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Identifying the Role of Manufacturing Execution Systems in the IS Landscape: A Convergence of Multiple Types of Application Functionalities

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Abstract. Manufacturing execution systems (MES) enable the detailed control of manufacturing operations, i.e. they facilitate digital and integrated shop-floor systems as envisioned by Industry 4.0. Yet, many manufacturing organizations struggle to integrate MES and demarcate it from other information systems (IS) in manufacturing. Therefore, this paper explores how MES can be functionally and technologically distinguished from other IS to determine its (future) role in the IS landscape. To provide an answer, this research applies the conceptualization of IS into five application functionalities and underlying enabling technologies. They are referred to as transaction processing, interactive planning, analytics, document management and process monitoring and control systems. We found that MES merges different types of application functionality into one system through its diverse functional requirements, and therefore can be characterized as technologically heterogeneous, in contrast to other 'classical' systems. MES then also takes on a central integrating role in the IS landscape. The findings offer an explanation for the challenges associated with the adoption of MES functionality, and highlight the importance of addressing integration questions in light of Industry 4.0.

Keywords: Industry 4.0 · Manufacturing execution systems · Application functionality · Integration

1 Introduction

Today more than ever companies are forced to optimize production processes and procedures to achieve efficiency and quality while keeping costs down. Also, customer demands put more pressures on companies, and e.g. demand the complete logging of production processes to ensure traceability. Developments such as just-in-time approaches can often be better achieved through detailed planning and the precise control of production. Many of the requirements today can only be met with sound information system (IS) support, i.e. digital and integrated shop-floor systems enabled by the adoption of Industry 4.0 technologies [1, 2]. This includes manufacturing execution systems (MES). MES facilitate the achievement of the integrated factory as envisioned by the computer-integrated manufacturing (CIM) movement and nowadays

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promoted in Industry 4.0 [3, 4]. MES support shop-floor processes, their control and integration by collecting and distributing data related to a diverse set of manufacturing activities [1]. MES are considered to be the middle layer in a multi-layered architecture between the world of real-time process monitoring and control on the manufacturing shop-floor and the world of IS applications in the offices of industrial organizations [5, 6].

Despite their growing popularity in enabling organizations to meet future market requirements, in practice organizations often struggle to integrate MES in their IS landscape [7]. Its implementation seems to be less rewarding than theoretically asserted. One contributing factor includes the ambiguity on the role and necessity of MES, considering the presence of other IS that provide support for similar functions, for example ERP systems, quality systems or maintenance systems [8, 9]. As de Ugarte et al. [8] point out, MES functions are generally difficult to classify and the concept of MES is therefore not easily grasped by manufacturers in practice.

In order to better understand the current ambiguity that organizations are confronted with, we need to conceptualize how MES can be functionally and technologically distinguished. To our knowledge, the precise role of MES and its distinctive technological characteristics of MES compared to other IS are hardly addressed in the literature. This is the goal of this research. We therefore identify five different classes of application functionalities with their corresponding technological characteristics. We then assess MES based on this conceptualization of IS. As opposed to most IS, we found that MES can hardly be classified as one single class of application functionality, and that MES takes on a central role to integrate technologically heterogeneous IS. Our findings then provide some explanation on the challenges of adopting MES and why it is often less straightforward than anticipated.

The paper is organized as follows. Section 2 provides the conceptualization of IS in manufacturing based on the type of application functionality and their enabling technology. This classification is used in Sect. 3 to evaluate generic MES functions in terms of the different dimensions specified in the classification. Based on the findings, Sect. 4 analyzes MES' role in the IS landscape to explain why organizations face challenges with regards to delineating MES from other systems. Section 5 concludes and presents ideas for future research.

2 Classification of Information Systems in Manufacturing

In this paper, we classify IS according to application functionality, i.e. the functionality exhibited by a certain application. In manufacturing we distinguish five main types of application functionalities, viz. Transaction Processing, Interactive Planning, Analytics, Document Management, and Process Monitoring and Control [10–12]. Each type of application functionality is characterized by a specific set of underlying enabling technologies, viz. Software Technology, User-interaction (UI) Technology and Database Technology, but also by the type of user and, if applicable, the time dimension. A summary is presented in Table 1. Each type of application functionality will be described in more detail.

1. **Transaction processing systems:** Systems providing transaction processing functionality form the information backbones of organizations [2]. They support business processes, integrate information flows and provide basic reporting for different types of users such as operations or quality managers [13, 14]. Transactional data is stored in records centrally in relational databases which is shared among departments and systems, usually by standard software packages labeled as enterprise resource planning systems (ERP). In manufacturing, ERP provides modules for e.g. inventory control, quality control, asset management, shop-floor control, tracking and tracing etc. The user interacts with the system through sessions that guide the user through several screens. These systems typically maintain actual states of objects (e.g. the object Work Order has states *planned, released, open, finished, closed*).
2. **Interactive planning systems:** These systems provide interactive planning functionality to planners and production supervisors. They support decision-making by relating possible proposed decisions to performance measures. They employ mathematical algorithms to develop plans that provide near optimal solutions, addressing all supply chain constraints [15]. Through in-memory computing, advanced planning systems support users through interactive planning addressing varying time horizons. These systems usually take a snapshot of objects' states from transactional systems before they start their calculations.
3. **Analytical systems:** Through analytic functionality, organizations can further cut the time to access and analyze data by collecting information on objects of the same type over a predefined period of time in a data warehouse. For example, analytical systems produce management reports for strategic and tactical decisions for analysts or managers. Based on online analytical processing technology (OLAP), they extract, transform and load (ETL) data from varying sources to produce aggregated reports but also graphical presentations to users via customized visual user interfaces [2]. Increasingly, data volumes continue to grow and innovative advanced techniques are further enhancing analytical application (e.g. big data, artificial intelligence).
4. **Document Management systems:** In the office environment of manufacturing engineers, document management functionality is required, usually provided by product data management systems (PDM). These systems manage and integrate product engineering data that originates from working with computer-aided-engineering (CAE) systems. Engineering data is often very complex and includes texts, drawings, documents or product structures that require an object-oriented database. The work flow is procedural, deals with one item at a time and creates complex data structures [16].
5. **Process monitoring and control systems:** These systems are deployed on the shop-floor to monitor and control different production parameters and variables in real-time. The data is used to measure the behavior of certain variables (e.g. pressure) to conduct real-time manipulation of selected production variables through actuators, if necessary. These systems are mostly hardware related, e.g. sensors or programmable logic controller (PLC), but also include software such as supervisory control and data acquisition (SCADA) systems [17]. Data is mainly stored in log files.

Table 1. Classification of different application functionalities in manufacturing

Application functionality	System user	Software technology	Database technology	User interaction technology	Time dimension
Transaction processing	Different types of functional end-users	Client-server (2 or 3 tier) 4GL	Relational database; Records	Sessions	Past and present
Interactive planning	Planner, supervisor	Advanced planning (APS)	In-memory database	Interactive planning work	Varying: present and future
Analytics	Analyst, manager	OLAP	Data warehousing	Graphical representations	Past (and future)
Document management	Engineer	Many CAE: Unix/Computer-aided engineering	Object-oriented-database; Files	Computer-aided engineering work	N.A.
Process monitoring and control	Operator	Real-time operating system, SCADA	Real-time databases/log files	Control rooms with many screens	Real-time (seconds) and future

3 Assessing the Role of MES and Its Functions

In Table 2, we provide an overview and definition of the specific MES functions as defined in the ISA95 standard [18]. To assess the role and boundaries of MES, we analyzed these MES functions in terms of the type of application functionality required in the fulfilment of that function (i.e. transaction processing, interactive planning, analytics, document management and process monitoring and control).

Table 2. MES functions related to types of generic application functionality

Resource allocation and status: Guiding what people, machines, tools and materials should, do, and track what they are doing. Application functionality: Tracking what resources do so is mainly *transaction processing*, but it is also increasingly necessary to track and control resources in real-time e.g. through IoT (*process control functionality);* guiding what resources should do is *interactive planning functionality.*
Operations/Detailed scheduling: Sequencing and timing of activities for optimized plant performance based on finite capacities. Application functionality: When scheduling the shop floor operations, the planner needs both in-memory (*interactive planning) functionality* and *transactional functionality*. The transactional functionality is needed for updating plans after decisions are made.
Quality Management: Recording, tracking and analyzing product and process characteristics against engineering ideals. Application functionality: *process control* (SPC) to e.g. calibrate machines or update control parameters; *transaction processing* to track product characteristics e.g. inspections; *analytics* to determine quality causes (event processing), analytical work is followed by updating, e.g. sample sizes in SPC or instructions in PDM.
Dispatching production units: Giving the command to send materials or orders to certain parts of the plant Application functionality: Mainly *transaction processing*, might also involve *interactive planning* when dispatching sequence involves some scheduling functionality on the shop-floor.
Product tracking and genealogy: Monitoring the progress of units, batches or lots of output to create a full history of products Application functionality: Both *transaction processing* paired with *document management* functionality, e.g. when creating a digital twin for a physical product.
Performance analysis: Comparing measured results in the plant with goals and metrics set by the corporation, customers etc. Application functionality: Mainly *analytics* functionality to compare and visualize performances. Output is used by managers and staff often on a weekly or monthly basis; hence data often addresses a longer time horizon (weeks to months).
Labor Management: Tracking and directing the use of personnel during a shift based on qualifications, work patters and business needs. Application functionality: Mainly *transaction processing* e.g. tracking employees working-time, man-hours available in a department etc. Increasingly, IoT technologies might enter the shop-floor in the form of trackers and sensors, which can have significant effects on employees *(process control).*
Maintenance Management: Planning and executing appropriate activities to keep equipment and other assets in the plant performing to goal. Application functionality: Mainly *transaction processing*, but also *document management* (e.g. providing instructions, and rendering via augmented reality); *analytics* to analyze machine status and performances.
Process Management: Directing the flow of work in the plant based on planned and actual production activities.

Application functionality: *Transaction processing* paired with *interactive planning*; *analytics* to compare planned and actuals (visualize processes); *process control* has to go together with some transaction processing, e.g. when a machine is operated, the runtime will be logged and posted to a maintenance application and so on.
Data collection/acquisition: Monitoring, gathering and organizing data about the processes, materials and operations from people, machine or controls. Application functionality: *Mainly process control*, for example tracking the status of a machine, thereby the run-tine will be logged and posted to a maintenance application. Transforming data into *transaction*s is necessary.
Document control: Managing and distributing information on products, processes, designs or orders, as well as gathering certification statements of work. Application functionality: *Document control* functionality: product design, machine programs and instructions are distributed to shop-floor resources from PDM system; in turn feedback can be collected in the form of photos or texts.

4 The Interfaced Functionality of MES

Based on the previous analysis, we found that MES and its functions cannot be classified as a single type of application functionality based on homogeneous technologies as traditionally seen in manufacturing. Rather, multiple types of application functionalities converge in MES, which we refer to as 'interfaced functionality' (Fig. 1).

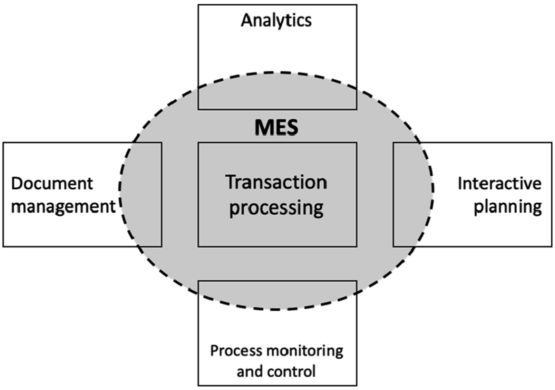

Fig. 1. Interfaced functionality of MES

Thus, there is no core application functionality and no single enabling technology of MES. MES takes on a central role integrating technologically heterogeneous systems, each with their own data model, user communication mechanisms and even its own database.

Specifically, we found that transaction processing is an essential requirement across almost all MES functions, but it is generally expanded with other types of application functionality, e.g. analytics or process control. Moreover, we identified two MES functions which could clearly be identified as requiring one single type of application functionality, namely document control and performance analysis. Going further than earlier research, which states that it is difficult to demarcate MES from other IS [8], this research explains the underlying reasons by means of an analysis into the technical and functional characteristics of IS.

The findings provide an explanation for the challenges that organizations face when implementing MES in their IS landscape. In the sphere of MES, different heterogeneous technologies converge resulting in high integration requirements accompanying typical integration problems. As previous research pointed out (e.g. [11]), even though technically possible, integrations are not trivial. Integrations are often costly, can block the upgrading of software, and can consequently make organizations less flexible and less future-proof. Organizations might also struggle with defining a suitable business case for MES, as direct returns on investment resulting from this integration might not be clearly depictable. Implementation, integration and maintenance of MES are usually expensive and hard to estimate upfront. This could explain why some organizations choose to expand their existing IS with MES functionality as opposed to implementing a separate MES. Alternatively, emerging technologies such as portals might also provide a solution to overcome these challenges.

Due to MES' central position in the multi-layered architecture, it magnifies the many issues organizations currently face with regards to integrating their IS and processes in their quest to achieve the vision of Industry 4.0, namely a fully integrated factory.

5 Conclusion

In this paper, MES and its role in the IS landscape has been analyzed from a functional and technological perspective to better understand why organizations face challenges integrating MES in their IS landscape. We conceptually distinguished five application functionalities that IS can traditionally be classified as, based on their enabling technology, their system user and if applicable, their time dimension. Assessing MES based on this classification showed that:

- MES provides different types of core application functionalities (transaction processing, interactive planning, analytics, document management and monitoring and process control) in contrast to traditional IS which usually comprise one application functionality.
- As MES is not based on one single type of technology it is technologically heterogeneous: it merges technologies from different application fields into one system.
- MES takes on a central integrating role between technologically heterogeneous information systems, therefore its integration requirements must be well addressed. This is one contributing factor why organizations struggle with the adoption of MES, e.g. costs, flexibility.

This research is currently mostly conceptual and future research should empirically validate and corroborate these findings. As MES incorporates several application functionalities and enabling technologies, it would be interesting to further study integration problems. Integration is a central aspect of Industry 4.0 and will supposedly intensify in the future. Integration between heterogeneous technologies (e.g. creating automated transaction from real-time data originating from process control technologies) can be challenging and complex due to e.g. different semantics, syntax or data types. The future integration requirements of MES and other systems that are technologically heterogeneous therefore must be well addressed, as well as its implications for e.g. flexibility or scalability.

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