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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.