more values, are also defined in a separate category. Under the category of basic functions for energy management stands the basic function "Energy Consumption Calculation". Its input parameters are the start and end times of the requested period of time and the data points that record the consumption of the related energy form. The output parameter is the value of the consumption. To calculate the OEE indicators, basic functions such as "Loading Time Calculation" and "Operating Time Calculation" are defined to represent the indicators of availability, performance, and quality according to OEE concept. An example of the definition of the basic function "Energy Consumption Calculation" in the MES function library is shown in the Table 2.

Table 1
Modeling elements in process library.

Hierarchy Level	Modeling Elements				
Process	Wort Producing				
Process Stage	Mashing	Lautering	Wort Boiling	Sedimenting	Wort Cooling
Process Operation	Heating Pause	Lautering Strring Main Wash Water Removing Spent Grains Circulating	Heating Hop Addition	Hop Sedimenting	Wort Cooling Casting

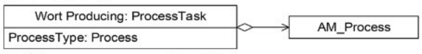


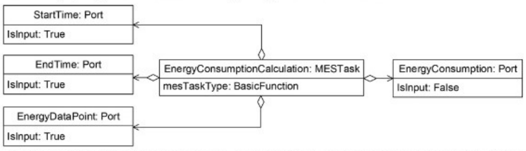
Table 2
Modeling elements in the MES function library.

Basic Functions for Energy Management

Name Energy Consumption Calculation

Formula $\Delta W = W_2 \mid WS\_Cons\ at\ end\ time - W_1 \mid WS\_Cons\ at\ start\ time$

Model



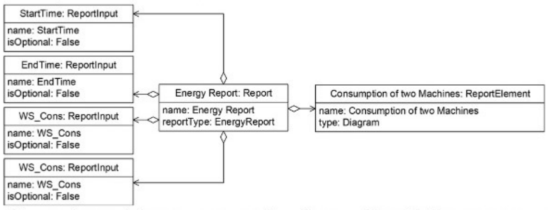
Description This basic function determines the consumption of a specific energy form in the period [StartTime, EndTime].

Table 3
Modeling elements in report library.

Energy Report

Name Consumption of two Machines

Model

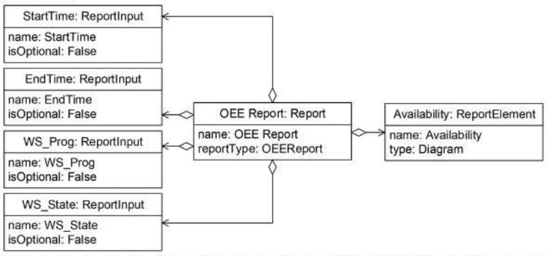


Description This report presents the energy consumption of two machines. Their energy consumption can be determined according to the data points for energy forms on both machines as input parameters of the report.

OEE Report

Name Availability

Model



Description This report determines the performance indicator of "availability" according to OEE.

5.1.4. Report library

The report library, in concert with the MES functions, consists of two categories: energy reports and OEE reports. Table 3 shows the predefined modeling elements in the report library with examples of energy and OEE reports.

5.2. Modeling of the elements in beer brewing

The introduced model-driven approach and the predefined modeling elements in each library were modeled in a modeling tool with selected notations from business process model and notation (BPMN) [38]. With the predefined elements in each library, a MES solution for

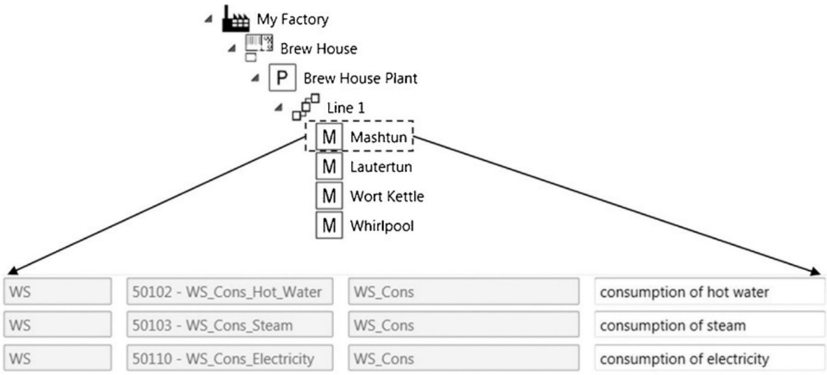


Fig. 8. Plant model of brew house.

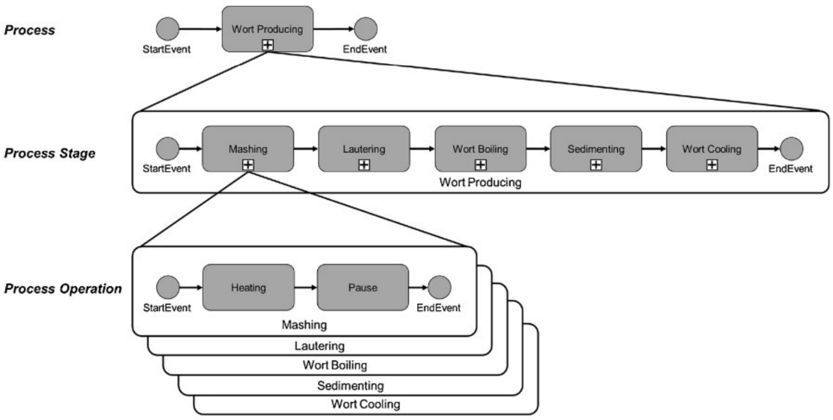


Fig. 9. Process model in brew house.

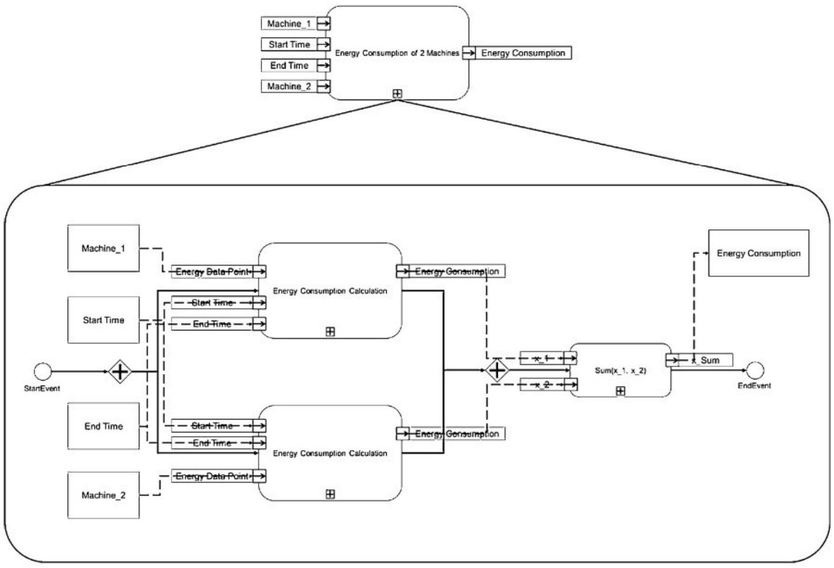


Fig. 10. MES function for calculation energy consumption of two machines.

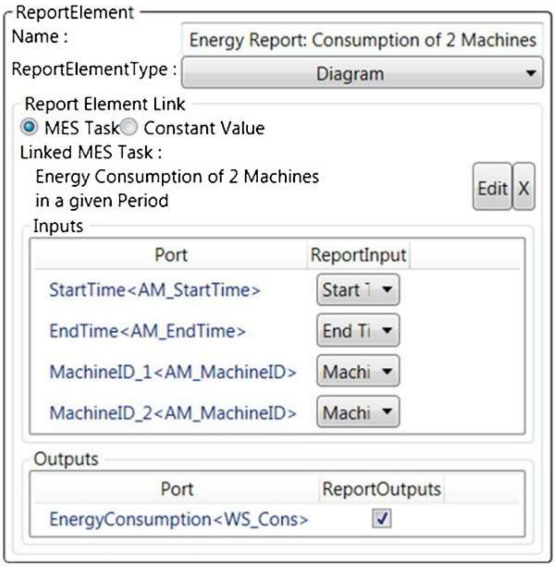


Fig. 11. Report for the MES functions in an example application.

energy management in a brew house can be modeled as the basis for the later automated generation. The brew house of the research brewery at the School of Life Sciences Weihenstephan in Germany was chosen for this use case.

The production line in the brew house includes a series of machines, the mash tun, lauter tun, wort kettle, and whirlpool. After choosing the modeling elements from the plant library and creating the model, the last step in the modeling phase is to modify the data points in the model to meet the requirements for energy management. Hot water, steam, and electricity are the main energy sources consumed in the brew house. Therefore, if the data points for collecting the consumption data at the machine level were already assigned to the elements, there is no need to modify the data points; otherwise, new data points must be added. The model of the technical systems with a more detailed view of the data points of the mash tun is shown in Fig. 8.

The second step requires mapping the different processes to their appropriate hierarchy level. The resulting process model is shown in Fig. 9. The overall process of wort production is modeled first. This process is described in greater detail with the elements at the process stage hierarchy level, which includes mashing, lautering, wort boiling, sedimentation, and wort cooling. At the process operation hierarchy level, each element in the process stage is again represented in greater detail. For example, the process operations in mashing are heating and pause (temperature holding).

To realize energy management with the MES, the basic calculation function for energy consumption is required. In this use case, the sum of the energy consumption of two machines in a given period of time is modeled (Fig. 10).

The related modeling element in the report library, namely, the energy report for the consumption of two machines, can be used for this calculation. The result of the MES function, namely, the energy consumption, is considered the output in the final report. The report for this MES function is shown in Fig. 11.

6. Evaluation

Based on the above use case, the presented approach can be evaluated according to the requirements at the beginning of the paper. A brewery can be divided into two areas with different focuses on the MES solution. The process area, including the brew house and fermentation house, focuses on reducing energy consumption to lower the production cost. The packaging area for filling focuses on improving production efficiency. The presented modeling elements for MES functions that indicate the energy consumption and OEE indicators effectively address the concerns of a brewery (R1). The introduced model-driven approach is based on predefined modeling elements in libraries for plant, process, MES function, and report models. In the use case, the modeling elements that necessary to model an MES solution for energy management in the brew house were found and used from each library (R2), although the modeling elements in the packaging area were not considered in the use case. The use of WS allows consistent communication between the machines and MES because it enforces a standardized set of signals for data processing from different MES functions (R3). The fourth requirement (R4) cannot be evaluated in this paper, as the modeling tool supports the usage of modeling elements from predefined libraries though, but a transformation tool from MES specifications into an operational MES solution has not yet been developed.

Additionally, the basis for a model-driven approach, namely, predefined modeling elements with the extended modeling language MES-ML, was evaluated by MES experts for feasibility. Three experts, a MES solution programmer and two MES project managers, from different firms as IT provider for MES solutions in the food and beverage industry have participated in the evaluation. Five criteria were defined for the evaluation, namely, profitability to show the benefits that can be brought to the automatic generation of MES with the application of predefined modeling elements. Comprehensibility to indicate if the modeling method and the modeling process with the predefined

Table 4
Evaluation for application of modeling element libraries.

Criteria	Evaluation Contents	Score	Average
Profitability	The predefined modeling elements has laid the groundwork for a later automatic generation of MES.	1	2
	The modeling process with the help of predefined modeling elements has reduced the duration for creation of MES model.	3	
	The graphical specification of MES contributes to the interdisciplinary communication at the modeling phase.	2	
Comprehensibility	The modeling process with the modeling elements in the libraries is understandable.	1	2.3
	To handle the modeling with predefined modeling elements, certain previous knowledge is not needed.	3	
	The plant model, process model, MES function model and report model as well as the connection among these models are clear and understandable.	3	
Simplicity	With the modeling element libraries, the modeling process can be simplified.	2	2
	It is easy to find the required modeling elements in the library.	2	
Completeness	The predefined modeling elements in the libraries can be used in a wide range.	4	3.5
	The MES functions that could be built with the elements in the libraries meet the requirements from the food and beverage industry.	3	
Sustainability	The modelling method can be used in the food and beverage industry continuously.	2	1.5
	This modeling concept is neutral and can be applied to other MES areas, besides the analysis of OEE and energy management.	1	

modeling elements can be understood easily. Simplicity to present if the application of predefined modeling elements can help reducing the modeling effort and they can be found and used systematically and progressively. Completeness to indicate if the predefined modeling elements can cover a relative wide range of requirements on MES solutions in the food and beverage industry. And sustainability to show the prospects of the presented approach and the application of predefined modeling elements. Each criterion was assigned a score on the school grade scale from 1 to 6 according to the degree of approval for each evaluation content. "One" means that the application of the modeling elements is extremely fitting(Table 4). As a result, an average score of 2 was given to the criteria of profitability that shows the defined modeling elements were evaluated as the necessary basis for the automatic generation of MES and the graphical modeling language can help the interdisciplinary communication among different co-workers involved in a MES project. As the duration for generation of model for a specific MES solution by using the presented approach was not compared with other methods, it cannot be evaluated at the moment of the interview, but the its possibility can be confirmed. For the criteria of comprehensibility, although the modeling method and the modeling process were easily understandable for the experts in the evaluation, certain previous knowledge is needed when the end users, such as the production manager or machine driver, are willing to know the details of the model for their MES solution. The criteria of simplicity has gotten an average score of 2, due to the reusability of the modeling elements and their clearly defined hierarchy in each library, the modeling elements can be reused and found quickly for a specific application scenario. Spoken to the completeness, a score of 3.5 was given as the modeling elements for each model were only defined for the production in a brew house with standard infusion brewing process, which can be different from the breweries that use other brewing concepts, such as decoction brewing process with mash kettle. Furthermore, two MES functions were defined in the library, namely energy management to calculate the energy consumption and performance indicator analyze to calculate the OEE, according to the definition of MES, they are only a small part which the MES can do and the many important requirements from food and beverage industry cannot be fulfilled completely, such as quality management, product tracking and operations scheduling. For the prospect of the presented modeling method and the predefined modeling elements for this method, an average score of 1.5 was given to the criteria of sustainability. It was also considered as the direction and motivation for future research for the transferability of this approach in other industries and enrichment of the extent for the modeling elements.

7. Conclusions and outlook

This paper presented a model-driven approach that allows the automated generation of MES solutions. The focus of this paper was to build the basis of the model-driven approach by defining the modeling elements in the modeling phase. The extended modeling language MES-ML was integrated, according to its metamodel, the modeling elements can be defined in four libraries for each model that needed to describe a MES solution, i.e. the plant model, process model, MES function model and report model. After the analysis of the requirements from food and beverage industry, two MES functions were treated as the target in this paper, energy management and calculation of KPIs (OEE). The production process of beer brewing in the brew house was chosen as the first application domain. In this paper, we demonstrated the feasibility of using these elements for modeling the MES solution to analyze the energy consumption in the use case. Thereafter, the MES experts verified the role of the defined modeling elements as the foundation of a model-driven approach in the direction to automated generation of MES.

The conventional process for implementation of the MES solutions consists of phases from the definition of requirements and the development of specification sheets to the design of MES solution and interface for machine communication, and further to the final implementation and maintenance of the MES solution. Compared to it, the presented approach with predefined modeling elements has promised an implementation process of MES with less effort: firstly, due to the usage of graphical modeling language, the requirements from viewpoints of different co-workers involved in a MES solution can be accommodated and communicated easily; secondly, the modeling elements for creation the models are already defined and can be reused directly from related libraries, which help reducing the complexity during the modeling phase; thirdly, as the Weihenstephaner Standards are integrated in this approach, there is no extra interface for the communication between machine and MES that must be defined; lastly, by using the modeling elements along with the presented approach, the MES solution can be generated automatically without more programming effort.

In future works, we plan to expand the range of modeling elements to other branches in the food and beverage industry that require focus on MES functions beyond energy management and KPIs. Important MES functions for the food and beverage industry, such as production scheduling, product tracing and quality management will be a focus for further development. The method for transformation from graphical models to the MES specification and the later automated generation of MES solution should be also developed. It is also planned to perform a validation for the model-driven approach with real production data from food and beverage industry and then to apply this approach in other industries for its interoperability.

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2.4 Publication IV – Transformation phase and generation phase of the model-driven approach

Manufacturing Execution Systems for the Food and Beverage Industry: a model-driven Approach

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Page 54 – 75

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In this study, the model-driven approach was extended to contain five phases: the analyzing phase to define the requirements on desirable MES; the modeling phase to build the MES model according to the requirements; the specifying phase to transform the information from the model into a software-utilizable format; the generating phase to prepare the user interface and establish the inner-connection of the MES based on the specification; the application model to employ the MES in the specific application scenario. This study primarily aims to define the design of the specification in the specifying phase and develop the method for the automatic generation of the MES in the generating phase. The specification should represent the information in the graphical MES model without losing any details to ensure the successful transformation, and it should be available and cost-efficient for the most manufacturing sectors and system providers in the food and beverage industry. The database table acts as the platform for the specification to represent the information after the graphical models are transformed. The Entity-Relationship Diagrams (ERD) are adopted to clarify the correspondence between the tables and the metamodel of the modeling language. The generator is split into two parts, i.e., toolbox as the storage for procedures that can be invoked for data processing and connection finder to transfer values in the correct order.

The presented model-driven approach is applied in a fictive brewhouse as the data provider, in which the MES meeting the requirements from the brewing process is generated automatically. The feasibility of the defined specification, the method for the generation, and the whole model-driven approach has been proven.

Contributions of the doctoral candidate – Conceptualization, Methodology, Software, Investigation, Resources, Data Curation, Writing - Original Draft, Visualization

electronics

MDPI

Article

Manufacturing Execution Systems for the Food and Beverage Industry: A Model-Driven Approach

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Abstract: Manufacturing Execution Systems (MES) are process-oriented information-technology (IT) solutions for collecting and managing information from manufacturing processes. Due to the individual programming effort and the complex integration with other manufacturing systems, though the food and beverage manufacturers can benefit from the MES, its implementation is not widespread in this industry. To simplify the implementation and engineering process, the concept of model-driven engineering (MDE) is considered as a solution. However, a feasible model-driven approach for MES engineering has not been established, not to mention for the food and beverage industry. This paper presents an approach for the automatic MES generation according to the MDE concept providing MES functions that are relevant to the food and beverage manufacturing processes primarily. It consists of necessary phases to cover the whole engineering process of the MES. Based on the application of the presented approach to the brewing process in a brewhouse, the feasibility and practicality of this approach were proven.

Keywords: manufacturing execution systems; model-driven engineering; food and beverage industry

1. Introduction

Information-technology (IT) systems have been used to improve production processes and are indispensable for manufacturing firms seeking to remain competitive in the global market [1]. To utilize the potential for improvement, manufacturing processes on the shop floor should not be ignored. With the increasing flexibility of processes and the diversification of products, the traditional operational IT systems (e.g., Enterprise Resource Planning (ERP)), are not able to react in real-time to meet the requirements of improvements on the shop floor. Manufacturing Execution Systems (MES) are process-oriented software systems that manage and analyze real-time information in the manufacturing processes. On one hand, MES implement production plans from systems on the enterprise-level in operative details to the production area. On the other hand, they provide essential key performance indicators, including specific energy consumption and machine efficiency metrics, to the enterprise for making business decisions and for the improvement of the manufacturing performance. The implementation of MES raises the transparency of manufacturing processes so that product quality and workflow efficiency can be optimized. Although the sectors in the food and beverage industry can benefit from MES, the special characteristics of the manufacturing processes and the lack of human, material, and financial resources have hindered their investment into MES implementation, in which considered efforts for programming, customizing, and integrating are indispensable to deal with the high complexity of MES, owing to the wide range of functions required to control the shop floor processes and the communications with intra- and extra-systems [2,3].

Using code-centric technologies to develop such a complex system requires a herculean effort [4]. An essential factor behind the development is the wide conceptual gap between the implementation domains. The concept of model-driven engineering (MDE) is concerned primarily with reducing this gap through the use of abstractions to software implementations [5,6]. For the software development using MDE concept, the primary artifacts of development are models, the transformation from models into running systems is relied on computer-based technologies. By raising the level of abstraction and automating labor-intensive and error-prone tasks, MDE has been seen as a solution to handle the complexity of software development [7]. However, though many researchers have focused on the industrial application of the MDE, such as for embedded software [8], mobile applications [9], and the automated production systems [10], a concrete approach that covers the whole lifecycle of the MES engineering has not been established yet.

This paper presents the first model-driven approach for the automatic generation of the MES and emphasizes specification as well as MES generation with validation to fulfill the requirements from the food and beverage industry. The feasibility of this approach is proven by its application to a brewing process for thermal energy management. The paper is structured as follows. Section 2 introduces the definition and functionality of the MES and gives a literature review to analyze the requirements and barriers from the food and beverage industry for MES implementation. Previous works related to MDE have also been presented in this section. Section 3 presents the requirements that should be fulfilled by a model-driven approach for MES engineering based on the literature review. Section 4 describes the developed model-driven approach in detail. Section 5 provides a use case on the application of this approach to a brewhouse and evaluates it according to the requirements presented in Section 3. Section 6 draws conclusions and outlines future work.

2. State of the Art

2.1. *Definition and Functionality of the MES*

For the manufacturing industry, to fulfill the requirement from the shop floor on the data collection and operation reaction in real-time, the idea of MES was firstly introduced by AMR Research in 1992, and also in this year, MESA (Manufacturing Enterprise Solutions Association) was established [11,12]. According to MESA, the core task of the MES is considered as an information center that enables the manufacturers to optimize production activities [13]. For different manufacturing environments, twelve MES functionalities were defined [14]: resource allocation and control, dispatching production, data collection and acquisition, quality management, process management, production tracking, performance analysis, operations and detailed scheduling, document control, labor management, maintenance management, and transport, storage, and tracking of materials.

According to hierarchy model defined in ISA-95 [15], the MES are located on level 3 and act as the bridge between the automation layer and the enterprise layer [16]. Due to the development of automation and information technology, the idea of Industry 4.0 was officially announced in 2013 as a German strategic initiative to keeping a pioneering role in the revolutionizing industries [17]. Three dimensions are contained in the paradigm of Industry 4.0: horizontal integration across the entire value creation network, vertical integration, and networked manufacturing systems; end-to-end engineering across the entire life cycle [18,19]. A three-dimensional model named RAMI 4.0 is proposed as the reference architecture model bringing the essential elements together with different standards in order to implement Industry 4.0 techniques (Figure 1) [20].

RAMI 4.0 supplements the hierarchy level defined in IEC 62,264 with a lower level of "Product" and an upper level of "Connected World", which integrates the control systems and establishes the environment of Industry 4.0. The left horizontal axis represents the life cycle of systems and products based on IEC 62890. With the six layers on the vertical axis, the components of Industry 4.0 are described structurally [21]. As the center for collecting, processing, and delivering the information both in the horizontal and vertical direction, the MES is indispensable in the developing manufacturing industries [22].

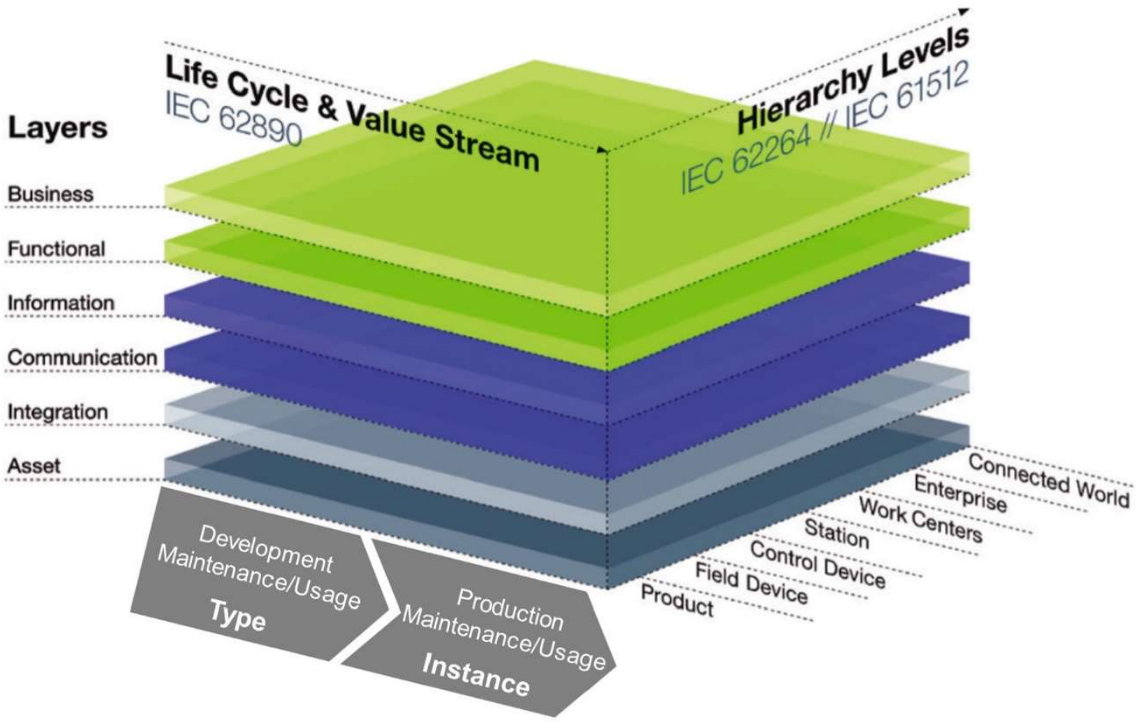


Figure 1. Reference Architectural Model Industry 4.0 (RAMI 4.0) [21].

2.2. *The Food and Beverage Industry*

Three different types of the production process can be found in the food and beverage industry [23]: batch process for the production of finite quantities of material by subjecting quantities of input materials; continuous process for the continuous material flow through processing equipment; discrete process for the production of units moving between processing stations. The differences of the food and beverage industry from the other manufacturing industries can be summarized as [24–26]: (i) the splitting and mixing lots lead to a combination of divergent processes with convergent processes in the production; (ii) production yields are uncertain as the property of materials is changing over time; (iii) products or semi-finished products are recycled during the production process; (iv) final products have a limited shelf-life and deteriorate over time.

To ensure the quality and safety of the final products, the transparency through the production must be enhanced to achieve efficient process management, which can be supported by the MES, as the MES is connected to the shop floor and serves as the center delivering critical process information to the co-systems [27]. Though researchers have analyzed the factors that can influence the choice of consumers for food and beverage [28], the price remains the most critical factor [29]. Due to the low-profit margins, sectors in the food and beverage industry, for reasonable pricing of the final products, have paid more attention to reduce the energy consumption and enhance the production efficiency [30]. By understanding the consumption of energy resources globally, the MES can contribute to managing and reducing energy consumption in the manufacturing processes [31]. MES can also support the application of lean principles, as it provides real-time information to fees and/or validate the lean processes to improve the efficiency of the production [32]. To satisfy the diverse demands of the consumers, the variety of food and beverage products is growing in the market [33]. By the continuous introduction of new products, the traditional ones can lose their viability in an unpredictable way [34]. The manufacturers have to shift their production strategy from make-to-stock to make-to-order to improve production flexibility, scheduling timeliness, and further to react to the product dynamics. The MES is considered as the basis for scheduling in the process industry, as the information form the whole enterprise, such as the order delivery time, the use of processing materials, and the machine availability, must be coupled to generate the production plans [35,36]. In the new industrial automation environment, owing to its essential role as information center for data processing and providing between the enterprise level and the automation layer, the modern technologies, such as Industry 4.0, cyber-physical systems, and digital factory, are enabled by the MES to optimize the food and beverage manufacturing processes [37,38].

2.3. MDE for Production Management Systems

To promote the reusability and to reduce the complexity of the software development process, the concept of MDE has been researched and used in a wide range of industrial applications [39], such as business imaging systems, electric systems for telecommunications, and robot operating systems [40,41]. For the development of control systems, Alvarez et al. [42] developed a model-driven approach named MeiA, which has integrated methods and techniques within the automation discipline, provided more accessible verification procedures and structured designs, and improved productivity by means of model reuse and code generation. In the area of business process management, the MDE proposed a set of methodologies, which can bridge the gap between business analysts and software developers [43]. Blal and Leshob [44] proposed a model-driven method to generate and specify services of service-oriented systems from business models expressed by Business Process Model and Notation (BPMN), a standardized graphical specification language for business process modeling and automation [45]. Due to the support of the modular engineering process, management of heterogeneity and complexity, reusability of design artifacts, MDE should not be waived to enable technologies of Industry 4.0 [46]. An MDE framework (MDE4IoT) was introduced in [47] to generate Internet of Things (IoT) systems supporting the modeling of Things and self-adaptation of connected systems. Leal et al. [48] developed a model-driven approach (smartHMI4I4) providing reusable Application Programming Interface (API) and widgets as a global framework to guide the HMI design and generation for different devices across Industry 4.0 application scenarios. Binder et al. [49] proposed a model-driven system development process integrating RAMI 4.0 to provide a common basis for the development of Industry 4.0 systems reducing the complexity of engineering processes and heterogeneity of platforms and toolsets.

For production management systems, some MDE approaches have already been established. For the implementation of an ERP system, a model-driven approach was proposed using the MDA framework by Dugerdil and Gaillard [50]. They defined a UML profile to model the business process in the level of ERP and used models to describe the transformation. In their approach, the ERP system was already implemented as a toolbox including different functional components. Instead of code generation, the components can be enabled or disabled to fulfill the requirements of the business process. A modeling approach that uses a state chart for describing and simulating the sequence of operation in MES was presented in [51]. However, the focus was on the modeling and simulation phase, and it lacked further steps for generating an operational system. Oliveira et al. [52] proposed an interpretive MDE approach for enterprise applications and compared the productivity, profitability, and return on investment (ROI) between the generative and interpretive MDE approaches based on its application to development of ERP systems. In this research, though the MDE concept has been implemented, the used modeling language, models and their specifications, and the transformation between them were not clarified. For the MES, an approach according to the MDA development method was presented by Mizuoka and Koga [53], in which the UML and XML Metadata Interchange (XMI) were used for modeling and platforms transforming. The application scenario of this approach was not declared, and it was also mentioned that the UML as a general modeling language may not be suitable for modeling MES [54], because the MES modeling is related to the target business process and requires interdisciplinary information from the co-workers of different departments, who may have different views on the same production processes [55].

The MES Modeling Language (MES-ML) was developed as a modeling language for the interdisciplinary specification of MES [56]. For the generation of operational MES according to the MDE concept, the metamodel of MES-ML was extended [57]. With this extension, the components of MES (plants, processes, MES functions, and reports) and their connections could be modeled completely, and the extended MES-ML was validated with a modeling example, which proved the feasibility of this language for the MDE of MES. However, it lacked an explanation of the steps that are needed to represent the information in the model and for the transformation between different models for automatic MES generation. The concept of model-driven engineering for MES by using the extended MES-ML was proposed first in 2017 [58]. Chen et al. [59] proposed in 2018 a model-driven approach for MES with more details, which consisted of three steps, modeling, specifying, and generating. Their research focused on the step of modeling with extended MES-ML that was integrated, in which libraries for predefined modeling elements were introduced. The feasibility and the necessity of the predefined modeling elements were also evaluated and proven by their research so that the basis for the model-driven engineering of MES was established. However, details of the latter steps, including specifying and generating, were not clarified.

3. Requirements on the Approach

Conventionally, seven phases are necessary to implement the MES in a manufacturing enterprise [60]: basic determination for determining the MES project scope and content; preplanning for analyzing the business, production processes, and the MES functions; basic planning for evaluating and drafting the MES concept and recommendation; realization planning for mapping the MES in detail; implementation for installing and integrating the hardware and software; commissioning for testing the MES software and training the users; completion for compiling the final report and drafting project accounting. The specific business and manufacturing processes must be considered in each phase to be executed, therefore, the MES must be adopted with considerable customizing and programming effort, which is cost-intensive and error-prone [61,62].

Based on the facts that more than 99% of the enterprises in the food and beverage industry are small- and medium-sized enterprises [63], and few rudiments of MES are specifically designed to fulfill the requirements from the food and beverage industry with relatively low programming and customizing effort, and further low cost, the MES implementation in the food and beverage is hindered by the unavailability of the resources from the side of the end-users and the lack of methods to reduce the implementation complexity from the side of the MES providers. Chen and Voigt [64] analyzed the barriers for the MES implementation in the food and beverage industry combined with their characteristics, and proposed solutions to deal with the barriers, i.e., the use of standardized information model for the information exchange in the whole enterprise to reduce the integrating effort, the service-oriented architecture for dividing the MES functions in independent services to achieve higher reusability, and the model-driven concept for engineering the MES to reduce the programming and customizing effort. Therefore, the requirements that should be fulfilled by the presented approach are defined as:

- Requirement 1 (R1): Development of a feasible model-driven approach for the MES. The model-driven approach should be designed so that it contains the necessary phases to carry the model information from graphical modeling of the desired MES to specifying the solution details and then to the automatic generation of MES functions as well as their application according to the target business processes. Furthermore, the contents of the used platforms in each phase and their transformations must be declared to ensure the interoperability of each phase and the correctness of the generated MES.
- Requirement 2 (R2): Representation of relevant MES functions in the food and beverage industry. The manufacturers in the food and beverage industry need support from the MES to face the challenges of reducing energy consumption, increasing production efficiency, improving production flexibility, and remaining competitive. Therefore, the model-driven approach should be able to represent the MES functions required by the manufacturing enterprises in the food and beverage industry, such as energy management, KPIs calculation, production scheduling, and predictive maintenance. Furthermore, considering the limited available resources of the food

and beverage manufacturing enterprises, the approach should be able to lower the programming and customizing efforts during the engineering process.

- Requirement 3 (R3): Capability of data flow. To implement the developed model-driven approach in different application scenarios without redefining the information interface, a consistent communication standard between the shop floor level and MES level should be supported. Additionally, a standardized communication interface should be used for data exchange to ensure the portability of the modeling elements, which are predefined and to be reused.
- Requirement 4 (R4): Automatic adoption of the generated MES. The model-driven approach should not be defined to serve definite application scenarios but could be applied to fulfill various demands on the MES from different domains. Thus, the basic elements that were used to establish the MES model must be defined neutrally. Due to the flexible sequence of the basic elements and further the information flow, the MES that modeled with the basic elements should be generated dynamically, so that it can be adopted automatically to each specific application scenario.

4. Approach for the Model-Driven Engineering of MES

This section presents each phase of the model-driven approach in detail, i.e., the analyzing phase, the modeling phase, the specifying phase, the generating phase, and the application phase (Figure 2).

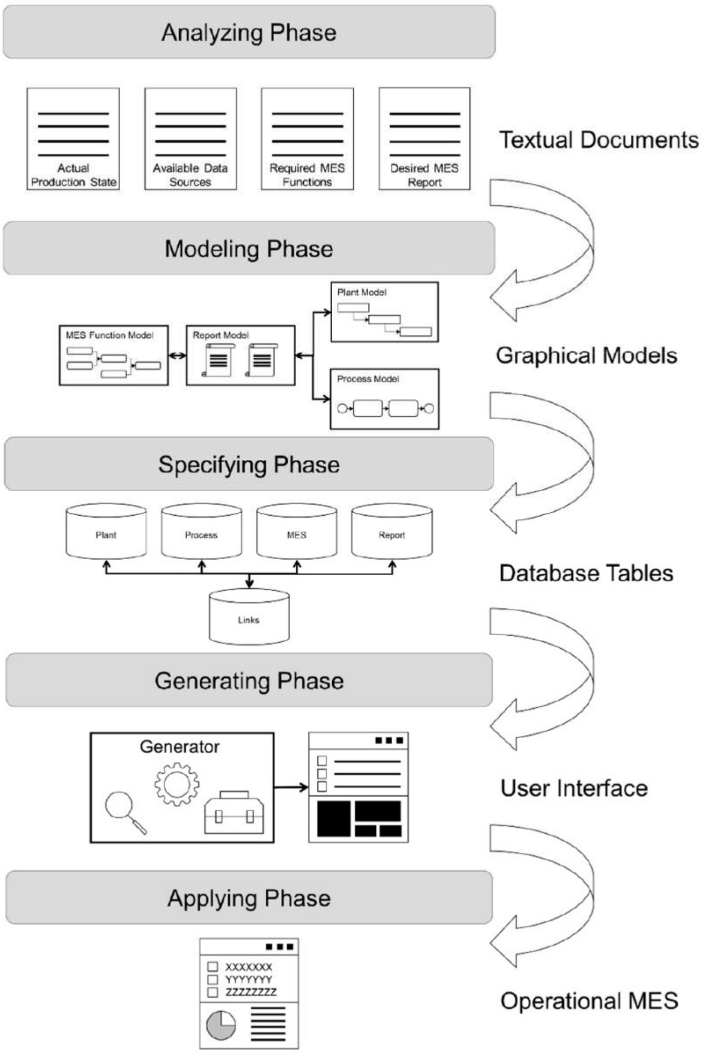


Figure 2. Five phases of the approach for model-driven engineering of Manufacturing Execution Systems (MES).

To ensure the consistency of data flow in the horizontal transformation from model to the operable system, as well as in the vertical integration between the automation level and enterprise level, "Weihenstephan Standards (WS)" [65] are integrated in this approach, which are widely used in the food and beverage industry. The WS is a standard information model that defines a universal communication interface for the communication between different process control systems and the MES. With WS, the processing of the machine and process data could be consistently defined for the MES functions. To ensure the portability of models, WS is used as the primary information model through the whole approach. The following sections present the engineering processes, the tasks, and the related tools of each phase.

4.1. Analyzing Phase

As the preliminary study before the modeling phase, the actual state of the production plant and its processes with their acquirable data sources, the demands on the MES functions, and the desired MES reports should be analyzed. This phase is addressed primarily at the end-users. The main concepts and entities of the domain are analyzed. Multiple co-workers (end-users with internal and/or external solution analysts) with different focuses and working backgrounds must work together to figure out the proper MES functions as well as the information flow among departments in a completed MES [56]. The results of this phase are textual specification sheets indicating the actual stand of the production state (technical systems and production processes), the available data sources from the production, the required functions, and the desired report of the MES.

4.2. Modeling Phase

At the modeling phase, the MES that fulfill the demands in the first phase must be modeled, based on the results of the analyzing phase. The extended MES Modeling Language (MES-ML) is a formal modeling language and was proven to be suitable for modeling the MES with a model-driven concept [57]. An editor that supports the extended MES-ML can assist the modeling process. The output of the modeling phase is a completed graphical model of the MES containing the necessary information for the transformation and generation in the later phases.

In the extended MES-ML, the plant model is structured as a tree diagram with six hierarchy levels to present the technical systems that are inspired by the ISA-95 [15,57], i.e., factory, area, plant, line, machine, and aggregate. Under each technical element in the hierarchy level, data points can be assigned to indicate the data that can be provided. The process can be modeled with three hierarchy levels with an increasing grade of detail; namely, process, process stage, and process operation, which are defined in ISA-88 as the first three levels in the process model [23]. To model the MES function, a series of basic functions were defined to compose the final MES function. The report is modeled with its name and the report elements belong to it. The data from the technical systems and the processes are the inputs, and the results of the MES functions are outputs of the reports. Each report element can display the information in a certain manner, such as text, table, or diagram, and is connected to an MES function providing the related outputs. Figure 3 presents the metamodel of the extended MES-ML for modeling the four components.

It should be noted that to ensure the independence and generality of each model, the connections between the models are established by the mapping function provided by the report model. Although the necessary data from technical elements and/or processes to be processed by the MES functions are modeled, the sources of them are not fixed in the modeling phase. In other words, for any technical elements and processes, which can provide the related data, the appropriate MES functions can be executed, i.e., the reusability can be ensured by the division of the data from the MES functions. By defining the inputs and outputs of the reports, the connections among the plant model, process model, and the MES function model are firstly established.

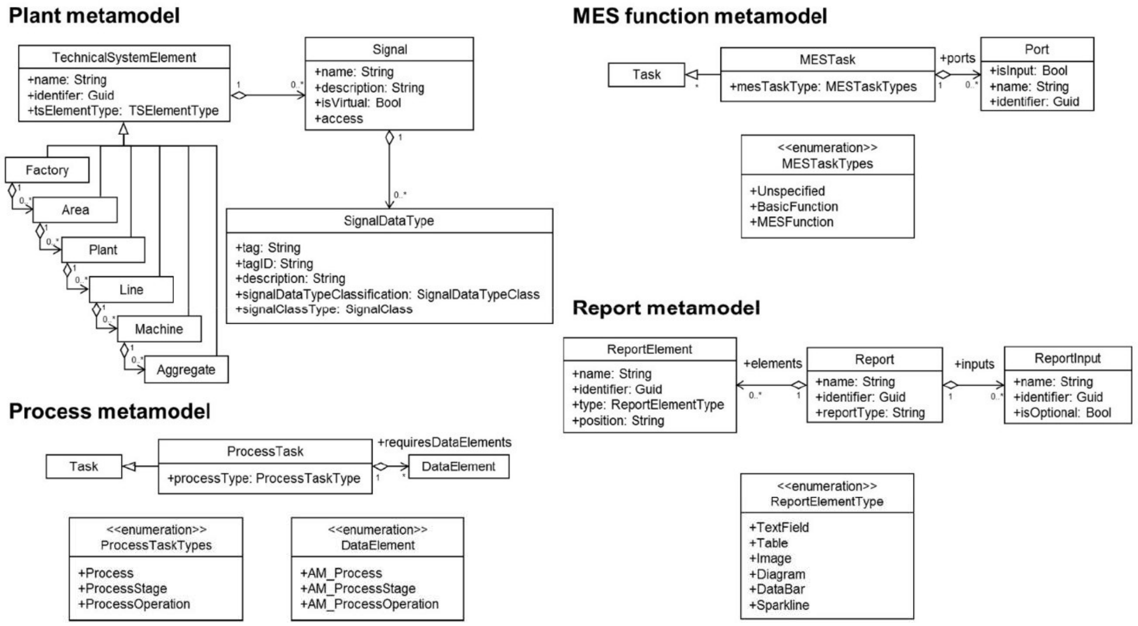


Figure 3. Metamodel of the modeling language MES Modeling Language (MES-ML) [57,59].

4.3. Specifying Phase

Following the modeling phase, taking the graphical MES model as the input, an MES specification as the output of the specifying phase is filled. The primary task of this phase is to transform the information from the graphical models into a format that software can utilize. The database tables are the platform for the MES specification. Different tables related to the four models in the modeling phase are defined to represent the information in the graphical model. In this phase, the transformation process is a mapping process, as the structure, content, and the relationship of the tables were defined as a one-to-one mapping of the extended MES-ML metamodel. This phase can be performed automatically by using a mapping tool that knows the relationship between the metamodel of the extended MES-ML and the database tables.

In the following, the related logical entity-relationship diagrams (ERD) of the database are presented using Crow's Foot Notation. As the technical systems are modeled using different hierarchies and the data points for collection can be assigned to each element in the plant model (according to the meta model of MES-ML), two tables named "Location" and "LocationDataPoint" are used to describe the plant model (Figure 4, left). The table "Location" contains attributes that are identical to the hierarchy level of the plant metamodel with factory, area, plant, line, machine, and aggregate being used to present the modeling elements on each hierarchy. The table "LocationDataPoint" presents the data points on each element. The types and descriptions of the data points can also be found with the attributes "DataPointType" and "DataPointDescription". Besides that, the attribute named "LocationLink" is made to indicate the relationship between a specific data point and its host element. Similar to the plant model, the information in the process model can be represented with two tables named "Process" and "ProcessDataPoint" (Figure 4, right). The name of the modeling elements on each hierarchy level in the process model can be found in the "Process" table. The type of the used process data points and their link to the process element can be described with the attributes "DataPointType" and "ProcessLink." Another table to indicate the correlation between the plant model and the process model is also defined (Figure 4, middle). By using the two attributes "ProcessLink" and "LocationLink" in the "LocationProcess" table, the link between the processes and technical systems can be found.

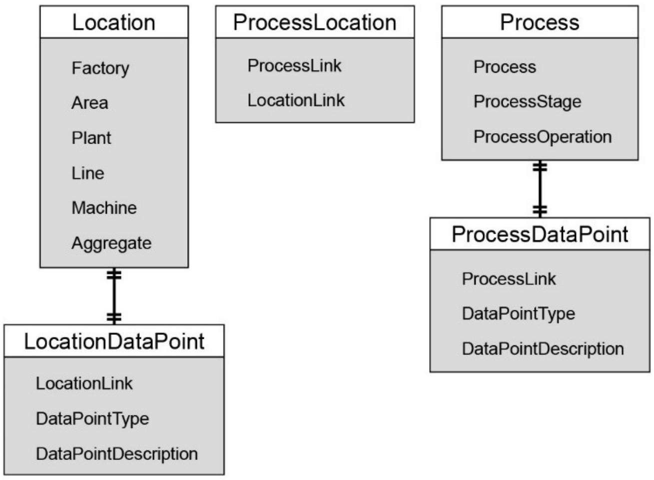


Figure 4. Entity-relationship diagrams (ERD) of tables for plant model, process model, and the link between them.

As the MES functions are composed of the basic functions, there are six tables to represent the information from the basic functions, MES functions, and the logical relationship between them. On the right side of Figure 5, the basic functions used to compose the MES functions and their input parameters are described in the tables named "BasicFunction" and "BasicFunctionInput." On the left side are the tables named "MESFunction" and "MESFunctionParameter" to represent the name of the MES function and the necessary attributes of the total input and output parameters to realize this MES function, such as the "Direction" to differentiate the input (Direction = 1) and output (Direction = 0) parameters. The two tables in the middle, namely the "MESFunctionInstance" and "MESFunctionInstanceParameter," serve as bridges in the specification for the MES function model to indicate on one side, the affiliation between the basic functions and the MES functions and on the other side, the assignment of the input and output parameters of the MES functions to the input parameters of the basic functions.

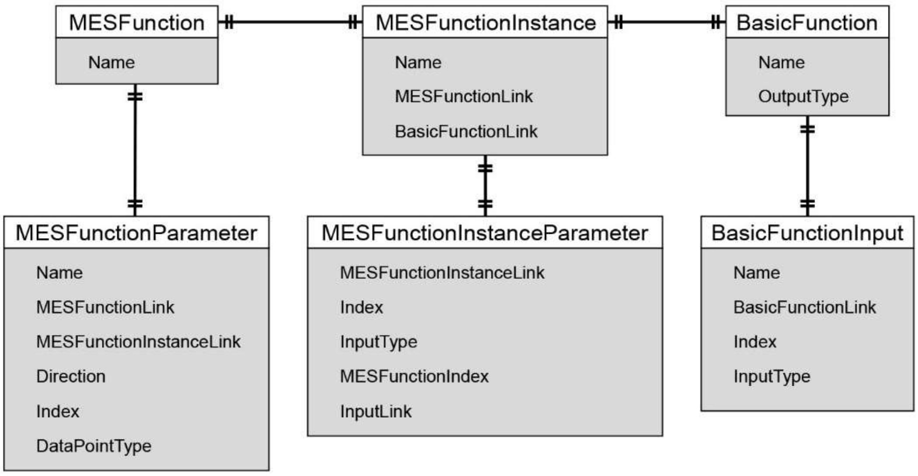


Figure 5. ERD of tables for MES function model.

The information in the report model can be transformed using the four tables that are shown in Figure 6. The table "Report" contains the name and the type of report. As a report can contain several report elements to present the results of different MES functions, and each MES function needs different data sources from the plant model and/or process model, the tables "ReportElement" and "ReportInput" are defined. The table "ReportElementOutput" is responsible for establishing the link between the report elements and the MES functions.

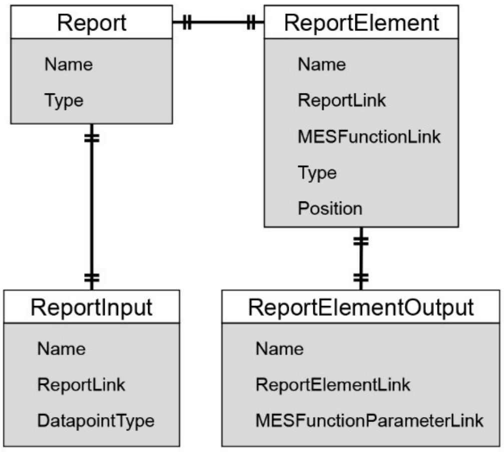


Figure 6. ERD of tables for report model.

4.4. Generating Phase

In this phase, based on the MES specification, MES with the demanded functions (without specific values for input parameters) is generated automatically with the help of a generator. The generator has two components, the front-end and the back-end. The front-end is a graphical user interface for the end-user to parameterize the inputs of the MES. The back-end, which realizes the data processing of the MES, can be divided into two parts, i.e., a toolbox and a connection finder.

The design of the graphical user interface is dynamically dependent on the MES specification. It contains two areas; input area and output area. In the input area, the input parameters are listed, and the values of input parameters are ready to be chosen and/or modified by the end-user. After the MES functions have processed the data according to the given values of input parameters, the results are assigned as the values of output parameters, shown in the output area (Figure 7).

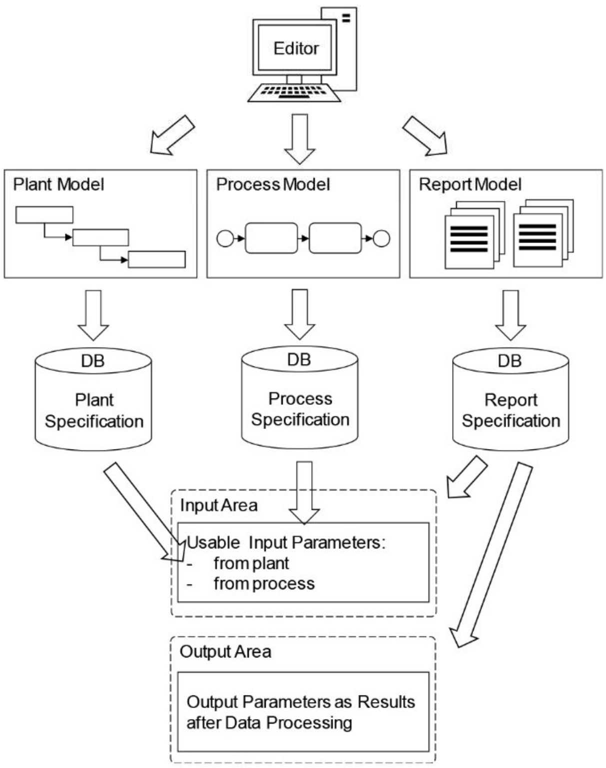


Figure 7. The front-end and its correspondence with the specification.

For the model-driven engineering of the software system that must be individualized, the MDA framework resembles the best practices: the first design of the business process is to be implemented and then processed with parameterization [50]. In this sense, the necessary MES functions are already implemented in the generating phase, while the specific sources of data (input parameters) that must proceed are not defined. This concept was proposed for the customization of ERP using a model-driven approach: there is no component to be generated or removed, but to be enabled/disabled. What needs to be generated is the constraints information for the parameterization to configure the system [50]. In the modeling and specification phases, no real function is implemented, but a description for the inputs and outputs of the functions, as well as the name of the basic functions and their connections with each other. The basic functions for data processing are defined in [59] and were firstly implemented as executable procedures in the toolbox. The connection finder that can invoke the basic functions from the toolbox is responsible for reproducing the sequence flow of basic functions to ensure the correct order of value passing among the basic functions (Figure 8).

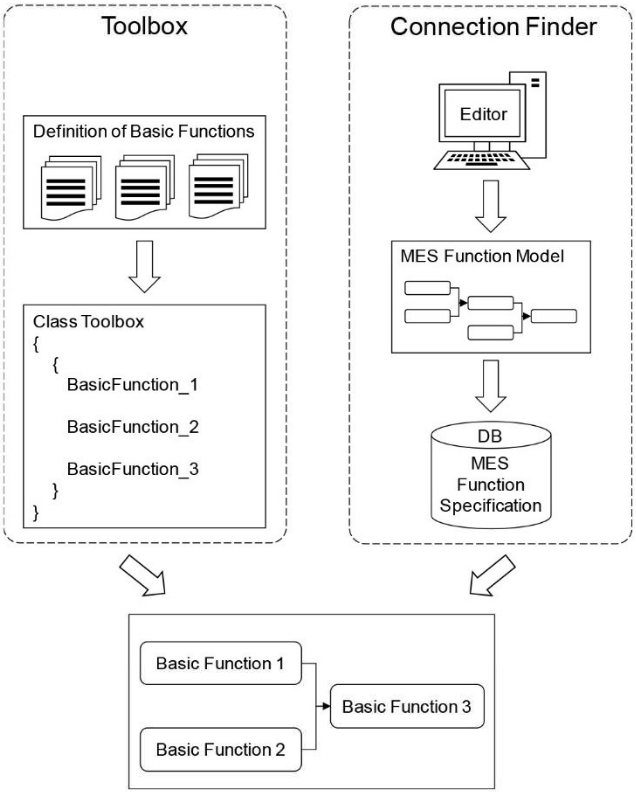


Figure 8. The back-end of the generator for data processing.

4.5. Application Phase

In the application phase, according to real business processes, the demands on the MES and the inputs are parameterized by the end-user so that the desired specific MES can be created. Generally, the data processing can be divided into four steps. First, retrieving the needed basic functions from the toolbox; secondly, assigning the input parameters from the input area to the basic functions; thirdly, processing the input parameters using the modeled sequence of basic functions and fourthly, showing the results as parameters in the output area of the graphical user interface.

5. Use Case: Energy Management for the Beer Brewing Process

As mentioned in Section 2.1, the most demanded MES functions are the functions that can support the improvement of the production efficiency, tracking and tracing, and energy consumption [66].

Chen et al. [59] also defined the modeling elements to manage energy consumption and analyze production efficiency that is relevant to the food and beverage industry. Based on their results, to evaluate the feasibility of the presented approach and the achievement of the requirements defined in Section 3, the approach was applied to the traditional brewing process in a fictitious brewhouse. This brewhouse provides the basis of the technical systems and production process that the generated MES is built for, and data for processing. The brewing process was chosen as it is a representative production type (batch process) in the food and beverage industry. Figure 9 illustrates the traditional brewing process in the brewhouse.

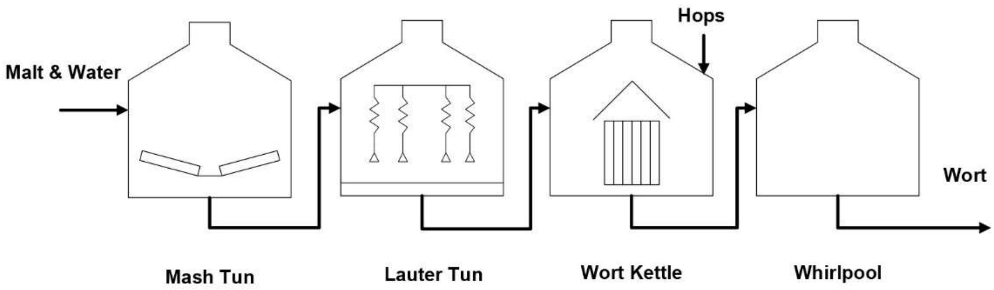


Figure 9. Traditional brewing process in the brewhouse.

In the brewhouse, to produce the wort for fermentation, malted barley, water, and hops are needed as raw materials. The malt and water are mixed and heated to specific temperature for extracting in the mash tun. The separation of the liquid phase (wort) from the grains is performed in the lauter tun. The wort kettle boils the wort together with hops for their sterilization and isomerization. Solid particles in wort, such as hops and proteins, are precipitated and separated at the bottom of the whirlpool. After that, the wort is cooled down and is ready for fermentation and storage in the fermentation room [67].

5.1. Analyzing the Demands and Actual State

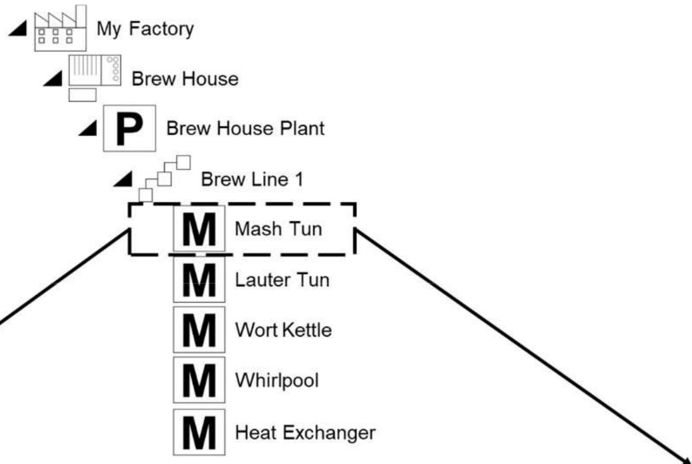
As the brewhouse is the main energy consumer of the whole brewery, namely 38% of total energy consumption [68,69], and the energy used in a brewhouse can be divided into two primary units, thermal energy, and electrical energy, each for 10.2–11.4 kWh/hl (hectoliter) SB (sales beer) and 0.84–2.3 kWh/hl SB in average [70,71], the targeted MES should focus on the management of the thermal energy in this use case. The wort kettle and the mash tun are the consumers of the thermal energy in the brewhouse, taking the share of 77.1% and 22.9% [70]. According to the data above, the consumption data of the brewery with a designed annual beer production volume of 200,000 hl are shown in Table 1. The consumption data with the data point defined in WS (WS_Cons_Steam) were stored in a database for the period from 1 January 2019 00:00:00 to 31 December 2019 23:59:59.

Table 1. Thermal energy consumption data of the consumers in the brewhouse.

Energy Consumer	Thermal Energy Consumption from the Literature on Average	Consumption per Year	Consumption per Second
Mash Tun	2.48 kWh/hl SB	496 MWh	0.02 kWh
Wort Kettle	8.32 kWh/hl SB	1664 MWh	0.07 kWh

5.2. Modeling the MES

The components in this use case were modeled in an editor that supports the extended MES-ML presented in [57,58]. The modeling elements that were defined in [59] were used. The production line in the brewery includes the mash tun, lauter tun, wort kettle, whirlpool, and heat exchanger. As mentioned above, the related data points for the energy data were assigned to the technical systems in the plant model. Figure 10 shows the model of the technical systems with a detailed view of the data point assigned to the mash tun.



Class	Tag Number	Tag Name	Description
WS	50103	WS_Cons_Steam	Consumption of steam

Figure 10. Plant model of the brewhouse.

The overall process of wort production in the brewery was described at the hierarchy level of process. This process was presented in greater detail at the process stage hierarchy level. Each element in the process stage was modeled with more details at the process operation hierarchy level. Figure 11 shows the resulted process model.

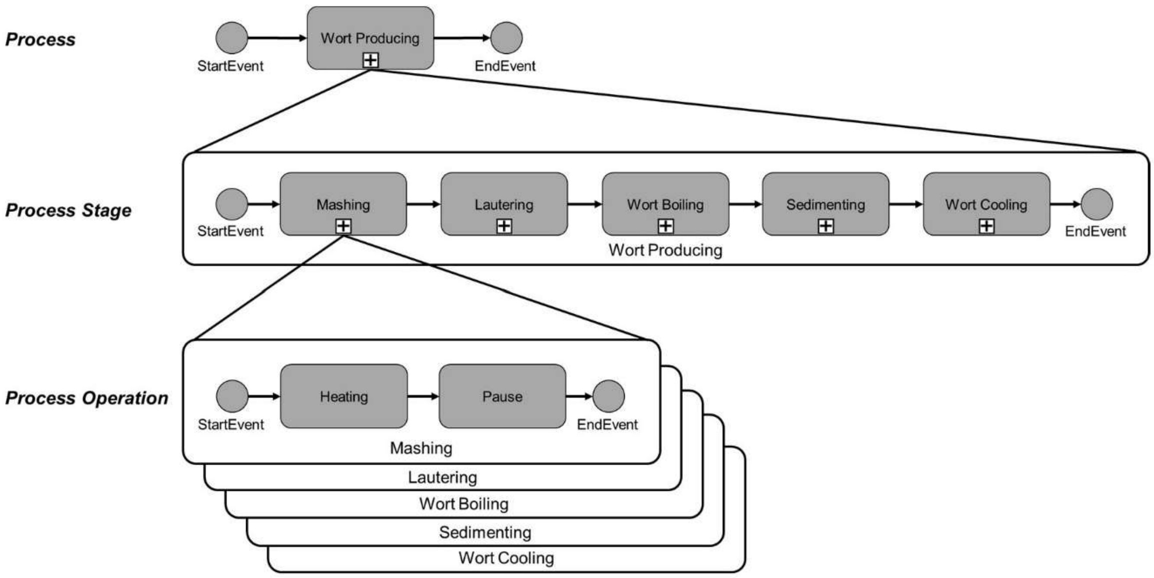


Figure 11. Process model of the brewing process.

In this use case, two MES functions were modeled: energy consumption of a specified machine in a given period of time, and the sum of the energy consumption of two machines in a given period of time.

Figure 12 shows the model for the second MES function, which was made up of two basic functions named "EnergyConsumptionCalculation" to calculate the energy consumption of a machine in a given period of time, and "Sum(x_1, x_2)" to sum the two consumption values. For the automatic generation of the desired MES functions, these two basic functions should be implemented in the toolbox of the generator.

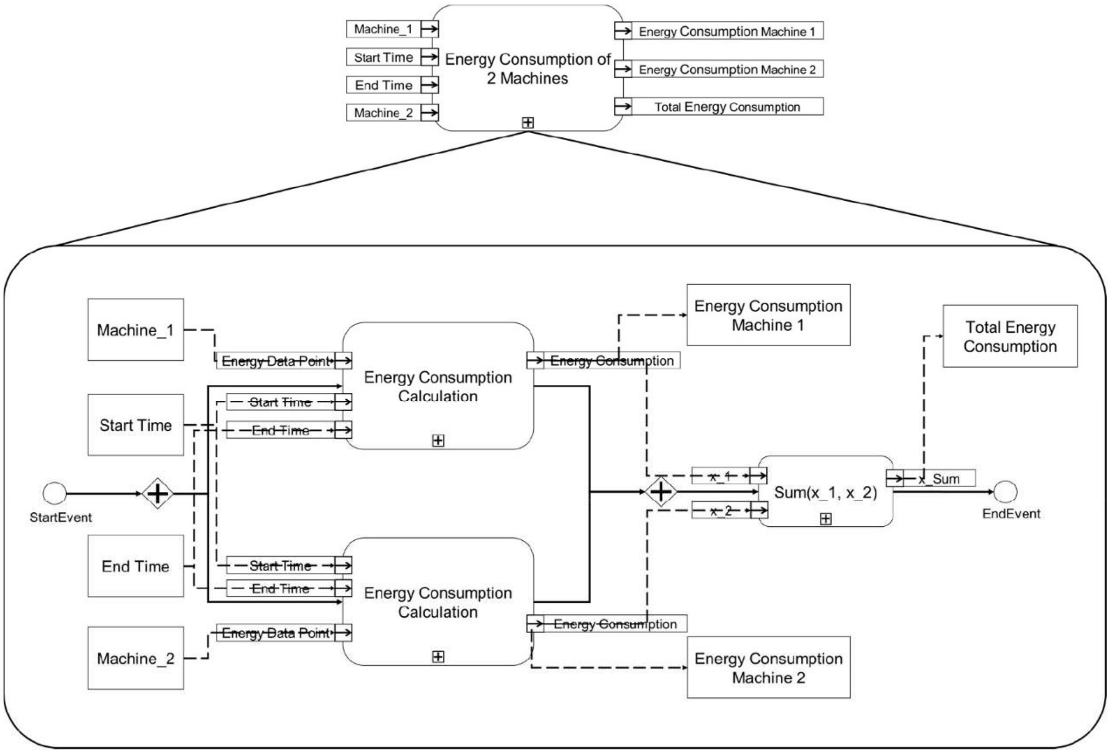


Figure 12. MES function model to fulfill the demands on the MES for energy management.

Figure 13 shows the related report element for the MES function "Energy Consumption of 2 Machines." The results of the MES function, namely the energy consumption of machine 1, the energy consumption of machine 2, and the total energy consumption, were considered as the outputs of the final report in text form.

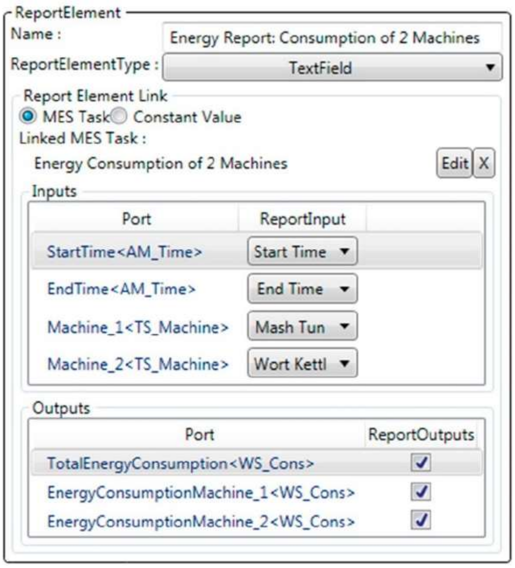


Figure 13. Element in the report model related to the MES function for calculating the energy consumption.

5.3. Specifying the Information from the Graphical Model

After the components of the MES were modeled, they were transformed into the database tables of the specification by the mapping function of the editor used in Section 5.2. As an example, to clarify the data structure of the specification, Tables 2 and 3 present the specification for the used basic functions and the description of their input parameters in the database tables named "BasicFunction" and "BasicFunctionInput".

Table 2. Specification in the "BasicFunction" table.

Key	Name	OutputType
1	EnergyConsumptionCalculation	Consumption
2	Sum(x_1, x_2)	Sum

Table 3. Specification in the "BasicFunctionInput" table.

Key	Name	BasicFunctionLink	Index	InputType
1	StartTime	1	0	StartTime
2	EndTime	1	1	EndTime
3	EnergyDataPoint	1	2	EnergyData
4	x_1	2	0	Value
5	x_2	2	1	Value

From the two tables we can reproduce the information. To compose the MES functions in this MES, two basic functions are needed, namely the "EnergyConsumptionCalculation" and "Sum(x_1, x_2)"; the first basic function ("Key" = 1 in Table 2) has three input parameters named "StartTime," "EndTime," and "EnergyDataPoint" ("BasicFunctionLink" = 1 in Table 3); the second basic function ("Key" = 2 in Table 2) has two input parameters named "x_1" and "x_2" ("BasicFunctionLink" = 2 in Table 3).

5.4. Generating the MES

Visual C# in Microsoft Visual Studio was chosen as the platform for the generator in this use case. For data processing, the implemented basic functions have access to the energy consumption database. Figure 14 presents the user interface of the generator at the beginning (left) and the report to be parameterized that was generated based on the specification (right). The input area contained text boxes to modify the values of input parameters. The output area was designed to indicate the energy consumption of each machine and their total consumption. To generate the user interface with input and output area, and to insert the parameters/components in each area, the information in tables named "MESFunction" and "MESFunctionParameter" should be utilized by the front-end of the generator.

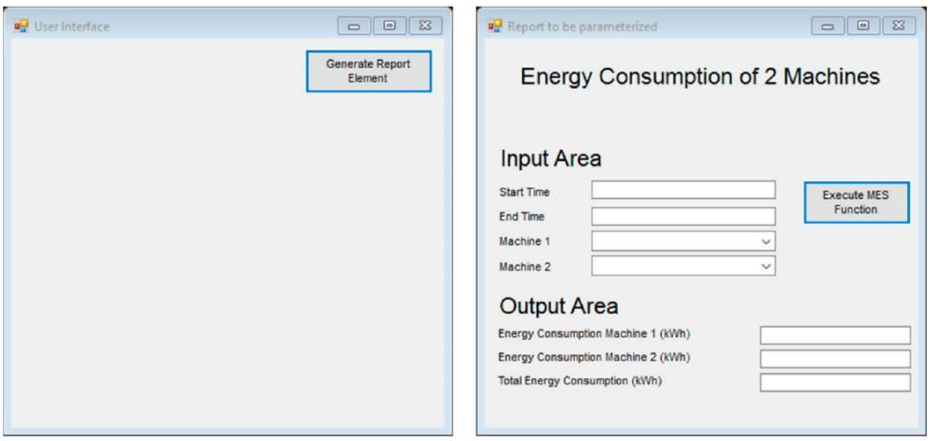


Figure 14. User interface of the generator (**left**) and the generated report to be parameterized (**right**).

5.5. Application of the MES

At the application phase, the input parameters were modified by the end-users according to their specific demands on the MES. As the mash tun and the wort kettle are the main thermal energy consumers, the input parameters of the generated MES were modified to calculate the thermal energy consumption of the two machines for a given period of time. Figure 15 illustrates the modified input area (left) and the results after data processing in the output area (right) pertaining to these two machines. The information in tables "BasicFunction", "BasicFunctionInput", "MESFunctionInstance", "MESFunctionParameter", and "MESFunctionInstanceParameter" was read by the back-end of the generator to invoke the procedures of the basic functions and pass the values between them.

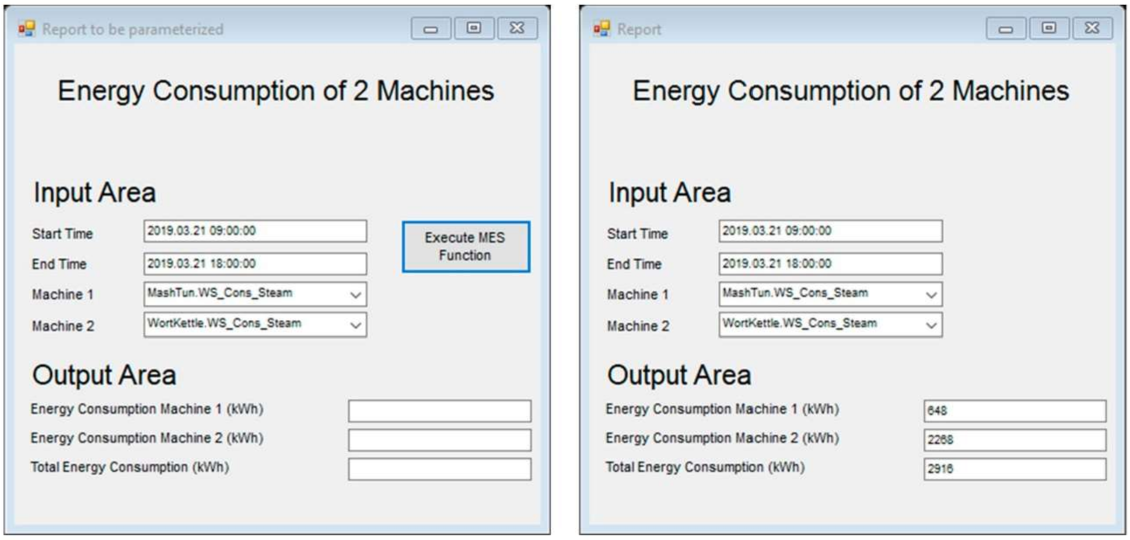


Figure 15. MES report with modified input area (**left**) and results in the output area (**right**).

5.6. Evaluation

In this use case on the brewing process in a brewhouse, after the requirements were analyzed, the MES for the management of the energy consumption was modeled using the modeling language, the extended MES-ML. This graphical model was transformed automatically into a specification in a series of predefined database tables. The information in the original model was reproduced by the specification resulting in the basis that was utilized by the MES generator. On one hand, the generator created a user interface based on the plant model, process model, and report model to establish communication between the end-user and the software. On the other hand, the internal connections of the basic functions for data processing were created with the help of the toolbox and the connection finder of the generator. As the possible input parameters/data sources can be chosen in the user interface according to the real business process, the generated solution can be parameterized specifically. Results according to the specific requirements of the business process were shown in the output area of the user interface. The mash tun and wort kettle each respectively consume 0.07 kWh/s and 0.02 kWh/s of the thermal energy in the brewhouse, which in return theoretically causes the consumption of 2268 kWh and 648 kWh in nine hours. The results calculated by the generated MES were identical to the theoretically expected values.

Based on the use case described above, and according to the requirements defined at the beginning of this paper, the presented approach can be evaluated. The model-driven approach for the engineering of the MES that was presented in Section 4 has been proven feasible by this use case, which clarifies each phase in this approach and the transformation between them (R1). The MES with the function to manage the thermal energy consumption in the brewhouse has been generated in the use case. Though the energy management is a relevant MES function for the food and beverage industry, to evaluate if other relevant MES functions in the food and beverage industry can be generated with this approach, the continuous process and the discrete process should be considered on one hand, as the use case focused on the batch process and the requirements, although the MES functions can be the same, the data availability, source, and processing may vary with the process type; on the other hand, more modeling elements, basic functions, and MES functions should be defined, applied, and validated with this approach. Once the solution of the MES was finished to be modeled in the modeling phase, the transformations from a graphical model to a software readable specification and the generation of an MES can be made without any other manual programming effort (R2). The WS were integrated into this approach to ensure data consistency. This offers standardized data signals for a consistent communication between the machines and MES, and ensures machine- and process-independent modeling of the MES functions as well as standardized data processing. The WS are the information basis for the whole model-driven approach, also for the further horizontal and vertical communication in the future (R3). Additionally, we have tested different application scenarios with the presented approach. It was confirmed that the MES with functions, which can be composed of the basic functions that are already implemented in the toolbox of the MES generator, can be generated automatically. In this sense, further adaption and expansion of the generated MES can be performed in the modeling phase, which reduces the customization effort, as an adopted and/or extended MES can then be generated automatically again (R4). Although two prototypes of software tools were used in the use case, i.e., the editor with mapping function to assist the modeling process and perform the mapping process, and the generator to generate the user interface and process the energy data, it must be indicated that there can be different variants of technology to realize the functionality of the used software tools, as the metamodel of the modeling language, the mapping from model to specification, and the methodology of the MES generation have been clarified in detail in Section 4.

6. Conclusions and Outlook

This paper presented an approach for the automatic generation of MES according to the model-driven concept with low programming and customizing effort. The presented approach has filled the theoretical gap in the research area for integrating the model-driven concept for the development of the MES, and further for other IT systems in the manufacturing enterprises. With the focus of its application, it can benefit the manufacturers in the food and beverage industry with limited flexibility to invest in conventional MES projects. The use case with the automatic generation of the MES for thermal energy management in the brewhouse has proven the feasibility and practicability of the presented approach.

Although the requirements were evaluated as fulfilled by the presented approach, as the first rudiment for the model-driven MES engineering in the food and beverage industry, there are still some limitations: (i) the use case focused on the MES function for energy management based on historical acquired data, the functions that concern the "execution" side (real-time reaction) of the MES were not considered, which can also be relevant for the food and beverage industry, such as the detailed scheduling, process management, and product tracking; (ii) the approach has not been validated with real production data, which may deliver meaningful potential areas for the improvement of the presented approach; (iii) although the standardized information model has been applied for consistent data communication, the integration of the MES with shop floor control systems and management systems on the enterprise level has not been considered in the developed approach. From the viewpoint of the software development, the prototype of the generator should be expanded and tested regarding to the computational complexity.

In future work, libraries should be enriched with more modeling elements for different application domains in the food and beverage industry to verify the interoperability of the presented approach. Additionally, the range of the predefined basic functions must be extended so that more MES functions with different focuses can be modeled and generated. Furthermore, MES functions for the execution of the process, such as dispatching production, production tracking, and detailed scheduling, should be applied with real production data for a more convincing validation of the whole approach. It is also planned to define the interface and key data for the communication between the MES, the control systems, and the enterprise management systems.

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2.5 Publication V – Further development and validation of the model-driven approach:

Model-driven Engineering of customizable Manufacturing Execution Systems for the Implementation in the Food and Beverage industry

Xinyu Chen; Christoph Nophut; Tobias Voigt

Page 76 – 96

Submitted at The International Journal of Advanced Manufacturing Technology of Springer, under review

This study has expanded the model-driven approach in a closed ring to cover the complete life-cycle of MES engineering. It consists of six phases, i.e., analysis of requirements on the target MES, modeling of the MES in four divided model components with graphical modeling language, specification of the graphical information into software-readable format, generation of the MES based on the specification, operation of the MES according to the specific application scenario and enhancement of the MES to cope with further requirements.

Since this approach is first to be employed to benefit the small and medium-sized enterprises (SMEs) in the food and beverage industry, two representative processes from the processing area and the packaging area are selected as the target processes to apply the model-driven approach, i.e., the raw milk processing in the operating room of a dairy and the beer brewing in the brewhouse in a brewery. The presented model-driven approach has been validated with real production data. With the identical approach, two different MES to analyze the energy consumption in the processing area and the production efficiency in the packaging area were automatically generated. In this sense, it has been confirmed that the developed approach can be exploited for the engineering of MES that should be customized in accordance with specific application scenarios. Furthermore, to improve the actual MES, this approach has provided a convenient way: only the MES model in the modeling phase should be modified manually, and the new MES to fulfill the upgraded requirements can be automatically generated again, which is a sustainable approach for the engineering of MES. With the results of this study, a feasible model-driven approach for the engineering of the MES in the food and beverage industry has been fully developed.

Contributions of the doctoral candidate – Conceptualization, Methodology, Software, Investigation, Resources, Data Curation, Writing - Original Draft, Visualization

Research Article

Model-driven Engineering of customizable Manufacturing Execution Systems for the Implementation in the Food and Beverage Industry

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Abstract

The Manufacturing Execution System (MES) is a process-oriented IT solution for collecting and managing information from the shop floor manufacturing processes. Due to the programming and customization effort required for specific production processes, the implementation of MES is not widespread in the food and beverage industry, as most food and beverage manufacturing enterprises are small- and medium-sized with limited resources to invest in MES. This paper presents a model-driven approach for engineering customizable MES with six phases covering the entire lifecycle of the MES engineering process. By using this approach, MES can be automatically generated and sustainably improved, which has the potential to reduce the complexity of implementation as well as the resources required for the engineering of MES. On the basis of two use cases in the processing and packaging areas in the food and beverage industry, the feasibility and practicality of the presented approach have been proven.

Keywords: MES Modeling; Manufacturing Execution Systems; Model-driven Engineering; Food and Beverage Industry

1 Introduction

The Manufacturing Execution System (MES) is a process-oriented software system for managing and analyzing information based on real-time data accrued from manufacturing processes. It connects the automation and enterprise layers in industrial manufacturing processes. On one hand, MES guides the implementation of rough production plans from enterprise systems, such as the Enterprise Resource Planning (ERP) systems, into detailed operations for technical systems on the shop floor. On the other hand, it provides the enterprise with critical key performance indicators (KPIs), such as energy consumption and machine efficiency, which enable commercial decisions to be taken and improve the performance of manufacturing processes. The Manufacturing Enterprise Solution Association (MESA) has proposed a formal definition that describes the core task of the MES in a manufacturing enterprise: "The MES delivers information that enables the optimization of production activities from order launch to finished goods. Using current and accurate data, the MES guides, initiates, responds to, and reports on plant activities as they occur. The resulting rapid response to changing conditions, coupled with a focus on reducing non-value-added activities, drives effective plant operations and processes. The MES improves the return on operational assets as well as on-time delivery, inventory turns, gross margin, and cash flow performance. The MES provides mission-critical information about production activities across the enterprise and supply chain via bi-directional communications" [1]. To cover all activities in the production environment, a series of MES functions has been defined in [1–3], such as production tracking, fine scheduling, performance analysis and energy management. Through the implementation of MES, the transparency of manufacturing processes can be improved such that the quality of products and efficiency of work flow can be optimized [4].

1.1 The food and beverage industry and MES

The food and beverage sector is the largest manufacturing sector in the European Union (EU), with a direct turnover of €1,192 billion and more than 4.7 million employees in 2019 [5]; it is also the largest energy consumer compared to other sectors [6]. For enterprises in the food and beverage industry, controlling production costs and providing products at reasonable prices in the competitive market, the improvement of energy efficiency in the production process cannot be ignored due to rising energy prices [7], new environmental regulations with associated costs for CO_2 emissions [8,9] and the growth of awareness of environmental issues from customers [10]. To illuminate the relationship between environmental and economic benefits and further to evaluate the sustainability of manufacturing processes, eco-efficiency indicators (EEIs) for the food and beverage industry were developed, in which process parameters and shop floor production data must be taken into consideration [11]. As the MES is connected to the shop floor and can directly monitor and control the production processes, it supports production managers and process owners in better understanding energy consumption in the process, calculating their own energy indicators, and exploring energy saving potentials. The ability of the MES to manage and reduce energy consumption in the manufacturing process has been indicated in [12].

The food processing industry is in need of efficiency-improving production methods to reduce production cost and to comply with increased regulations [13]. Weinekotter [14] indicated that the food packaging machinery remains severely under-utilized, which can be attributed to shorter production runs and frequent changeovers. For companies to be production-efficient, the development of more efficient production techniques to increase the overall equipment effectiveness (OEE) is required. Lean manufacturing is considered as a potential methodology to improve productivity and further decrease production cost in manufacturing organizations. Research by Borges Lopes et al. [15] indicated that improved productivity and production flexibility in food and beverage manufacturing could be realized through the application of lean manufacturing principles and tools. Based on the collection and analysis of production data, Desai et al. [16] applied the Six Sigma methodology on a pilot milk powder packaging line, which reduced the rejection rate of the final products and improved the annual financial benefits. The application of lean principles can be supported by the implementation of the MES, as useful real-time information can be provided by the MES to trigger, feed, or validate the lean decision-making processes to improve production efficiency [17]. The method for integrating the single minute exchange of die (SMED) principle into MES to reduce changeover time and improve planning and production efficiency has been established in [18].

As an essential component in the automation diabolo, introduced by Vogel-Heuser et al. [19] as a global information architecture for industrial automation, MES, which is the essential information processing and delivery layer between business processes and control systems, is inseparable from modern technologies. In 2013, to enhance its country's position in global manufacturing, the German Government proposed the concept of Industry 4.0. Under this concept, the entire factory environment would become 'smart' and enable mass customization through the advanced application of information and communication systems in manufacturing [20]. The utility of MES to the developing manufacturing industry was confirmed in [21] through an analysis of the technologies that will accompany Industry 4.0.

According to a survey in the brewing industry regarding the implementation of MES [22], from the viewpoint of the system provider, the main benefits that MES can bring to manufacturers is the improvement of product tracking, increased production efficiency, the optimization of quality control and efficient energy management. From the viewpoint of end users, they indicated that their demands on MES are the increase in production efficiency, the improvement of product tracking, efficient energy management and the optimization of machine maintenance.

1.2 Model-driven engineering of the MES

Although support from MES can help manufacturers in the food and beverage industry optimize their processes and gain more transparency, so that energy use and production efficiency can be improved, small and medium-sized enterprises (SMEs), which constitute the majority of the food and beverage industry (of the 285,000 companies in the EU, more than 99% are deemed SMEs [5]), are in an awkward position. Due to the specific characteristics of the production process, with low profit margins and slow adaption of modern technologies, SMEs in the food and beverage industry have limited resources to invest in the conventional MES projects [23]. As MES is designed for a specific manufacturing process in each enterprise [24], the engineering costs of MES primarily arise from the programming effort to customize it, for example the functionality of MES and the plants in which it is used must be correspondingly adapted and the interfaces of MES and programmable logic controllers must be implemented [25,26]. Instead of MES, many SMEs still use cheap but error-prone IT systems to provide some of the functionality of MES, such as KPI calculation and detailed production scheduling with spreadsheet programs [26]. For both sides involved in an MES project, namely the MES provider and manufacturer in the food and beverage industry, a method with low programming and customizing efforts for the engineering of MES should be established. The use of the model-driven concept discussed here could be a solution.

Models are created to serve particular purposes, such as presenting an apprehensible description of some aspect of a system [27]. Model-driven engineering is an approach to reducing the conceptual gap between problem domains and software engineering [28]. The heterogeneity of the developed system and its concerns can be reflected by using models. In the model-driven engineering version of software development, models serve as the primary artifacts and the developers rely on computer-based technologies to transform these into running systems, which increase the reusability and reduce programming effort during the engineering process [29,30]. However, little research has focused on the model-driven development of MES covering the entire engineering process, not to mention applying it to the food and beverage industry. Mizuoka and Koga [31] have introduced model-driven architecture into the development of MES for the machine processing industry with models described in XML metadata interchange, which is exported by a modeling tool from the model in UML. However, Lara et al. [32] have pointed out that the general purpose modeling language used in model-driven engineering may not be able to fulfill the specific requirements from different application domains, and so the domain-specific language should be defined and related to the specific domain. Flad et al. [33] proposed a concept for the model-driven engineering of MES for the food and beverage industry. This concept includes three steps: modeling of the components in an MES solution, specifying the information in the models into a software-readable format and automatic generation of the MES solution with a generator. However, the concrete approach of these three steps to realizing the concept was not developed. Based on this, Weißenberger et al. [26] extended the MES Modeling Language (MES-ML), which has proved suitable for use in the model-driven engineering of MES, aiming at the automatic generation of MES. Chen et al. [34] defined the domain-specific modeling elements as libraries for MES functions to manage energy consumption and analyze production efficiency in the food and beverage industry by using the extended MES-ML, so that the modeling effort of the required MES solution and programming effort of the generator can be reduced by reusing the already defined modeling elements. However, a completed approach covering the entire lifecycle of the MES that can be applied to the food and beverage industry has not yet been proposed.

This paper presents an engineering approach of customizable MES that makes use of a model-driven concept. With this approach, the MES must no longer be programmed with high customizing effort but modeled with predefined, specific modeling elements for different application domains. In addition to that, the possibility for the improvement of the generated MES solution has also been considered. On the basis of the use cases with real production data, the feasibility and practicality of the presented approach have been proven. The remainder of this paper is structured as follows: Section 2 presents the model-driven approach in detail. Section 3 shows two use cases for different application areas in the food and beverage industry. Section 4 evaluates the feasibility and applicability of the presented approach. Section 5 concludes and outlines future work.

2 A model-driven approach for engineering customizable MES

Based on the features of the food and beverage industry and research in the area of model-driven engineering presented in section 1.1 and 1.2, a model-driven approach for the engineering of a customizable MES in the food and beverage industry has been developed. It consists of six phases: primary analysis, MES modeling, MES specification, MES generation, MES application and MES improvement (Figure 1).

the "Weihenstephan Standard" communication standard is introduced. The Weihenstephaner Standard is a standardized information model for communication between technical systems/production machines on the shop floor and the MES at the process control level [35]. With the Weihenstephaner Standard, the data availability from the machines and processes, as well as the processing of the data, can be consistently defined for each MES function.

2.1 Primary analysis

The analysis of requirements serves as the primary study before the implementation of MES. The actual state of the production plant and process, with their available datasets, the required MES functions, and the desired reports are clarified in this phase. Through the cooperation of multiple co-workers with different areas of focus and working backgrounds within the enterprise, a

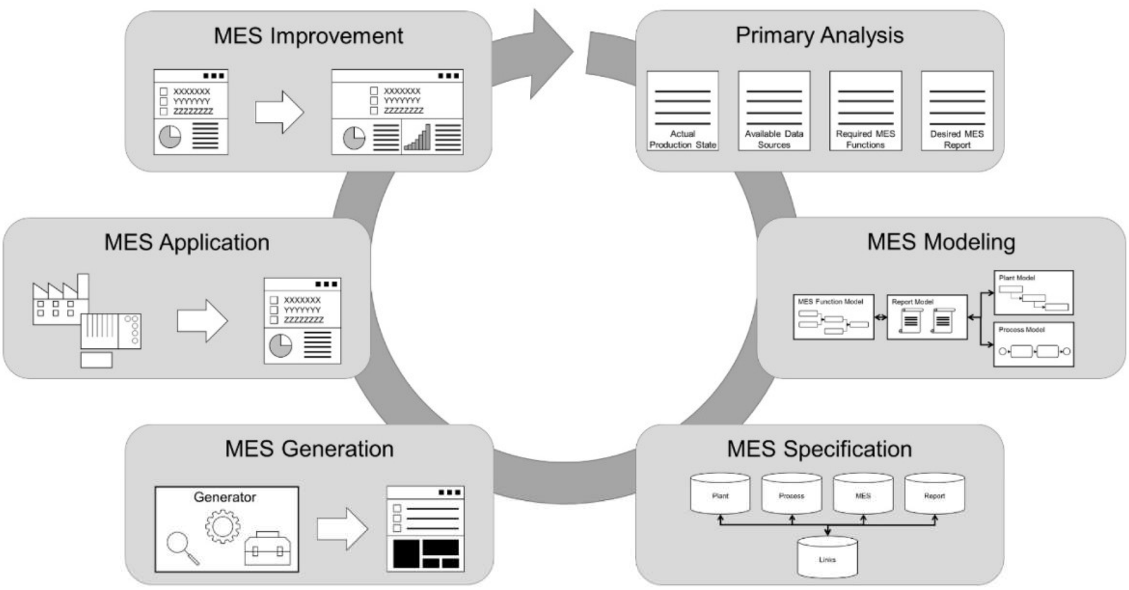

Figure 1: Model-driven approach for the engineering of customizable MES

Based on the features of the food and beverage industry and research in the area of model-driven engineering presented in section 1.1 and 1a model-driven approach for the engineering of a customizable MES in the food and beverage industry has been developed. It consists of six phases: primary analysis, MES modeling, MES specification, MES generation, MES application and MES improvement (Figure 1).

To ensure barrier-free data exchange, transformation, and processing in this approach,

practicable MES that can fulfill the requirements from various viewpoints can be discovered [36].

2.2 MES modeling

Based on the results from the requirements analysis, the required MES is modeled in this phase. The MES is closely connected to the shop floor; moreover, the MES functions and reports, as well as components on the shop floor that provide data on the plant and production process to be processed, cannot be ignored. Therefore, the

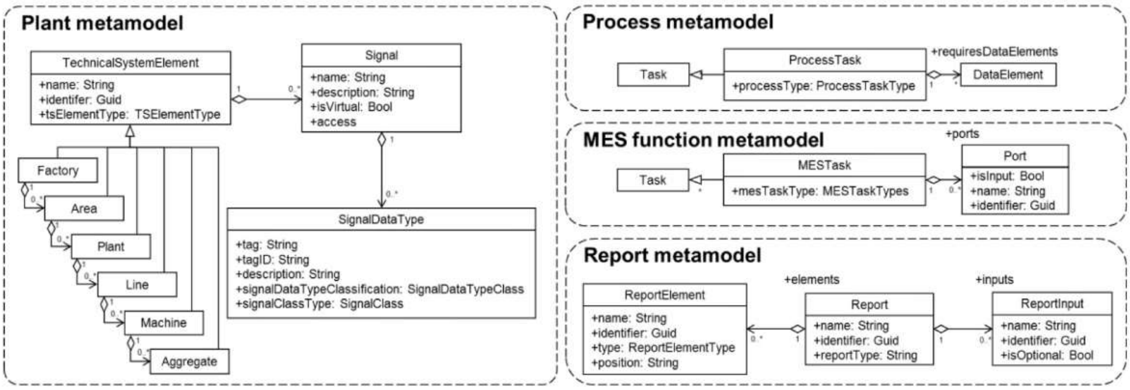

Figure 2: Metamodel in extended MES-ML [21,31]

production plant, production process, MES function, and MES report should be modeled together in this phase. Figure 2 shows the metamodel of the extended MES-ML, which is able to model the MES in relation to the four components and is considered suitable for automatic MES generation [26,34]: the plant model in a tree diagram illustrating the production plants, the process model with three hierarchies describing the production processes, the MES function model composed of the predefined basic functions representing the required MES functions, and the report model linking the available data for processing and showing the results of the MES functions.

2.3 MES specification

In this phase, the information in the graphical models is transformed into a software-utilizable format without losing any details. As the focus of each enterprise in terms of MES can be varied according to the manufacturing process, the MES specification must generally be designed to be usable for mixed functionalities in different implementation scenarios [37]. The database tables were chosen as the platform of the specification, as it is a standard and widely used technology in the manufacturing industry, and the information in different models can be easily represented by tables with definite relationships. Figure 3, Figure 4, and Figure 5 present the entity-relationship model (ER model) of the tables using Chen's notation [38,39].

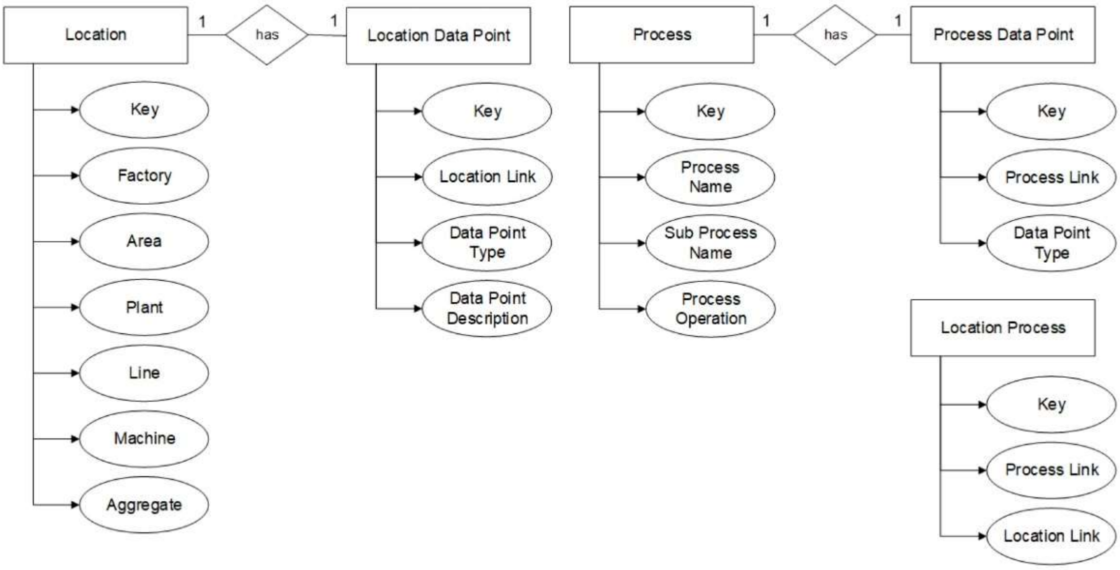

Figure 3: ER model to represent the information graphical MES model [32]

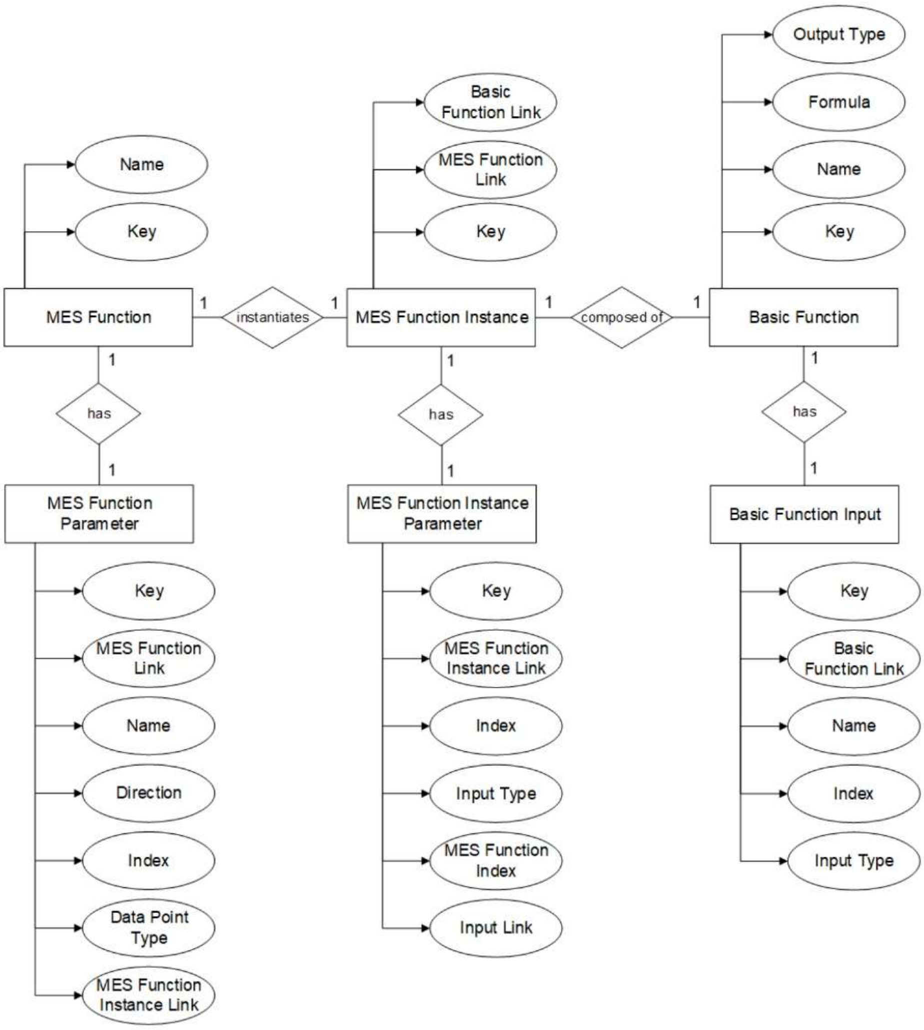

Figure 4: ER model of the tables to represent the information in the MES function model

Taking the two tables to specify the information of the plant model as an example: the table named "Location" has six attributes according to the hierarchy levels defined in the metamodel of the extended graphical modeling language MES-ML. With the attributes "DataPointType" and "DataPointDescription" in the table named "LocationDataPoint," detailed information about the data points can be represented. Through the attribute "location link," we can identify the affiliation between the data points and their assigned plant elements.

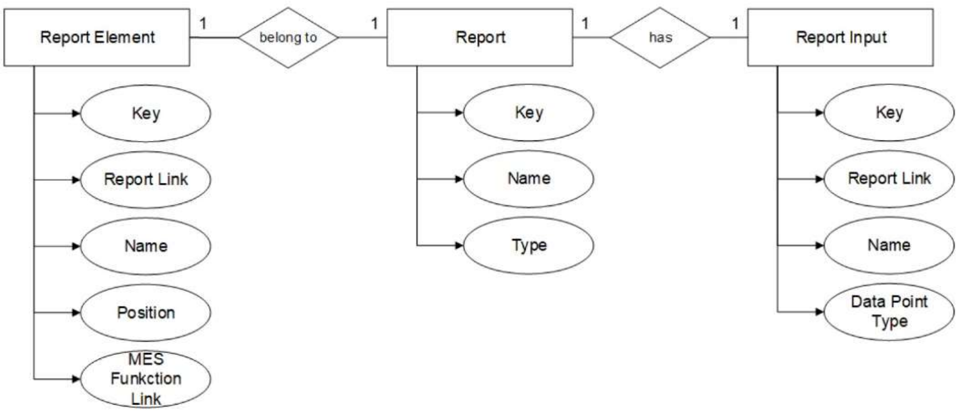

Figure 5: ER model of the tables to represent the information in the report model

2.4 MES generation

In the generation phase, a user interface of the MES without specific parameters can be generated automatically by the MES generator. The generator consists of a toolbox and connection finder. In the toolbox, the basic functions are programmed as procedures, which are the fundamental elements composing different MES functions and were defined in Chen's research [34]. The use of the predefined basic functions is the precondition for automatic generation, as the basic functions in the model should be known to the generator. The connection finder reads the specification that transformed from the graphical model, invokes the procedures from the toolbox, and regulates the value passing between them in the correct order modeled. Figure 6 shows the generation process in this phase.

2.5 MES application

The user interface of the MES produced in the generation phase was not fed with any parameters in the input area, which enable data processing by MES functions. This means that the generated MES is still generally usable and not specific to any concrete business process. In the application phase, end users can modify the MES to fulfill their specific requirements by modifying the parameters in the input area of the user interface of the MES. After that, the MES functions behind the user interface can process the data according to the input parameters and provide the desired report in the output area.

2.6 MES improvement

The improvement phase is designed to deal with new requirements on the already generated MES. Since these new requirements were clarified and the related model was adopted, the MES can be improved without additional programming effort, as the transformation from graphical models into a software-readable specification and the further generation of new MES is automatically executed. In this sense, the sustainability of the MES generated by the model-driven approach presented can be ensured.

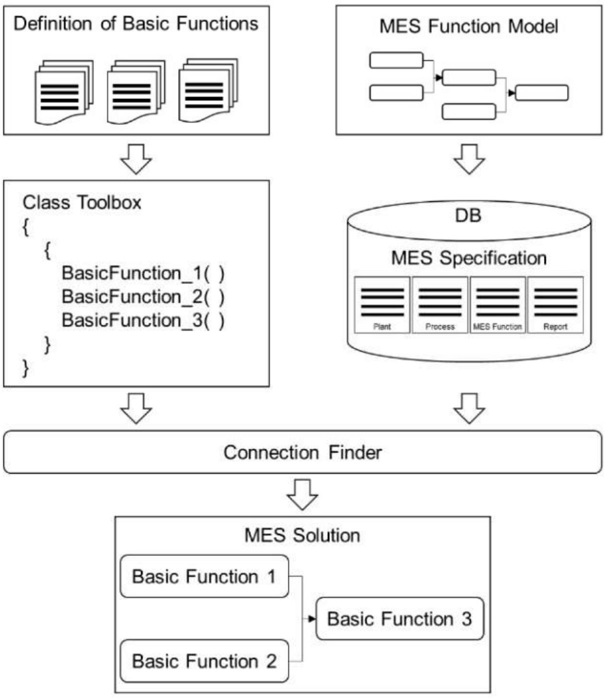

Figure 6: Collaboration of the toolbox and the connection finder in the MES generator to realize the MES function

3 Use cases in the processing and packaging area of the food and beverage industry

Processing and packaging are two essential areas of operation in the food and beverage industry [13]. In the processing area, materials are mainly processed through batching and/or as continuous processes. The discrete parts manufacturing processes predominate in the packaging area. To evaluate the feasibility and practicality of the presented approach, it was also applied to processing and packaging areas with two use cases. The first use case shows the application of this approach to the processing area in the operating room of a dairy plant to analyze process-related energy consumption. In the second use case, the approach is applied to the packaging area on the bottling plant of a brewery to analyze the technical efficiency of a beer bottling line for returnable glass. According to the literature [26,33,34], the prototype of an editor for modeling and transformation and a generator for automatic MES generation has been developed and used in two use cases.

3.1 Use case 1: Processing area of a dairy

The processing of milk is regulated in a number of laws, such as European Commission (EC) Regulation No. 852/2004, 853/2004, 854/2004 and 882/2004, which came into force on May 1st, 2005, and describe the required operating processes for hygienic raw milk, heat-treated milk and other milk-based products [40–43]. To avoid the formation of harmful germs, milk and its related products must be heated correctly and rendered compliant with the entire cold chain during processing. EC 853/2004 [41] requires that the raw milk temperature should not exceed 10 °C on arrival at the dairy. Before pasteurization, the raw milk must be cleaned by a separator or filter. For sufficient pasteurization, a temperature/time combination of 72 °C with a contact time of 15 seconds must be achieved. In the operating room of a dairy, after the delivery of the raw milk, it is separated into skimmed milk and cream. The two components must be pasteurized and then cooled to be stored in tanks or further processed. Figure 7 shows the processing of raw milk with a centrifuge and heat exchanger in the operating room of a dairy plant.

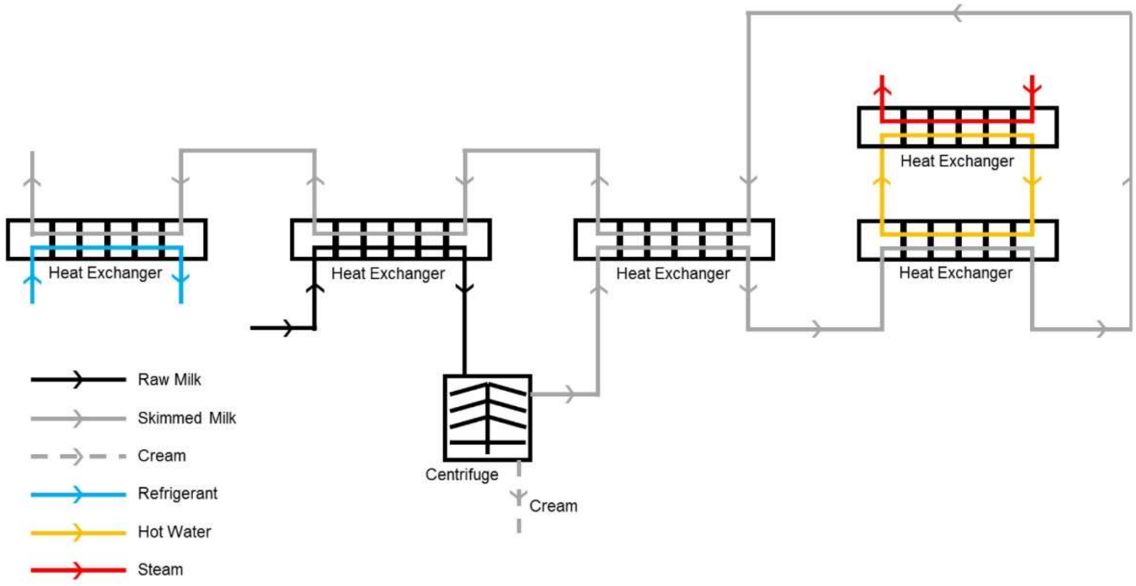

Figure 7: Processing of raw milk in the operating room

3.1.1 Analyzing phase of requirements and data availability

In the operating room, the primary energy consumer is the heat exchanger for heating the skimmed milk to be disinfected with the dosage of steam and cooling the skimmed milk to be stored in tanks with refrigerant [44,45]. Thus, the analysis of process-related energy consumption is the main requirement in this use case. As the machines in the operating room of the dairy are not equipped with an automated data acquisition system, the data were acquired with temperature sensors and flow meters for one week. Data on the milk flow rate and inlet/outlet temperature of the heat exchanger for heating and cooling were acquired as the basis for the analysis. These data were preprocessed so that the milk flow rate and average temperature at the inlet and outlet of the heating exchanger for heating and cooling can be stored in a databank related to the day number with data points defined in the Weihenstephaner Standard.

3.1.2 Modeling phase

Plant model

As presented in Figure 7, the technical systems that attend to the processing of raw milk in the operating room are the heat exchanger and centrifuge. Figure 8 presents the plant model. According to the acquired data, the related data points are also assigned to the related elements in the model, namely the "WS_Vol_Flow" for the milk flow rate and the "WS_Temp_Mean" for the temperature of milk at the heat exchanger inlet and outlet.

According to the selected day number and process name, the MES function can calculate the energy consumption related to the sterilizing and cooling process of skimmed milk. This MES function is composed of the basic functions, "Inlet Temperature Identifying," "Outlet Temperature Identifying" and mathematical operation for subtraction "Sub(x_1, x_2)" and "Multi(x_1, x_2)." Figure 10 presents the created MES function model.

The basic functions, "Inlet Temperature Identifying" and "Outlet Temperature Identifying," determine the temperature values at the inlet and outlet of the process-related heat exchanger. The difference between the two values is calculated by the basic function, "Sub(x_1, x_2)." The basic function "Multi(x_1, x_2)" has been used twice to multiply the volume flow and the constant of the milk heat capacity, together with the temperature difference. The value of the second basic function "Multi(x_1, x_2)" is the energy consumption of the related process that should be calculated.

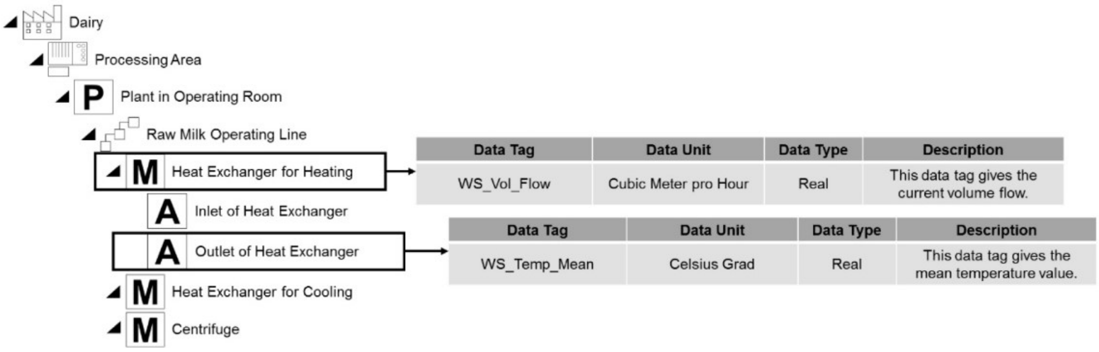

Figure 8. Plant model of the technical systems in the operating room of a dairy plant in use case 1

Process model

The processes in the operating room are modeled with three process hierarchy levels. The general description, "Milk Operating," is located on the process level. This process has been described at the process stage level as two parallel processes for separated cream and skimmed milk. At the level of process operation, the processing of skimmed milk is modeled in detail. The process model is presented in Figure 9.

MES function model

Report model

As the required MES for analyzing process-related energy consumption in this use case can be realized by the MES function, "Process Energy Consumption Calculation," according to the metamodel of the extended MES-ML, the report model containing the element, "Process Energy Consumption Report," presents the result of this MES function. The report model is shown in Figure 11.

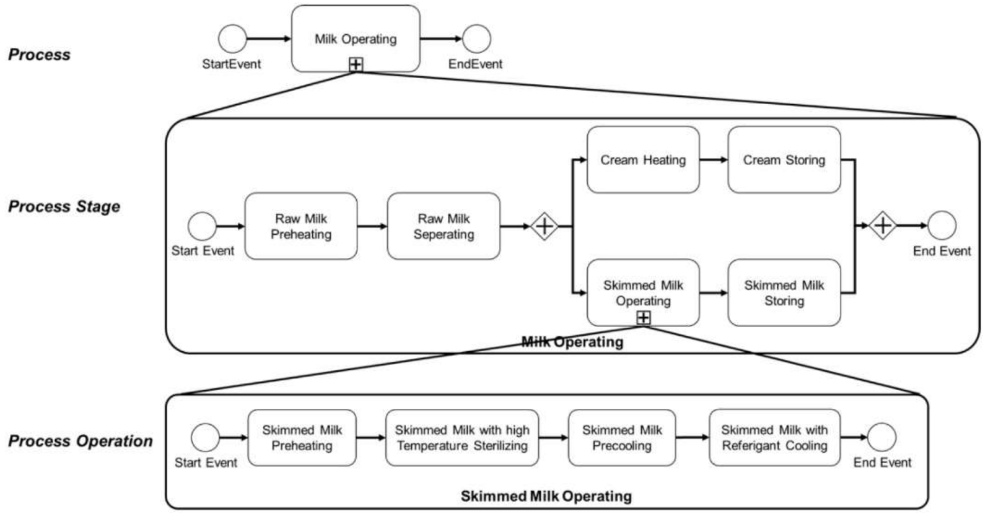

Figure 9. Process model of milk processing in the operating room in use case 1

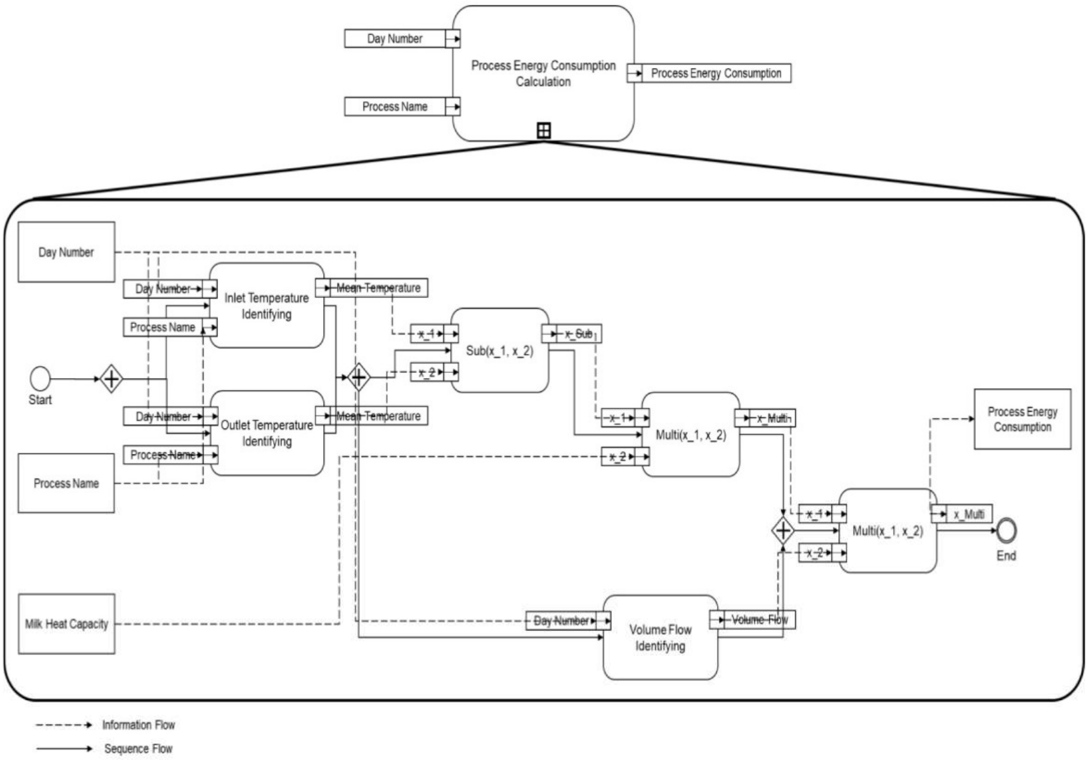

Figure 10. MES function model to analyze process-related energy consumption in use case 1

3.1.3 Specifying phase

With the mapping function of the prototype of the editor, the graphical information in the models was automatically transformed into database tables. As an example, the contents in the "Basic Function" and "Basic Function Input" are shown in Table 1 and Table 2, which represent the used basic functions to compose the MES function and their input parameters.

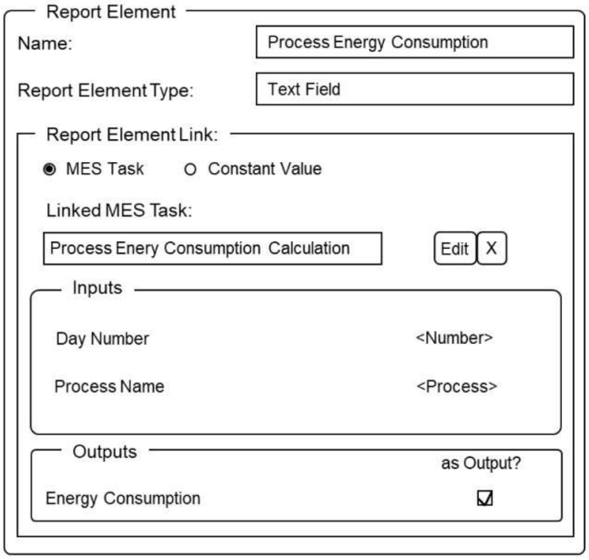

Figure 11. Report model to indicate the process energy consumption calculated by the MES function in use

Table 1. Specification in table “Basic Function” in use case 1

Key	Name	OutputType
1	Inlet Temperature Identifying	Temperature
2	Outlet Temperature Identifying	Temperature
3	Sub(x_1, x_2)	x_Sub
4	Multi(x_1, x_2)	x_Multi

Table 2. Specification in table “Basic Function Input” in use case 1

Key	Name	BasicFunctionLink	Index	InputType
1	Day Number	1	0	Number
2	Process Name	1	1	Process
3	Day Number	2	0	Number
4	Process Name	2	1	Process
5	x_1	3	0	1. Value
6	x_2	3	1	2. Value
7	x_1	4	0	1. Value
8	x_2	4	1	2. Value

3.1.4 Generating phase and operating phase

The predefined modeling elements for MES function were programmed as executable procedures in the toolbox of the generator. With the help of the connection finder, the sequence flow and information flow between the basic functions can be reproduced. Figure 12 presents the automatically generated graphical user interface of the generator before (left) and after (middle) the reading of the specification. The Microsoft Visual Studio 2019 was used as the developing environment for the prototype of the generator and was programmed in C# with WinForm.

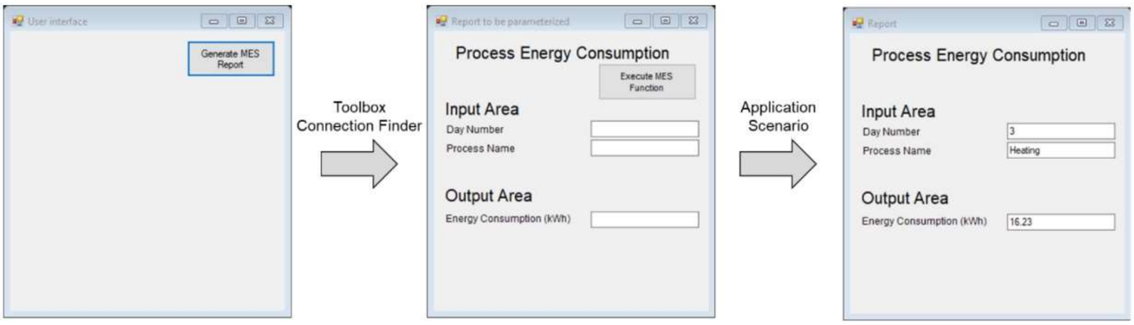

Figure 12. Graphical user interface before (left) and after (middle) the reading of the specification and final consumption report (right) in use case 1

The graphical user interface was generated in the generating phase with input area to be parameterized for a specific application scenario. The end user can operate the MES solution to meet their demand. Figure 12 (right) presents the report of the energy consumption of the heating process on the first day of data acquisition.

3.1.5 Improvement of the MES

The generated MES contains the MES function to calculate the energy consumption related to one of the selected processes. This can be improved to calculate the energy consumption of two processes simultaneously and summarize the total energy consumption. As the technical systems in the operating room and production process have not been changed, the plant model and process model remain unchanged. Figure 13 and Figure 15 present the improved MES model and report model.

According to the model, new basic functions are not required to compose the improved MES function. Therefore, the toolbox of the generator must not be updated. In this sense, the new MES can be generated automatically without any additional programming effort. Figure 14 shows

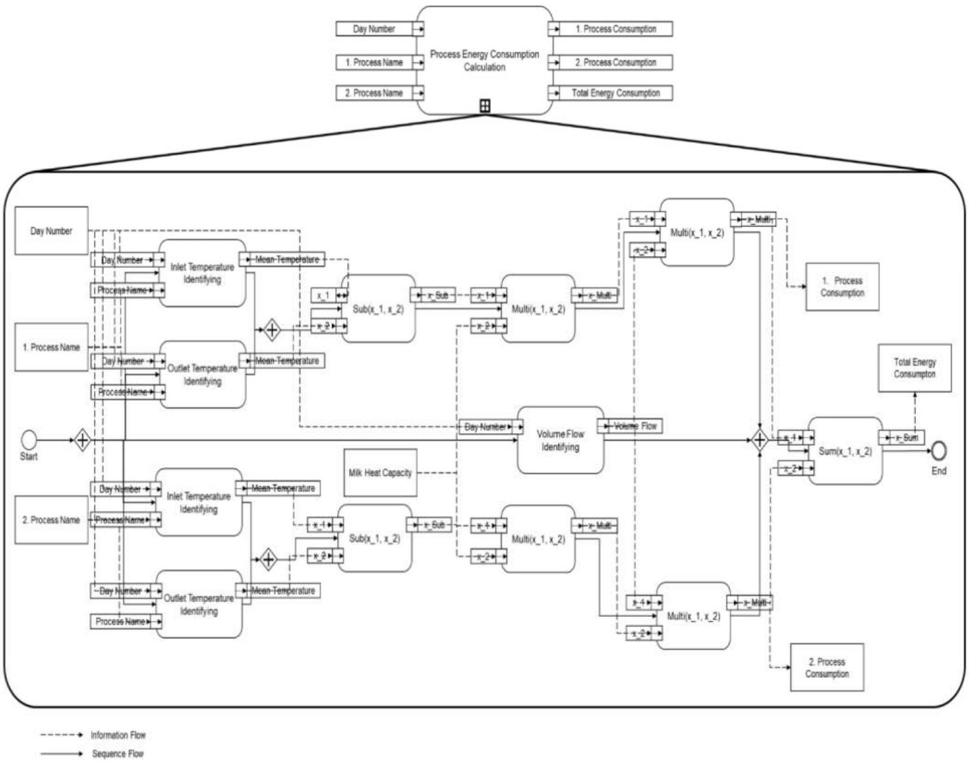

Figure 13. Improved MES function model for use case 1 to calculate the total energy consumption of two processes

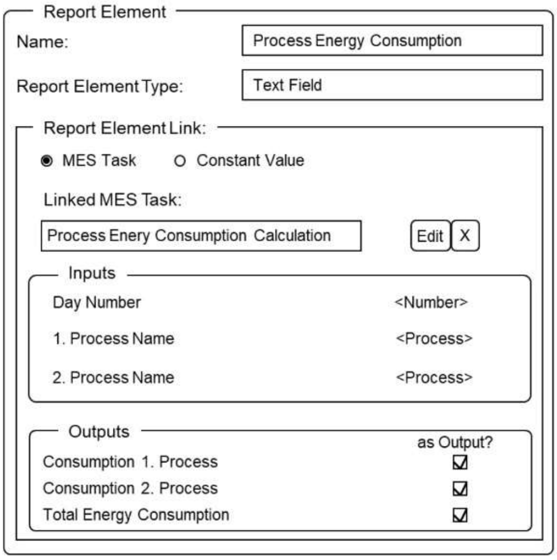

Figure 15. Report model after the improvement of use case 1

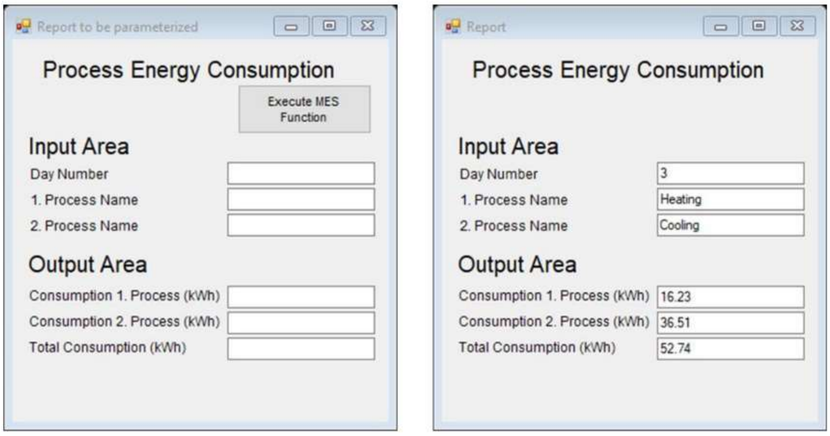

Figure 14. MES report following the improvement

the generated graphical user interface of the improved MES before and after specific parameterization.

3.2 Use case 2: packaging area of a brewery

The packaging process is the last highly automated step of modern food and beverage production. It is performed in high-performance packaging lines that involve various machines interlinked with buffering transport elements [46]. For the bottling of beer in returnable glass bottles, machines for depalletizing, unpacking, cleaning and control of the containers and bottles, bottle filling and capping machines, bottle labeling machines, packing palletizing and transport, are utilized [47]. The design of a typical beer bottling plant for returnable glass bottles is shown in Figure 16.

The second use case considered is an industrial beer bottling and packaging plant for returnable glass bottles in a medium-sized brewery. The target plant is designed for a nominal output of 15,000 bottles/h and its main use is for filling returnable 0.33 l glass bottles. As the two phases for specifying the model information and generating the MES solution are executed automatically, only the phases for analyzing requirements, modeling, and application of the MES are presented in the second use case.

3.2.1 Analyzing phase of requirements and data availability

As mentioned in Section 1.1, in order to improve the production efficiency, the MES function to analyze plant production efficiency is the main focus of the packaging area in this use case. The

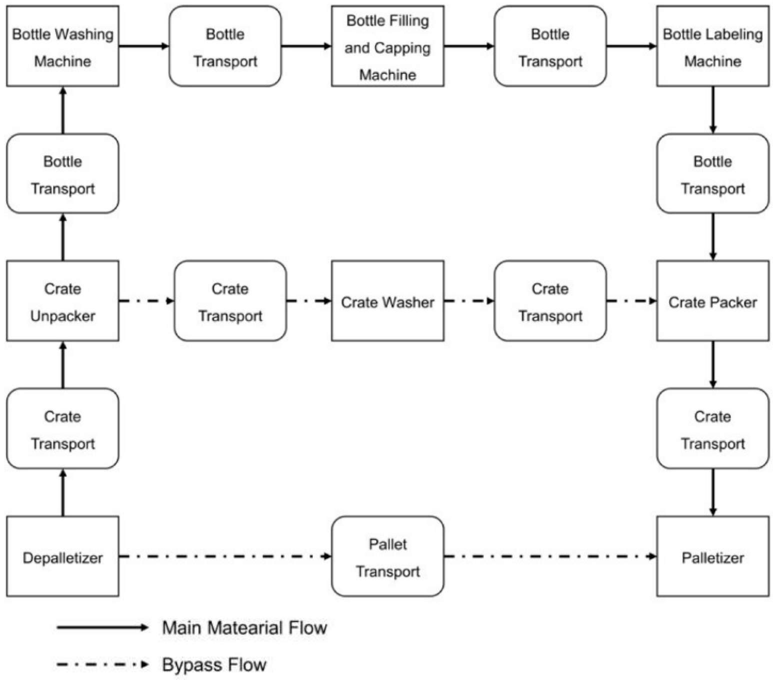

Figure 16. Design of a beer bottling plant for returnable glass bottles

technical efficiency (E_S) defined in DIN 8743 was considered the primary efficiency indicator [48]. The bottle filling and capping machine is considered as the central machine in the data acquisition phase, as it has the lowest performance in the entire bottling line and a key influence on the quality of the final product. The data regarding the total duration of the data acquisition (with the data tag "PE_Tot_Duration"), sellable quality output of the entire bottling line (with the data tag "WS_Good_Packages"), the set performance of the bottling and capping machine (with the data tag "WS_Set_Mach_Spd"), the duration of its downtime (with the data tag "PE_DownTime") should be documented. The data tags with a prefix of "WS" are tags that are defined in the Weihenstephan Standard. As there is no data tag defined in this that record the event duration, the tag prefix "PE" stands for production efficiency was created for this use case. The data were acquired over six days, for eight hours on each day. As a result, the acquired data were stored in a databank that served as the basis to be processed by the MES.

Data Tag	Data Unit	Data Type	Description
WS_Good_Packages	Number of units	Integer	number of processed good packages
PE_Tot_Duration	Seconds	Integer	total duration of the data acquisition

Data Tag	Data Unit	Data Type	Description
WS_Set_Mach_Spd	Units per hour	Integer	set machine speed
PE_DownTime	Seconds	Integer	duration of down time

Figure 17. Plant model of the beer bottling line for returnable glass in use case 1

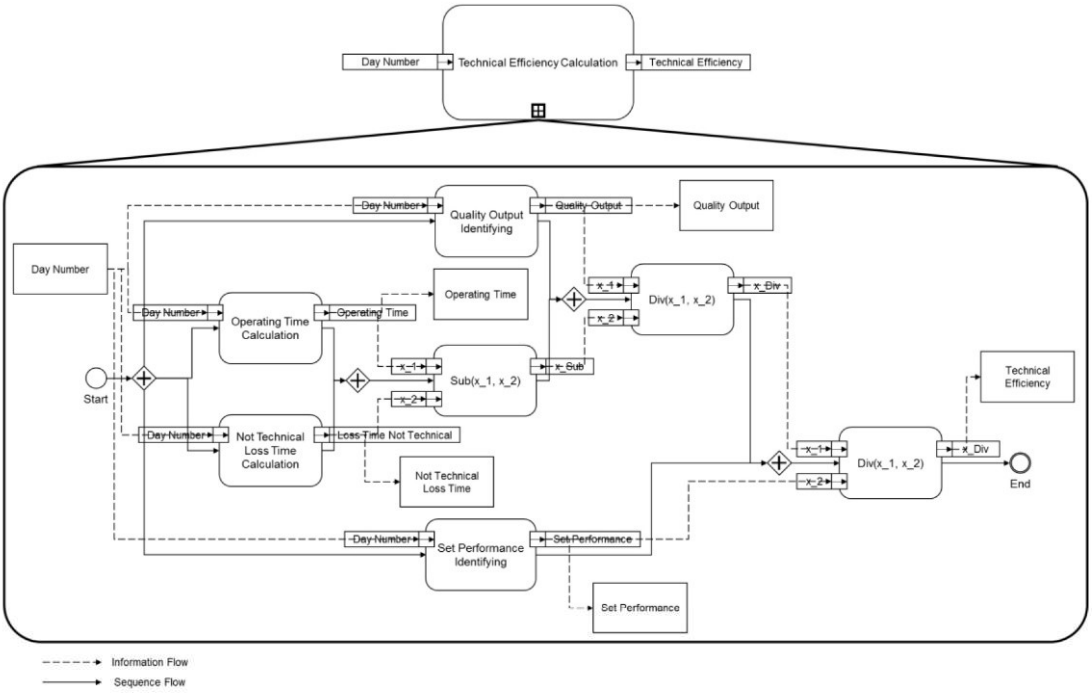

Figure 18. MES function model to analyze the production efficiency in use case 1

3.2.2 MES modeling

To analyze the production efficiency, according to DIN 8743, no information about the process must be provided. Therefore, the process model is not created in this use case. The technical systems that participate in the beer bottling line are modeled in the plant model. According to the type of acquired data, the data points that indicate the data availability are assigned to the line level (PE_Tot_Duration, WS_Good_packages) and the bottle filling and capping machine on the machine level (WS_Set_Mach_Spd, PE_DownTime). Figure 17 shows the plant model.

The basic functions for the mathematical subtraction, multiplication, division and calculation of the operating time, as well as the non-technical loss time, are necessary to analyze the production efficiency. Figure 18 presents the MES function model.

As defined in the metamodel of the extended MES-ML, the report model contains one report

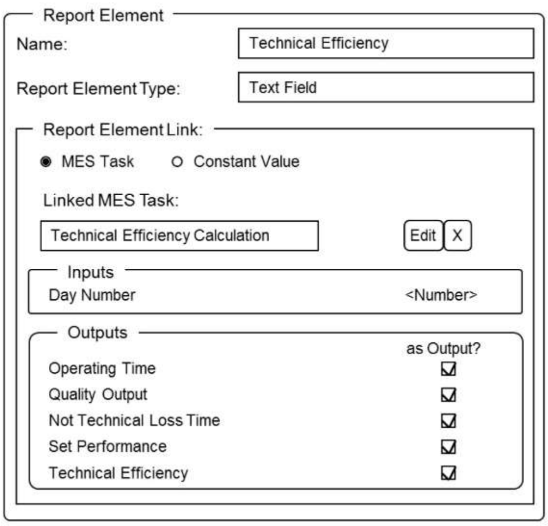

Figure 19. Report model to analyze production efficiency in use case 1

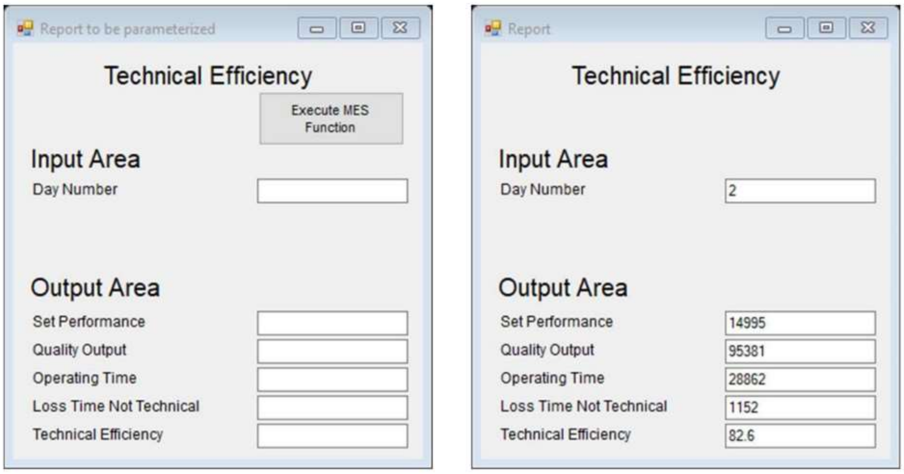

Figure 20: MES report for the production efficiency of the bottling line

element to present the result of the MES function "Technical Efficiency Calculation" in text format. The report model includes the input parameters necessary to execute the data processing of this MES function and its result as an output parameter, and is shown in Figure 19.

3.2.3 MES application

Related to the MES function model, there is one parameter in the input area that must be assigned by the end user, namely the day number of the data acquisition. According to the day number, the operating time, the quality output, the not technical loss time, set performance, and the resulted technical performance, are shown in the output area (Figure 20).

4 Evaluation

In section 3, the desired MES was generated successfully by using the presented approach. Based on the two use cases, the feasibility of this model-driven approach for the engineering of customizable MES has been confirmed. While the procedures to realize the basic functions and routine to establish the connections of basic functions of the MES generator must be programmed in advance, the following steps for information transformation and MES generation were executed automatically after the model had been created, i.e., the programming and customization effort for MES engineering can be reduced through the implementation of this approach.

The standard information model, the Weihenstephaner Standard, ensures the compatibility of the information flow and data exchange during the transformation from textual requirements into a graphical model, and then into a software-readable specification and operational MES. However, as parts of the data points were not standardized, the compatibility of the basic functions, and from these the MES functions, may not be satisfied. Along with the further development of the Weihenstephan Standard that should contain data points covering requirements on data exchange in different domains, the data consistency and compatibility of the entire model-driven approach can be improved.

The improvement of the MES was also considered in this approach that further MES functions can be integrated into the already existed MES to fulfill the new requirements. To update the MES, only the models must be modified in the modeling phase, as the further phases can be executed automatically. In the first use case, the original MES was used to calculate the energy consumption related to a definite process. The MES function model and report model were expanded with more basic functions and parameters in the input and output areas, while the plant model and process model remained unchanged. After the improvement, the MES was able to calculate the energy consumption of two selected processes at the same time and return the consumption value of each process, as well as the total energy consumption. As a result, the presented approach ensures the sustainability of the engineering process.

This model-driven approach was applied to the processing and packaging areas in the food and beverage industry, which exact different requirements from MES: the analysis of the energy consumption for milk processing in the operating room of a dairy and the analysis of production efficiency for beer bottling in the filling room of a brewery. The successful application and validation with real production data has demonstrated the viability of the presented approach to the engineering of MES that requires customization. However, the engineering of a MES that can realize real-time MES functions through this approach remains to be verified, as the two generated MES are both based on the processing of historical production data. The real-time functions, such as operations scheduling, product tracing and quality management are also the main focuses of the MES. Thus, the application of the presented approach should be extended to realize the real-time MES functions. Furthermore, more basic functions can be defined and implemented to apply this model-driven approach across a broader range, not only in the food and beverage industry, but also in other industries to evaluate the compatibility of the presented approach.

5 Conclusion and outlook

This paper presented a model-driven approach for engineering customizable MES in the food and beverage industry. It consists of six phases: i) a primary analysis of the MES requirements; ii) MES modeling with graphical modeling language of four model components; iii) specification of the graphical information into software-readable databank tables; iv) the automatic generation of the MES on the basis of the specification; v) the application of the MES to fulfill the specific scenarios; and vi) the improvement of the adopted MES in light of the new requirements. With this approach, the MES can be generated automatically after the MES has been modeled. This approach has reduced the complexity of MES implementation with respect to programming and customization efforts. As the manufacturers in the food and beverage industry are mostly SMEs with limited resources to invest in MES implementation, this approach is considered as a solution that promises to benefit manufacturers in this sector.

The main focus of this paper was on verifying the feasibility and practicality of the presented approach by its use cases, one from the processing area and the other from the packaging area, which are the two essential areas in the food and beverage industry. In the first use case, the MES was generated to analyze the process-related energy consumption in the operating room of a dairy. The MES in the second use case focused on the analysis of the technical efficiency of a beer bottling line in the filling room of a brewery. The requirements of the two use cases were fulfilled with the generated MES by using the presented approach. Moreover, the MES solution can be improved to react to new requirements. As a result, it has been shown that the model-driven approach presented can be used to engineer MES to fulfill different requirements, to which the generated MES should be customized.

In future work, in accordance with the results of this evaluation, collaboration with the working group of the Weihenstephan Standard is planned to define more data points corresponding to different MES functions and to achieve better integration of the Weihenstephan Standard into the model-driven approach. It is also planned to analyze the requirements from other industries and define more basic functions to compose MES functions that fulfill their requirements, so that the approach presented here can also be applied widely. Furthermore, important real-time MES functions will be a focus of further development in order to provide the model-driven approach with higher compatibility for the generation of MES.

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3 Discussion and conclusion

This thesis initially reviewed the benefits of the MES that can be brought to the food and beverage industry and the possible solutions to reduce the complexity of the MES implementation. Standardized information models for the communication in the vertical and horizontal direction, service-oriented architecture (SOA) to divide the MES functions as services, and model-driven engineering (MDE) of the MES with automatic generation have been considered as the rudiments that are capable of implementing the MES with low programming and customizing efforts during the engineering process. As a result, a model-driven approach integrated with the standard information model and concept of SOA for the engineering of the MES that can fulfill the requirements from the food and beverage industry was developed. This thesis consists of five pieces of research in a logical order that progressively delves into the model-driven approach, i.e., from the literature review, to the development of the modeling language, the definition of the modeling elements, the development of the specification design and the generation method, and further to the extension of the engineering process and the application in different areas with validation based on real production data. According to the requirements defined in Section 1.4, the findings of this thesis are discussed and summarized in the following sections.

3.1 R1: Development of a feasible model-driven approach

The development of the model-driven approach has been evolved through three stages. As the pre-work for the whole approach, the modeling language MES-ML has been extended in Publication II. With the extended MES-ML, the MES can be modeled in four independent components, i.e., the plant model that illustrates the technical systems, the process model that describes the production processes, the MES function model that represents the required MES functions, and the report model that acts as the interface between the MES and the end-users. In Publication III, the model-driven approach was proposed as consisting of three steps, i.e., modeling, specifying, and generating. The emphasis of this publication is placed on the establishment of the basis for the model-driven approach, i.e., the definition of modeling elements. Publication IV has considered the analysis phase to define the requirements on the expected MES and the application phase to parameterize the MES as the required phases. It extended the model-driven approach in five phases, i.e., analyzing phase, modeling phase, specifying phase, generating phase, and application phase. Moreover, the design (content and structure) of the specification and the generating method of the final MES have been clarified in this study. The approach in a closed ring with six phases has been proposed in Publication V, which has covered the whole life-cycle of the engineering process for the MES using a model-driven concept: i) primary analysis of requirements on the expected MES following the actual state of the manufacturing process and data availability; ii) MES modeling phase to build the graphical models of four components relevant to the MES, i.e., plant model, process model, MES function model, and report model; iii) MES model specifying phase to transform the information in graphical models into a software-utilizable format; iv) MES generating phase to generate the graphical user interface and establish the inner-connection of basic function procedures for data processing; v) MES operation phase to parameterize the completed MES that can fulfill specific requirements in a concrete application scenario; vi) MES improving phase to update the MES dealing with new demands.

The feasibility of the presented model-driven approach has been proven with the validation in two use cases with real production data in Publication V. In the first use case, this approach has been applied to the raw milk processing in the operating room of a dairy, and the MES to analyze the process-related energy consumption has been implemented with the presented model-driven approach. The process of beer bottling in the filling room of a brewery was selected as the target process in the second use case. Here, the MES has been generated using the same approach to analyze the technical efficiency of the production plant to assess its production efficiency. The two use cases represent the essential areas in the food and beverage industry, i.e., processing area and packaging area, raising different requirements on the MES. Through their successful implementation, the developed approach can be proven to be suitable for MES engineering in the food and beverage industry that should be customized to be adapted in specific application scenarios.

Compared with the conventional process of the MES implementation introduced in Section 1.2, the model-driven approach requires only manual effort at the modeling phase, and the final MES can be generated automatically without additional programming and customizing effort. Although the developed model-driven approach has been applied to generate limited MES functions (energy management and performance analysis), the fundamental elements of this approach, i.e., the modeling language for the MES, the predefined modeling elements assemblies, the MES specification, the MES generator, and the transformation between them, have been constructed completely and designed generally for any MES function, i.e., there is no notation or constrain in the fundamental elements related to the MES functions and other MES functions can also be generated using the presented approach.

3.2 R2: Definition of modeling elements for the food and beverage industry

Through the interviews with manufacturers in the food and beverage industry, three representative production processes have been selected as the first use cases, namely the wort producing process in the brewery, the milk operating process in the dairy, and the beverage filling process in the filling factory, in accordance to three main process types (the batch process, the continuous process, and the discrete process). Besides that, the identification of the energy consumption and the assessment of the production efficiency with Overall Equipment Effectiveness (OEE) indicators have been considered as the functions needed to be realized by the MES initially.

Based on the interview results, modeling elements have been defined as assemblies in libraries of each model for reuse (Publication III). Table 2, Table 3, and Table 4 present the modeling elements of the brewhouse, the milk operating room, and the filling hall in the plant model library. The modeling elements in the process model library can be found in Appendix I.

Table 2: Modeling elements for the technical systems in the brewhouse (from Publication III & IV)

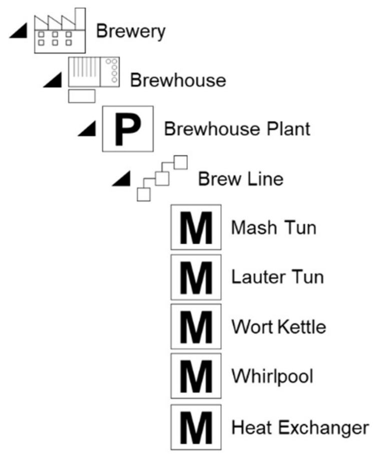
Level	Element	Model (in extended MES-ML)
Factory	Brewery	
Area	Brewhouse	
Plant	Brewing Plant	
Line	Brewing Line	
Machine	Mash Tun	
	Lauter Tun	
	Wort Kettle	
	Heat Exchanger	

Table 3: Modeling elements for the technical systems in the milk operating room (from Publication V)

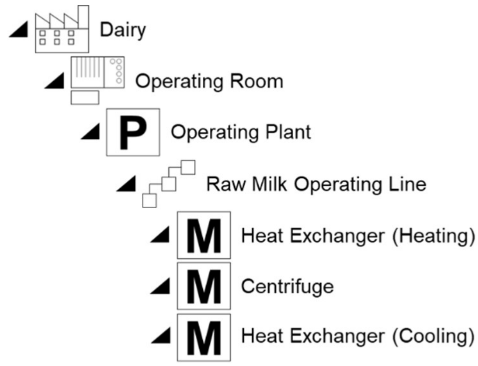
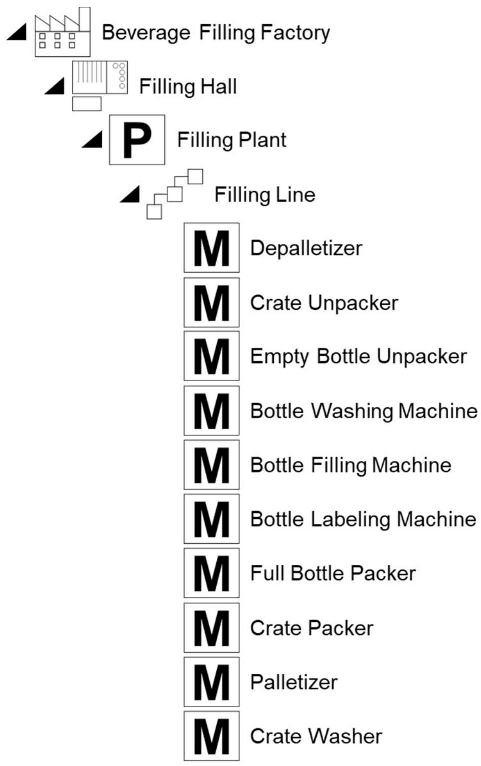
Level	Element	Model (in extended MES-ML)
Factory	Dairy	
Area	Operating Room	
Plant	Operating Plant	
Line	Raw Milk Operating Line	
Machine	Heat Exchanger (Heating)	
	Centrifuge	
	Heat Exchanger (Cooling)	

Table 4: Modeling elements for the technical systems in the beverage filling hall (from Publication V)

Level	Element	Model (in extended MES-ML)
Factory	Beverage Filling Factory	
Area	Filling Hall	
Plant	Filling Plant	
Line	Bottling Line (Glass)	
Machine	Depalletizer	
	Crate Unpacker	
	Empty Bottle Unpacker	
	Bottle Washing Machine	
	Bottle Filling Machine	
	Bottle Labeling Machine	
	Full Bottle Packer	
	Crate Packer	
	Palletizer	
	Crate Washer	

To realize the two MES functions, namely energy management and performance analysis, six categories of basic functions (as the smallest elements to compose the final MES functions) have been defined as modeling elements in the library of the MES function model, i.e., mathematical basic functions, basic functions for plant data processing, basic functions for process data processing, basic function for production order and batch data processing, basic functions for energy management, and basic functions for OEE indicator analysis. Table 5 and Table 6 describe the basic functions named “summation” and “energy consumption calculation” in categories of basic functions for mathematical operation and for energy management. More description of the defined basic functions can be found in Appendix II.

Table 5: Description of the basic function named “Summation”

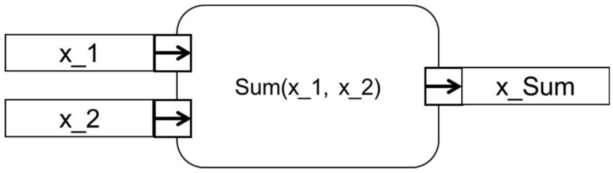
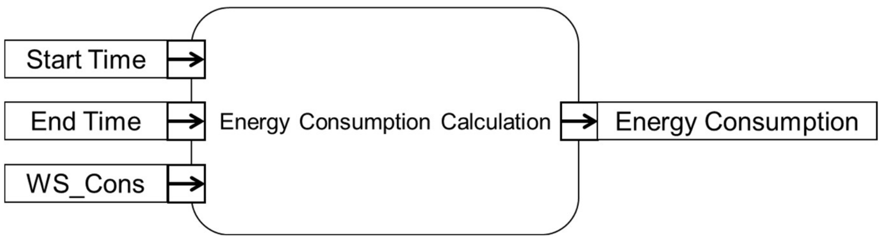
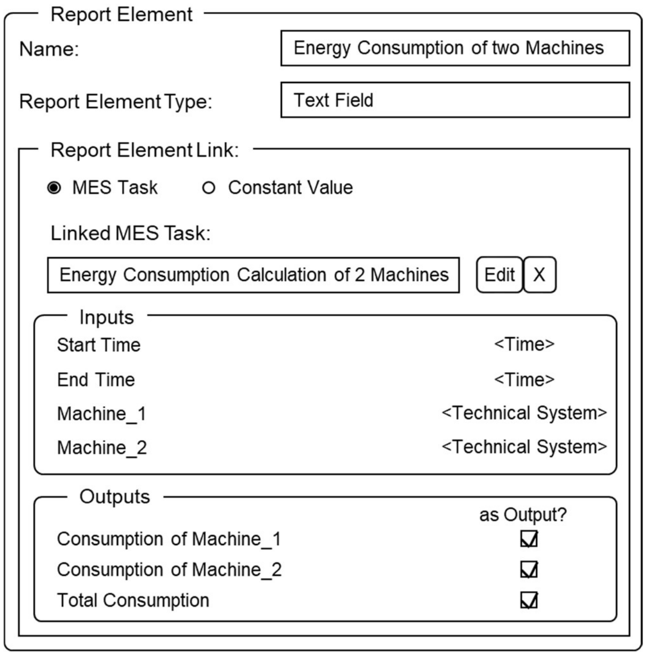
Category	Mathematical Basic Function
Name	Summation
Formula	x_Sum = x_1 + x_2
Model	
Description	The function calculates the sum of two values, x_1 and x_2.

Table 6: Description of the basic function named “Energy Consumption Calculation”

Category	Energy Management
Name	Energy Consumption Calculation
Formula	ΔW=W_2| WS_Cons at end time-W_1|WS_Cons at start time
Model	
Description	This basic function determines the consumption of a specific energy form in the period [StartTime, EndTime]. WS_Cons ist a group of data points representing the energy consumption of different energy forms.

Related to the two MES functions, the defined modeling elements for the report model have also been divided into two categories, energy report and performance report. Table 7 presents the energy report for the energy consumption of two machines. More modeling elements can be found in Appendix III.

Table 7: Description of the Energy report named "Energy Consumption of two Machines"

Category	Energy Report
Name	Energy Consumption of two Machines
Model	
Description	This report presents the energy consumption of two machines. Their energy consumption can be determined according to the data points for energy forms on both machines as input parameters of the report. Three output parameters can be chosen as the results to be shown in the report, the energy consumption of the machine No. 1, the energy consumption of the machine No. 2, and the total energy consumption of the two machines.

The modeling method and the defined modeling elements were evaluated with a use case of a traditional brewhouse and compared with the actual state of the MES engineering method by the MES experts in the food and beverage industry. As a result, the predefinition of the modeling elements before the implementation of the model-driven approach has been evaluated as the necessary basis for the automatic generation of the MES. The graphical and reusable modeling elements have simplified the interdisciplinary communication of co-workers with different backgrounds in an MES project and reduced the modeling complexity. The model-driven approach with predefined modeling elements has also been considered as portable to other industries.

According to the interviews with manufacturers in the food and beverage industry, the modeling elements have been defined aiming at generating two main MES functions, energy management and performance analysis, which are considered as the first functions that should be realized by the implementation of the MES. The functions for real-time reaction to changes in the production process and those for scheduling of the production orders have not been covered by the already defined modeling elements, such as process management, production tracking, and maintenance management, which are also relevant to the manufacturers in the food and beverage industry and can contribute to enhancing the production efficiency and reducing energy consumption. However, as the first rudiment to generate the MES using the model-driven concept in the food and beverage industry, this work has established the fundamental framework of the model-driven approach and proven its feasibility. Because the requirements on the MES are related closely to the real business process, based on the results of this work, further real-time MES functions should be identified together with manufacturers, more related modeling elements should also be defined, adapted and integrated in the presented approach, and this approach should be verified and optimized with more use cases and production data.

3.3 R3: Support of a standard information model

The Weihenstephaner Standards (WS) define a universal communication interface for connecting different machines and process contrail systems to a higher ranking MES and also define the data that should be available for acquisition. Four domains, i.e., food processing, beverage packaging, baking processes, and beer brewing, are included in the WS. The WS have been introduced as the information model to the model-driven approach, which enabled the "plug-and-play" functionality and ensured the portability of the modeling elements so that various MES functions can be created with limited predefined basic elements.

In this work, data points have been assigned to the modeling elements to indicate the necessary data that should be collected and processed to realize the MES functions, energy management and performance analysis, which are the first requirements based on the interviews with manufacturers in the food and beverage industry. To enhance the reusability of each modeling element, data points have been classified. Table 8 presents the data points, which are related to the two MES functions and already defined in the WS (with the prefix "WS" based on WS_07).

Table 8: WS data points related to the MES functions for energy management and performance analysis

Data Point Class	Data Point Number	Data Point Name
WS_Tracing	00061	WS_Set_Batch_ID
	00062	WS_Cur_Batch_ID
	00063	WS_Set_Order_ID
	00064	WS_Cur_Order_ID
WS_Mode	00100	WS_Cur_Mode
WS_Prog	00200	WS_Cur_Prog
WS_State	00300	WS_Cur_State
WS_Mach_Spd	00401	WS_Cur_Mach_Spd
	00402	WS_Set_Mach_Spd
	00403	WS_Mach_design_Spd
WS_Amount	50005	WS_Tot_Bottles
	50006	WS_Good_Bottles
	50220	WS_Tot_Packages
	50230	WS_Good_Packages
WS_Cons	50101	WS_Cons_Clean_Water
	50102	WS_Cons_Hot_Water
	50103	WS_Cons_Steam
	50104	WS_Cons_Sterile_Air
	50105	WS_Cons_CO2
	50106	WS_Cons_Detrergents
	50107	WS_Cons_Additives
	50108	WS_Cons_Lubricant
	50109	WS_Cons_N2
	50110	WS_Cons_Electricity

Besides that, new data points were defined specifically to realize functionalities that require other information, such as the start time of a process, the name of process operation, or the volume flow of a heat exchanger (with the prefix "AM" for "automatic generation of MES"). Table 9 presents the data points and their class used in the presented approach.

Table 9: Defined data points to complete the functionality of the MES functions

Data Point Class	Data Point Number	Data Point Name
AM_Time	09701	AM_Start_Time
	09702	AM_End_Time
AM_TechnicalSystem	09801	AM_Factory
	09802	AM_Area
	09803	AM_Plant
	09804	AM_Line
	09805	AM_Machine
	09806	AM_Aggregate
AM_Process	09901	AM_Cur_Process
	09902	AM_Cur_Sub_Process
	09903	AM_Cur_Prc_Operation
AM_VolumeFlow	59001	AM_Cur_VF_Heat
	59002	AM_Cur_VF_Cool
	59003	AM_Cur_VF_Recycle

Although the two use cases (in Publication V) with real production data taken for the validation are located in the domains that are already covered by the WS, some deficiencies are identified: i) not all of the data can be collected automatically, such as the machine state can not be collected with a one-to-one correspondence to the definition in WS; ii) enterprises cannot keep abreast with the updating of their manufacturing equipment to support the WS; iii) to realize particular MES function (e.g., the function that requires time stamps of specific machine state or manufacturing process), more data points must be defined in WS, e.g., the data points that have been defined in Table 9. To enhance the consistency of data flow in the developed approach and its further application, co-work to define the data points and to promote their application in a broader range is required together with the WS working group.

3.4 R4: Support of a generic specification of the MES

As presented in Publication IV, database tables were selected as the platform of the specification. On one hand, the design of the specification can be presented user-friendly with an entity-relationship diagram. On the other hand, the database refers to a mature technology extensively adapted in the manufacturing enterprises, which is accessible for most software systems, thereby underpinning information exchange in the whole enterprise. To represent the information of the whole MES model without losing any detail, the specification has been designed with four main components according to the metamodel of the extended MES-ML. Figure 4, Figure 5, and Figure 6 present the entity-relationship diagrams (ERD) of the MES specification using Crow’s Foot Notation (from Publication IV & V).

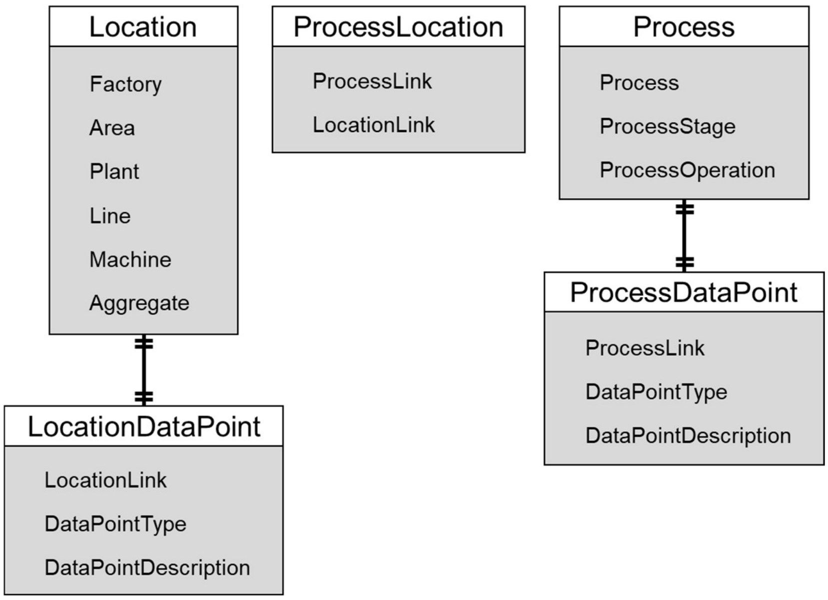


Figure 4: ERD of the MES specification for plant model, process model, and the link between them

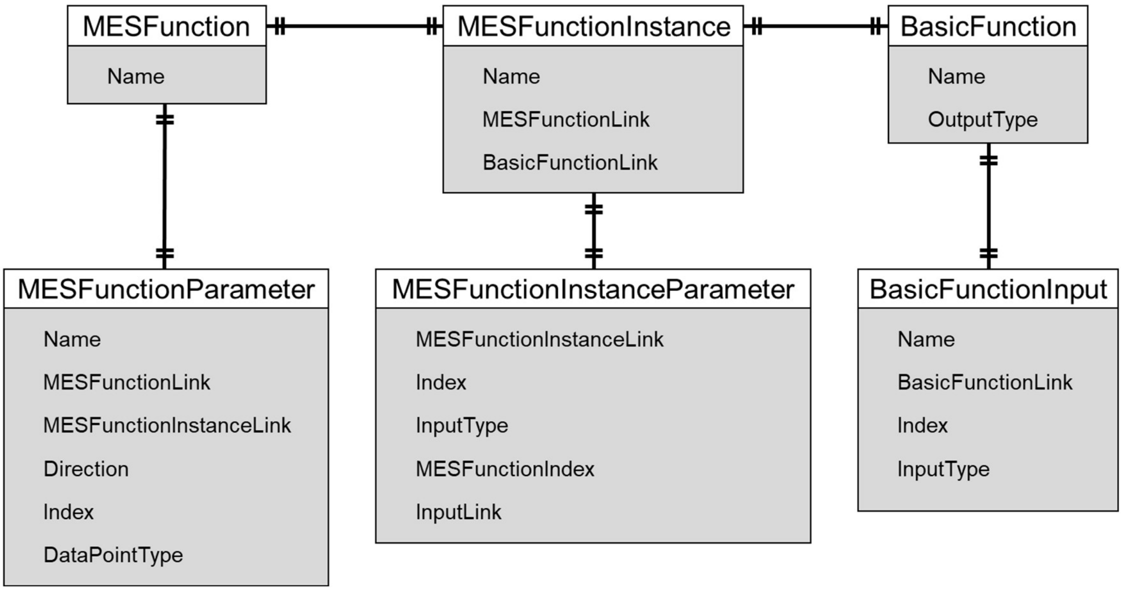


Figure 5: ERD of the MES specification for MES function model

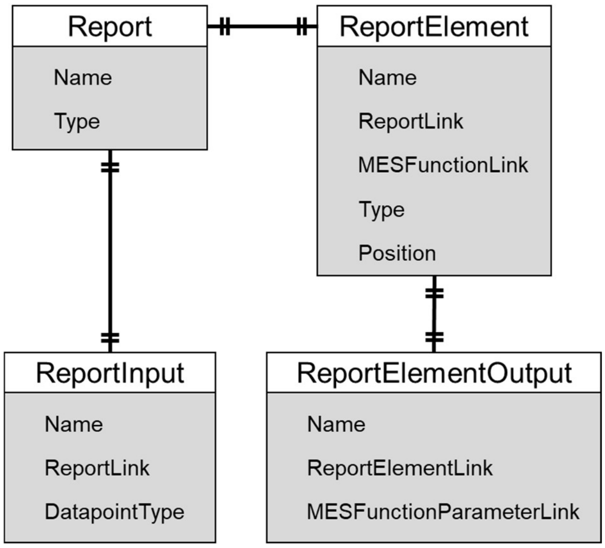


Figure 6: ERD of the MES specification for report model

Based on the use cases in the processing and packaging area in the food and beverage industry (in Publication V), it was confirmed that the design of the specification is generic enough to carry the information of different MES functions, as the MES functions, energy management and performance analysis, have been successfully generated by using the same specification without any further modification. However, the two MES functions in the use cases are functions that analyze historical data, i.e., no real-time data and reaction is necessary, to prove the generality of the specification in a further step, the developed specification and the completed approach should be verified in application scenarios that require both real-time and historical data-based MES functions, e.g., production scheduling and tracking.

3.5 R5: Dynamic generation of the MES

The MES is generated by a programmed generator, which utilizes the information in the specification. The generator consists of two parts, the front-end and the back-end (Figure 7). The front-end is a graphical user interface for the end-user to parameterize the generated MES. The input area and the output area are predetermined elements in the graphical user interface. The parameters in these two areas are dynamically dependent on the report model, which should be modified by the end-users according to their requirements from the business processes. The back-end is composed of two components, a toolbox and a connection finder. The toolbox is a group of finished programmed procedures that realize the functionality of each predefined basic function and can be invoked when the related basic functions are assigned in the specification. The connection finder establishes the inner-connection of each procedure of basic function to ensure the correct value passing and realize the composed MES functions.

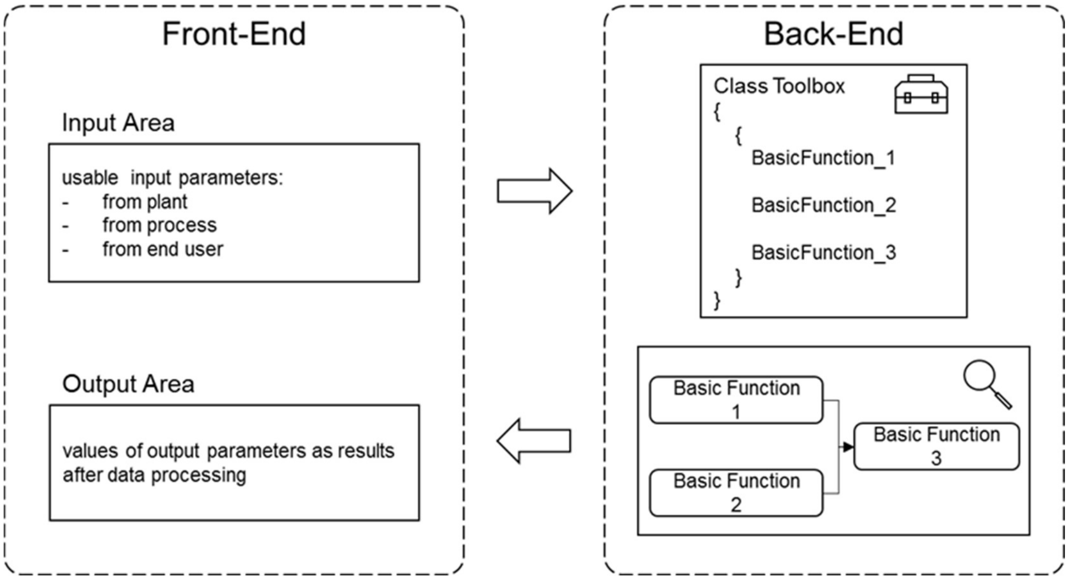


Figure 7: MES generator with the front-end and the back-end

The use case in Publication IV has shown that the MES can be generated correctly in correspondence with the models. Moreover, by employing this model-driven approach in two different use cases, i.e., processing area and packaging area in the food and beverage industry (Publication V), it was proven that the customized MES for different application scenarios can be generated automatically with the same generation method. In this sense, the presented generation method and the model-driven approach can be applied to implement different MES functions and meet various requirements on MES from different domains.

3.6 Final remarks and outlook

This thesis presents a model-driven engineering approach for manufacturing execution systems in the food and beverage industry. It has been developed with six phases, i.e., requirements analyzing phase, MES modeling phase, specifying phase, generating phase, applying phase, and improving phase. To realize this approach, the cornerstones have been established: i) the graphical MES modeling language MES-ML has been extended to be suitable for automatic generation of the MES with four models (plant model, process model, MES function model, and report model); ii) modeling elements have been defined to ensure the reusability of the models and the feasibility of the automatic generation of the final MES; iii) a generic MES specification in form of database tables was defined to represent the information from the graphical model; iv) an MES generator with a front-end (graphical user interface) and a back-end (toolbox as the container for procedures of basic functions and connection finder for the establishment of data flow between basic functions) has been programmed to generate the MES according to the real business process.

Based on the interviews with the manufacturers in the food and beverage industry, two MES functions were considered as the first functions that should be implemented, namely energy management and performance analysis. Although the two MES functions are the first focus of this work, the cornerstones of this approach are designed and constructed generally for its application in various scenarios for different MES functions. By the realization of the automatic generation of the two MES functions, the feasibility of each fundamental element and the whole approach has been proven. Furthermore, as the first practical rudiment to apply the model-driven engineering concept for MES implementation in the food and beverage industry, it has been considered as capable of simplifying MES implementation by minimizing the programming and customizing effort in the engineering process. However, the two MES functions are functions depending on historical data from the manufacturing processes, the functions, which can perform the real-time reaction to the processes, have not been applied with this approach.

In future work, the implementation of the MES with real-time functions in the food and beverage industry using the presented approach should be primarily highlighted to expand the scope of its application field. In such scenarios, more modeling elements should be defined to compose new MES functions, and subsequently, the compatibility of the specification design and the generation method should be verified and validated. Moreover, to enhance the data consistency, the co-work with the Weihenstephaner Standards working group is required, as data points providing information to realize more MES functions should be defined. Furthermore, given a broader analysis of the requirements, it is also planned to apply the model-driven approach to generate MES for other industries. As the MES functions are split into small basic functions in this model-driven approach, which can be considered as a variant of service that provides its own information to others, the development of a service-oriented architecture for the MES and a cloud-based MES can also be a direction of the subsequent studies.

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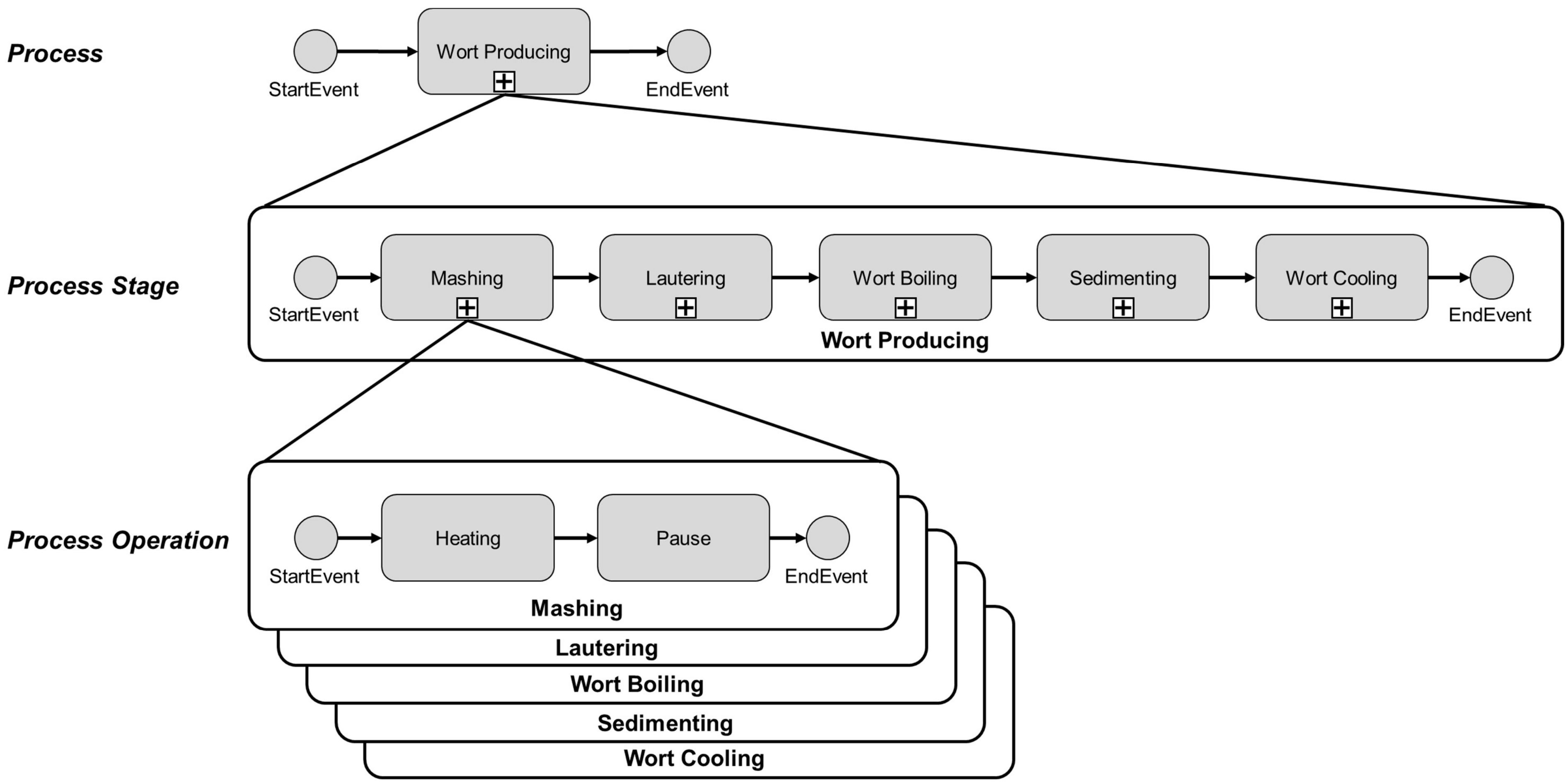
Appendix I – Modeling elements in process model library

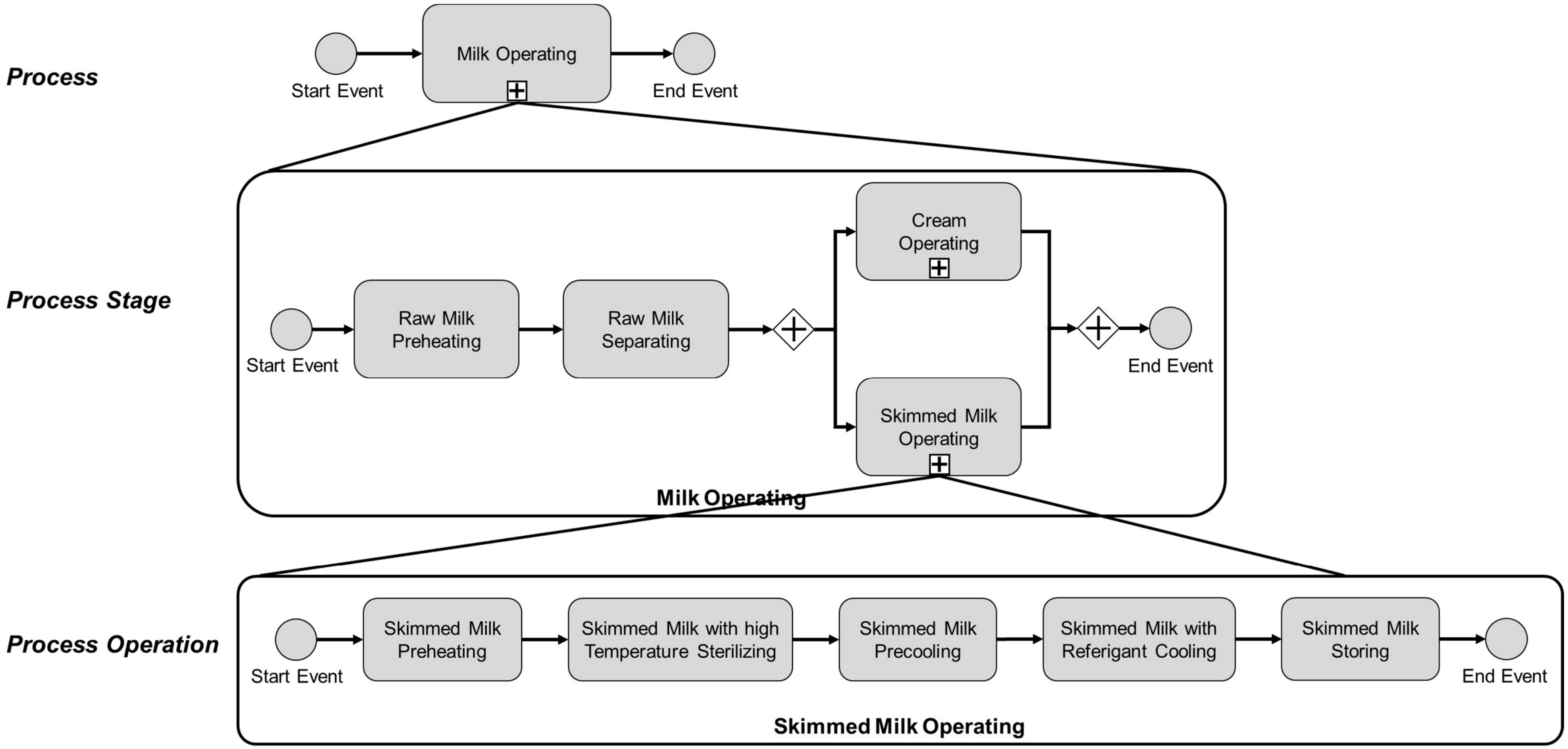
i) Defined modeling elements in process model library for wort producing and its model in extended MES-ML (in Publication III & IV)

Level / Area	Process	Process Stage	Process Operation
Brew House	Wort Producing	Mashing	Heating
			Pause
		Lautering	Lautering
			Stirring
			Pumping Master Brewing Water
			Pumping Sparging Brewing Water
			Removing Sprent Grain
		Wort Boling	Heating
			Recirculating
			Adding Hops
		Sedimenting	Sedimenting Hops
		Wort Cooling	Cooling Wort
			Pumping Cool Wort


Process
StartEvent
Wort Producing
EndEvent
Process Stage
StartEvent
Mashing
Lautering
Wort Boiling
Sedimenting
Wort Cooling
EndEvent
Wort Producing
Process Operation
StartEvent
Heating
Pause
EndEvent
Mashing
Lautering
Wort Boiling
Sedimenting
Wort Cooling

ii) Defined modeling elements in process model library for milk operating and its model in extended MES-ML (in Publication V)

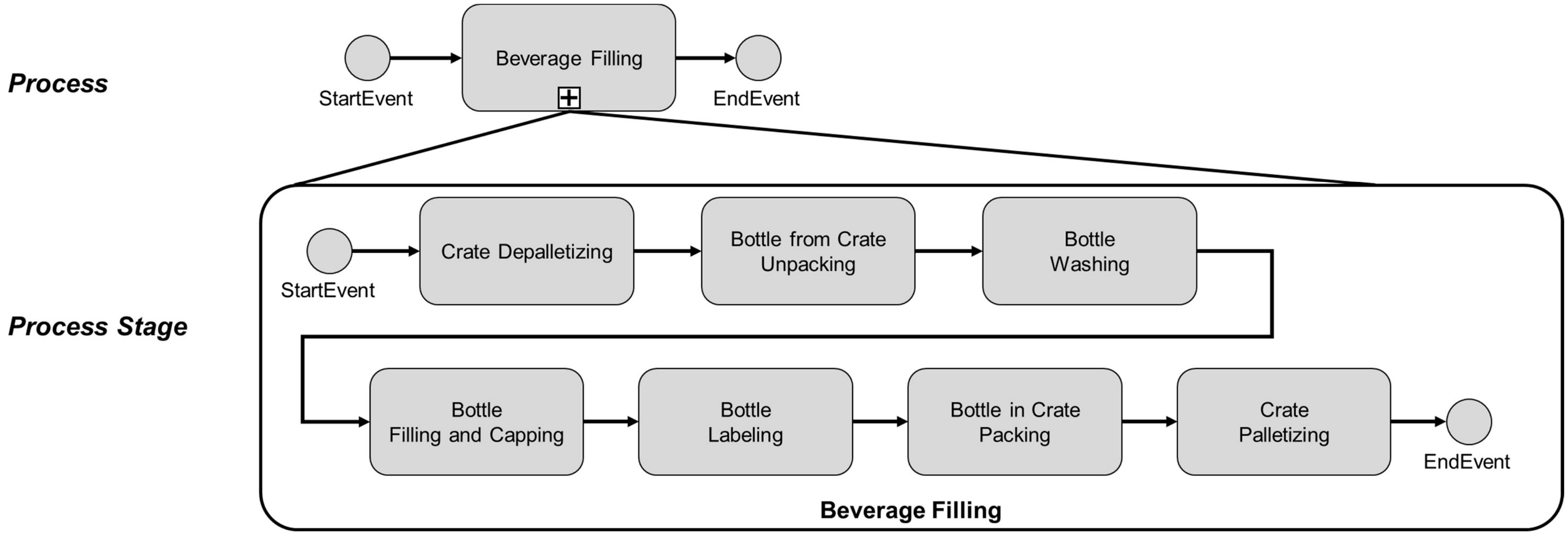
Level / Area	Process	Process Stage	Process Operation
Milk Operating Room	Milk Operating	Raw Milk Preheating	
		Raw Milk Separating	
		Cream Operating	Cream Heating
			Cream Storing
		Skimmed Milk Operating	Skimmed Milk Preheating
			Skimmed Milk with high Temperature Sterilizing
			Skimmed Milk Precooling
			Skimmed Milk with Referigent Cooling



Process
Start Event
Milk Operating
End Event
Process Stage
Start Event
Raw Milk Preheating
Raw Milk Separating
Cream Operating
Skimmed Milk Operating
End Event
Milk Operating
Process Operation
Start Event
Skimmed Milk Preheating
Skimmed Milk with high Temperature Sterilizing
Skimmed Milk Precooling
Skimmed Milk with Referigant Cooling
Skimmed Milk Storing
End Event
Skimmed Milk Operating

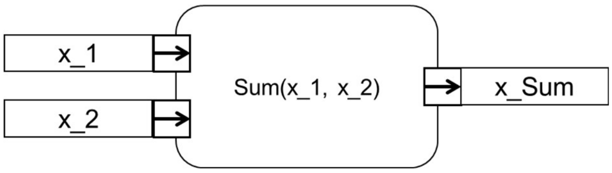
iii) Defined modeling elements in process model library for beverage filling and its model in extended MES-ML (in Publication V)

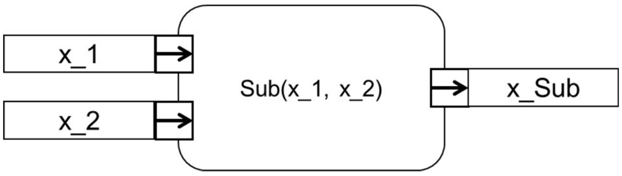
Level / Area	Process	Process Stage	Process Operation
Beverage Filling Room	Beverage Filling	Crate Depalletizing	
		Bottle from Crate Unpacking	
		Bottle Washing	
		Bottle Filling and Capping	
		Bottle Labeling	
		Bottle in Crate Packing	
		Crate Palletizing	
		Crate Washing	

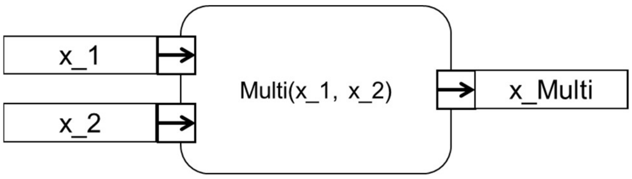

Process
StartEvent
Beverage Filling
EndEvent
Process Stage
StartEvent
Crate Depalletizing
Bottle from Crate Unpacking
Bottle Washing
Bottle Filling and Capping
Bottle Labeling
Bottle in Crate Packing
Crate Palletizing
EndEvent
Beverage Filling

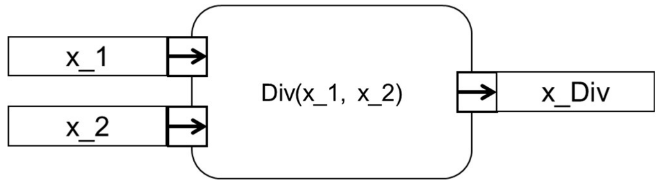
Appendix II – Modeling elements for basic functions in MES function model library

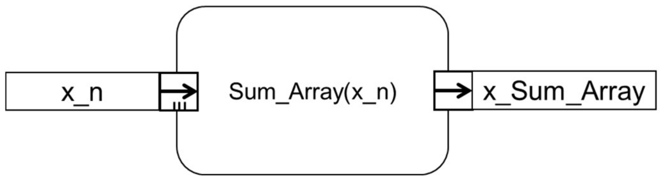
i) Basic functions in the category of mathematical basic functions

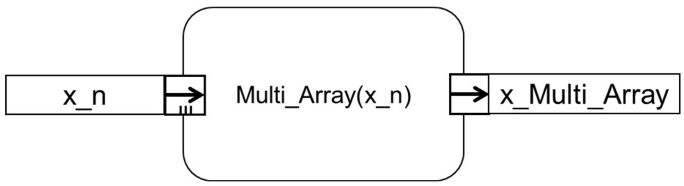
Name	Summation
Formula	x_Sum = x_1 + x_2
Model	
Description	The function calculates the sum of two values, x_1 and x_2.

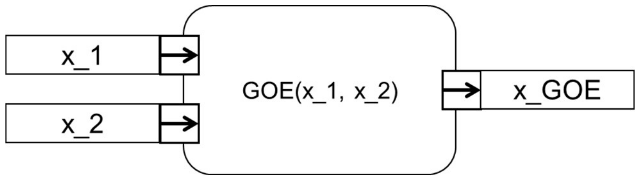
Name	Subtraction
Formula	x_Sub = x_1 - x_2
Model	
Description	The function calculates the difference between two values, x_1 and x_2.

Name	Multiplication
Formula	x_Multi = x_1 × x_2
Model	
Description	The function calculates the multiplication of two values, x_1 and x_2.

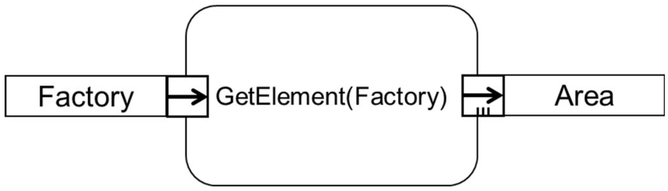
Name	Division
Formula	x_Div = x_1 / x_2
Model	
Description	The function calculates the division of two values, x_1 and x_2.

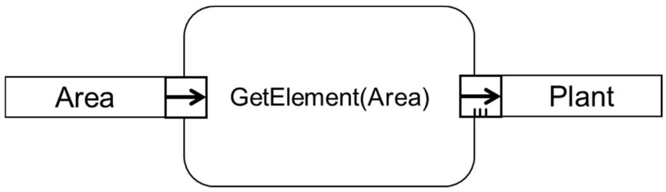
Name	Summation (Array)
Formula	$x\_Sum\_Array=\sum_{i=1}^{n} x_i$
Model	
Description	The function calculates the sum of several values, x_n.

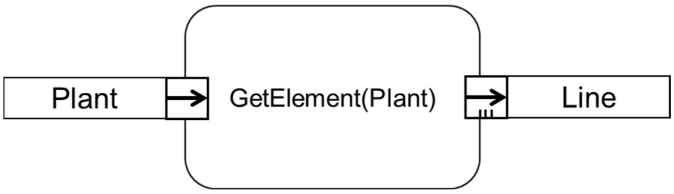
Name	Multiplication (Array)
Formula	$x\_Multi\_Array=\prod_{i=1}^{n} x_i$
Model	
Description	The function calculates the multiplication of several values, x_n.

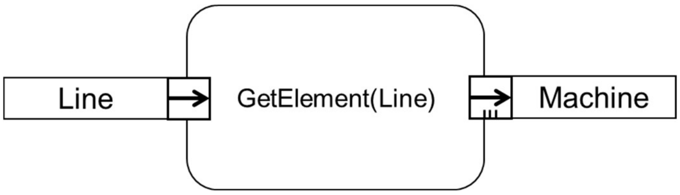
Name	Great Or Equal
Formula	$x\_GOE = \begin{cases} 1, \text{ if } x\_1 \geq x\_2 \\ 0, \text{ if } x\_1 < x\_2 \end{cases}$
Model	
Description	This function compares the two input values, x_1 and x_2, with each other. If x_1 is greater than or equal to x_2, the result of this function x_GOE is 1, otherwise 0.

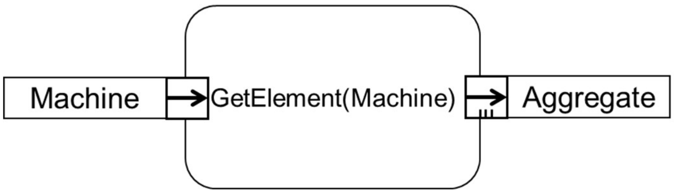
ii) Basic functions in the category of plant data processing

Name	Get Factory Element
Model	
Description	This function returns all areas assigned under the corresponding factory.

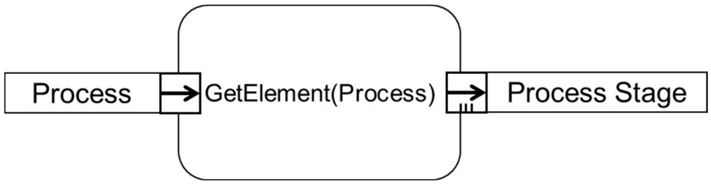
Name	Get Area Element
Model	
Description	This function returns all plants assigned under the corresponding area.

Name	Get Plant Element
Model	
Description	This function returns all lines assigned under the corresponding plant.

Name	Get Line Element
Model	
Description	This function returns all machines assigned under the corresponding line.

Name	Get Machine Element
Model	
Description	This function returns all aggregates assigned under the corresponding machine.

iii) Basic functions in the category of process data processing

Name	Get Process Element
Model	
Description	This function returns all process stages assigned under the corresponding process.

Name	Get Process Stage Element
Model	
Description	This function returns all process operations assigned under the corresponding process stage.

Name	Get Process Information
Model	
Description	This function returns all processes with their start and end times within a given period [StartTime, EndTime] on a specific line.

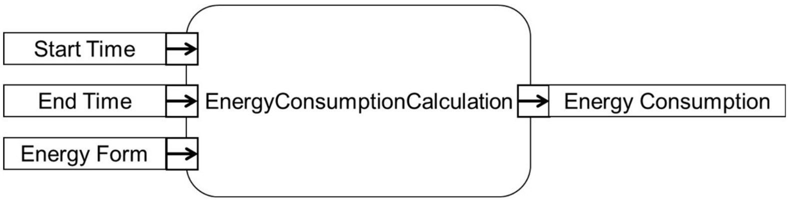
Name	Get Process Stage Information
Model	
Description	This function returns all process stages with their start and end times within a given period [StartTime, EndTime] on a specific machine.

iv) Basic functions in the category of production order and batch data processing

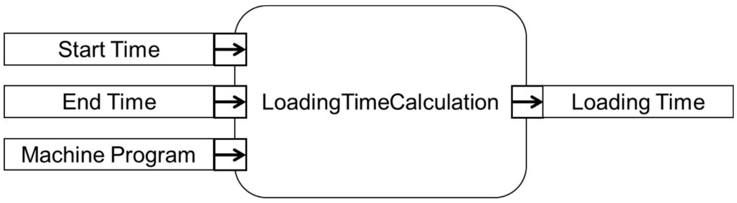
Name	Get Order Information
Model	
Description	This function returns the start time and end time of the period, in which the order was processed, and the plant that was responsible for processing the order.

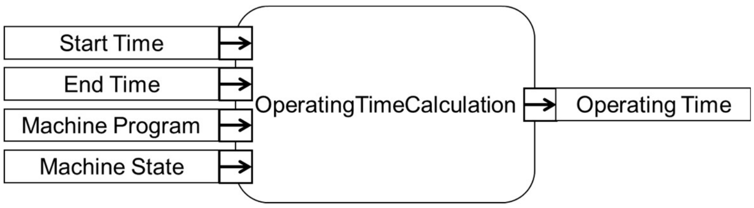
Name	Get Batch Information
Model	
Description	This function returns the start time and end time of the period, in which the batch was processed, and the machine that was responsible for processing the batch. For this basic function, the batch ID is identifiable together with the order ID.

v) Basic functions in the category of energy management

Name	Energy Consumption Calculation
Model	
Description	This function returns the energy consumption (according to the energy form) in the given period [Start Time, End Time].

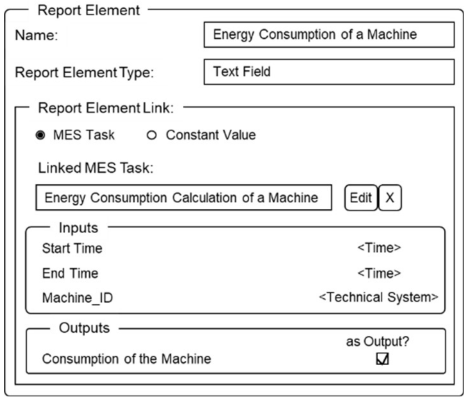
vi) Basic functions in the category of OEE indicator analysis

Name	Loading Time Calculation
Model	
Description	The calculation of the loading time is carried out via the machine program. All the times during which the central unit is in the program “Production”, “Start Up” and “Run Down” must be summed by this function.

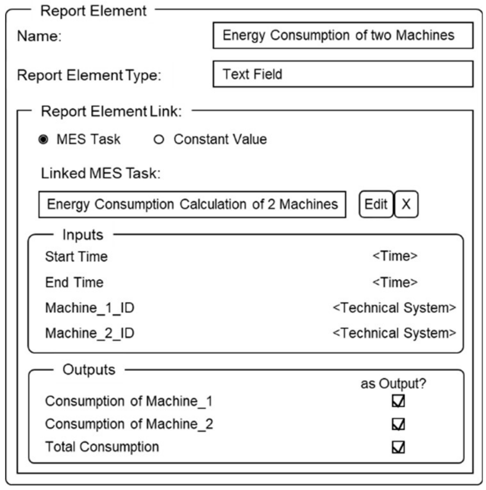
Name	Operating Time Calculation
Model	
Description	The operating time must be determined via the machine program and the machine operating state. For this calculation, all of the periods during which the central unit is in the program “Production”, “Start Up” and “Run Down” and in the operating state “Operating” must be summed by this function.

Appendix III – Modeling elements in report model library

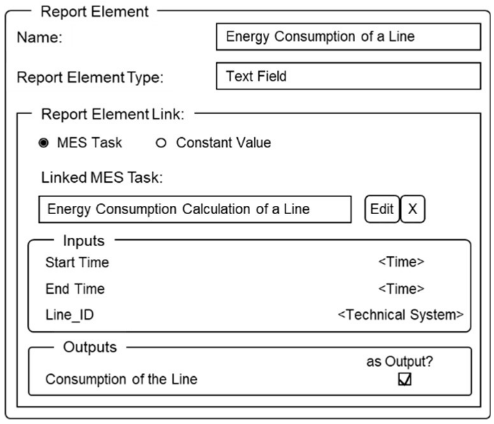
i) Modeling elements in the category of energy report

<table>
<tr><td>Name</td><td>Energy Consumption of a Machine</td></tr>
<tr><td>Model</td><td>


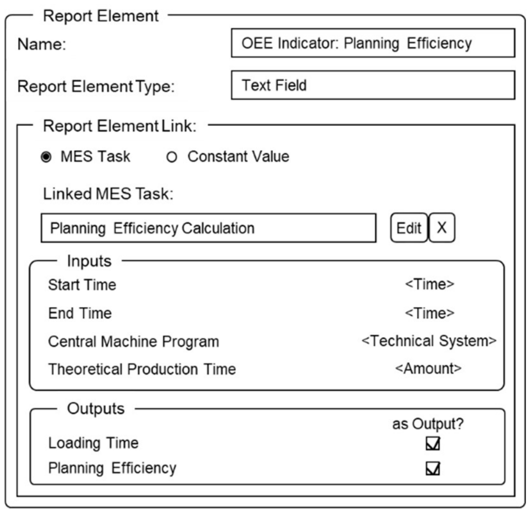
</td></tr>
<tr><td>Description</td><td>This report presents the energy consumption of a definite machine. Its energy consumption can be identified according to the ID of this machine as input parameter of the report. The energy consumption of this machine is chosen as the output in the final report.</td></tr>
</table>

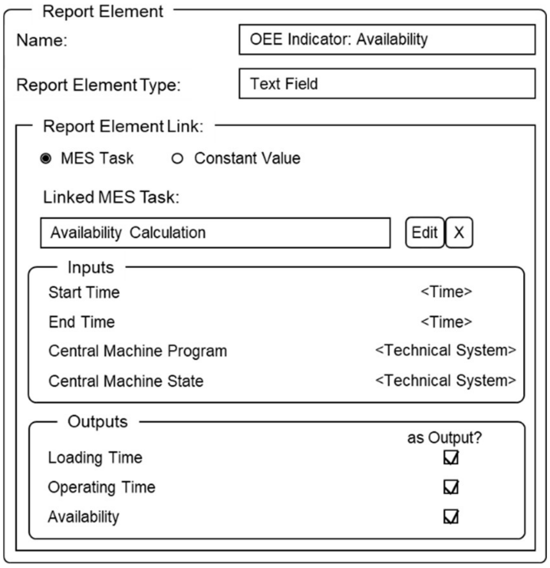
<table>
<tr><td>Name</td><td>Energy Consumption of two Machines</td></tr>
<tr><td>Model</td><td>


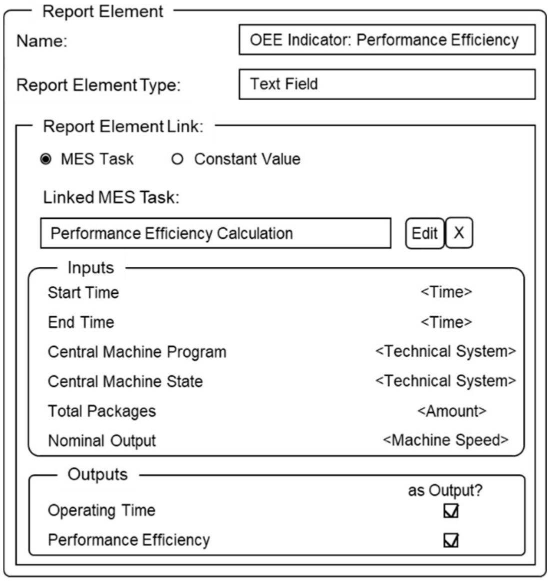
</td></tr>
<tr><td>Description</td><td>This report presents the energy consumption of two machines. Their energy consumption can be identified according to the IDs of the two machines as input parameters of the report. Three output parameters can be chosen as the results to be shown in the report, the energy consumption of the machine No. 1, the energy consumption of the machine No. 2, and the total energy consumption of the two machines.</td></tr>
</table>

Name	Energy Consumption of a Line
Model	
Description	This report presents the energy consumption of a definite line. Its energy consumption can be identified according to the ID of the line as input parameter of the report. The energy consumption of this line is chosen as the output in the final report.

ii) Modeling elements in the category of performance analysis report

Name	OEE Indicator: Planning Efficiency
Model	
Description	This report model presents the performance indicator named planning efficiency in the expanded OEE concept. The calculated loading time and the final planning efficiency are chosen as the outputs in the final report.

<table>
<tr><td>Name</td><td>OEE Indicator: Availability</td></tr>
<tr><td>Model</td><td>
</td></tr>
<tr><td>Description</td><td>This report model presents the performance indicator named availability in the OEE concept. The calculated loading time, operating time, and the final availability are chosen as the outputs in the final report.</td></tr>
</table>

<table>
<tr><td>Name</td><td>OEE Indicator: Performance Efficiency</td></tr>
<tr><td>Model</td><td>
</td></tr>
<tr><td>Description</td><td>This report model presents the performance indicator named performance efficiency in the OEE concept. The calculated operating time and the final performance efficiency are chosen as the outputs in the final report.</td></tr>
</table>