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ABSTRACT

Being confronted with IT strategic questions of how to constantly reduce IT operating costs and at the same time live up to ever increasing manufacturing demands, automobile manufacturers are encountering problems to find appropriate IT support for production planning and execution. Moreover, they are facing the challenge to clearly define and demarcate Enterprise Resource Planning (ERP) and Manufacturing Execution Systems (MES) functionality. Despite the existence of a number of standardization efforts addressing MES functionality, automobile manufacturers are still struggling to reach a common understanding for the term MES and a clear functional design. The paper addresses this need by developing a functional reference model for MES in the automotive industry based on a multiple case study approach. The case studies examine the design and implementation of manufacturing-related functionality in four leading automotive manufacturing companies.

Keywords

Manufacturing Execution System, Functional Reference Model, Automotive Industry

1. INTRODUCTION

1.1 Motivation and Problem Statement

Being confronted with IT strategic questions of how to constantly reduce IT operating costs and at the same time live up to ever increasing manufacturing demands (such as decreasing model life cycles or short-term change requests), automobile manufacturers are struggling to find appropriate IT support for production planning and execution [26, p. 21]. In addition, these companies need to replace proprietary systems that have reached their end-of-life and are not capable of fulfilling future manufacturing requirements.

Beyond these IT strategic challenges, one major difficulty results from different levels of detail and accuracy regarding production status information needed on different company levels. The problem is even more challenging in industries which are characterized by numerous, strongly diverging manufacturing processes and highly versatile products. This is the case in the automotive industry, typically involving batch production in press plants, highly automated production lines for car body construction, and assembly with its typical requirements on load balancing and documentation. What such manufacturing companies need is an integrated, consistent view along their entire value chain, allowing for optimal utilization of capacities by having access to real-time information on manufacturing process, quality target achievement, rework costs etc. [17]. Enterprise Resource Planning (ERP) systems have proven to be not capable of meeting this requirement, as they provide only a coarse granular perspective on company-wide business processes [18, p. 24-3]. Therefore, a new category of information systems, called Manufacturing Execution Systems (MES), has emerged, promising consistent collection and processing of data on current machine and production statuses and related business process standardization. While parallel operation of ERP systems and MES seems reasonable, a major challenge today is a clear demarcation of the ERP and MES layer [24, p. 272]. Application systems on both layers partly provide support for similar functions (e.g. Quality Management, Gross Planning, Inventory Management) leading to a high degree of interconnection but also redundancy between the systems. On one hand, this leads to difficulties integrating these systems as well as to increased IT costs [1, p. 10]. On the other hand, it hinders the ambition of automobile manufacturers to standardize not only on the ERP, but also on the MES layer whilst at the same time preserve flexibility in manufacturing execution.

1.2 Research Question and Structure of the Paper

Although a number of cross-industry MES standards exists, automobile manufacturers are still struggling to answer the question which functionality should be covered by MES and which can be supported by e.g. ERP. This research question can be operationalized as follows:

- What is actually meant by the term "Manufacturing Execution Systems"? What functional scope should MES cover?
- How can different planning and controlling functions as well as processes be assigned to and covered by ERP systems and MES?

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The paper at hand addresses these questions by developing a functional reference model for MES in the automotive industry based on a multiple case study approach. The case studies examine the specification and assignment of manufacturing-related functionality for four leading automobile manufacturers and derive best practices for the design of the reference model. Thereby, the reference model contributes to the goal of standardizing manufacturing-related application functions.

The remainder of the paper is structured as follows: Chapter 2 provides background information on the automotive industry as well as on MES and defines fundamental terms of this paper. Thereafter, in chapter 3 we present our research methodology including the Design Science Research (DSR) process that lead to the functional reference model. Chapter 4 presents the functional reference model for integrated manufacturing. The chapter is divided into two parts: While chapters 4.1 and 4.2 describe the reference model after the two iterations of the DSR process, how it was derived and applied within the case studies, chapter 4.3 discusses configuration parameters for future application. The case studies themselves are not elaborated in detail due to space limitations (see [29] for further information). The presented functional reference model is then subjected to evaluation in chapter 5 based on established criteria for reference model evaluation. Chapter 6 concludes the paper with a brief summary of the study findings and gives an outlook on future research challenges.

2. BACKGROUND

2.1 Requirements in the Automotive Industry

The study focuses on the automotive industry. Accordingly, the topic is investigated and analyzed against the background of characteristics specific to the automotive industry. Automobile manufacturing is characterized by short delivery times, decreasing model life cycles, versatile production (i.e. numerous product variants), and short-term change requests. For the manufacturers this means that they need up-to-date status information on the production process in order to be able to react at short notice.

As already suggested in the motivation section, the automotive industry is characterized by numerous, strongly diverging manufacturing processes: batch production in press plants, highly automated production lines for car body construction, and assembly with its typical requirements on load balancing and documentation. Particularly, adequate support of different production process types (batch production for simple components, flow production in assembly, and a mixture of both in the manufacturing of complex components, such as engines) constitutes a crucial challenge for automobile manufacturers. This heterogeneity of manufacturing processes is directly reflected on the application level leading to numerous isolated applications and, thus, to difficulties ensuring both horizontal integration along the production process and vertical integration across the different layers [25, 26].

With current proprietary systems for production planning and control reaching their end-of-life automobile manufacturers aim at replacing them. However, new applications have to fulfil two conflicting requirements: on the one hand, they need to live up to the aforementioned manufacturing requirements necessitating comprehensive and flexible IT support, on the other hand, they should provide maximum standardization in order to conform with the need of reducing IT operating costs.

2.2 Demarcation between MES and ERP

MES are a relatively new class of information systems designed particularly to support shop floor processes and their integration into the company's information system architecture [18, p. 24-3]. MES constitute the "interface" between the planning (ERP) layer and the production layer. They are an essential component for vertical integration, as illustrated in Figure 1.

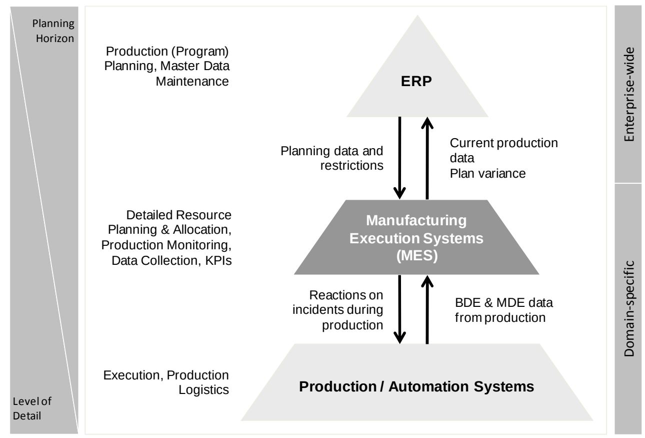

Figure 1: MES – Connecting ERP and the Shop Floor (based on [1, p. 11, 18, p. 24-6])

In contrast to ERP systems, which generally provide a very broad functionality covering all business functions of an enterprise along its operational supply chain, MES aim at enabling companies to quickly respond to events occurring in the production process. MES take a microscopic, more granular view on production data (often restricted to a single plant or production area), compared to the macroscopic, holistic view of ERP systems, and therefore are intended to compensate one of the main shortcomings of ERP system production modules: the incapability of providing integration of real-time manufacturing data generated on the shop floor [24, p. 272, 35, p. 139]. This incapability basically results from an inadequacy of ERP production plans to respond to changing demands or deviations in the manufacturing process. Neither are these systems capable of handling the enormous amount of data coming from the shop floor, nor do they provide short response times and sufficient levels of detail [18, p. 24-3].

As MES in the past have not been subject of extensive scientific research (some exceptions being the recent works of Kletti [16], Sauer [25] and Schäfer et al. [27]), a well-established definition of the term has not been given so far. However, there are leading standardization organizations in the domain of manufacturing integration, most notably the Industry, Systems, and Automation Society (ISA) and the Manufacturing Execution Solutions Association (MESA), that have put some effort into finding a common definition and specifying generic MES functionality. So MES are defined as "systems that deliver information enabling the optimization of production activities from order launch to finished goods. Using current and accurate real-time data, MES guide, respond to, and report 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 operation and processes." [20, p. 1]. This definition implies the following characteristics of MES:

- high level of detail (data acquisition from manufacturing processes),

- relatively short planning horizon (reactive planning),
- bi-directional communication to both ERP systems and shop floor systems (interfacing).

3. RESEARCH METHODOLOGY

3.1 Reference Models

Reference Models are characterized by three attributes [11]: Universal applicability denotes the possibility to deploy a reference model in more than one specific organization. This, in turn, fosters reusability meaning that generic conceptual patterns can be used repeatedly by simply applying pre-defined adaptation mechanisms reducing the effort for redevelopment. Finally, reference models contain best practices providing recommendations for conducting business.

Reference models can be classified according to the target groups as well as the intended usage [31, p. 71]. Becker and Schütte suggest, amongst others, a classification [6, p. 77] based on the Architecture of Integrated Information Systems (ARIS) which distinguishes five different views (function view, organization view, data view, output view and control view) and three different levels (requirements definition, design specification and implementation description) for analyzing and designing information systems (cf. [28]). The reference model presented in this paper defines requirements derived from the manufacturing processes (requirements definition level) that are to be supported by application functions (functional view). Thus, the functional reference model provides an overview on and specifies application functions for manufacturing processes on a conceptual level abstracting from implementation details.

Basically, reference models can be derived either by generalizing findings from a number of investigated cases or by adapting an existing reference model to particular requirements [5, p. 49]. In this paper, we pursue a combined approach: The initial reference model consisted of a number of functional blocks that were derived from a qualitative literature review (cf. [19]) of MES related scientific publications and specifications of major MES standardization bodies. The MES standards provide a functional reference for application across companies and industries. It lacks, however, consideration of automotive-specific requirements and, consequently, prevents OEMs from applying these standards. Or as one of the Senior Managers for IT and processes in component manufacturing at Volkswagen (VW) put it: "When you study the specification of existing MES standards, you notice that they are deeply rooted in the chemical industry." This lack motivates our research of defining a functional MES reference model specific to the needs of the automotive industry.

Based on the literature review as well as initial interviews with Solution Managers for Production IT and MES from HP and SAP, we derived our initial functional reference model for the automotive industry (see section 4.1). Furthermore, we designed a questionnaire that consisted of both open and closed questions and served as a guideline for the data collection workshops. While the main focus of the questionnaire was on analysis of the automotive manufacturers' functional architecture by mapping the application's functional structure of each Original Equipment Manufacturer (OEM) to the initial reference model, questions on four further MES-related subject areas were included, namely strategic MES goals, organizational embedding of MES within the company, application landscape and performance measuring.

With the goal of providing an intuitive graphical representation of the functional reference model – the so-called MES function map (see for example Figures 3 and 4) – we followed existing approaches that are used to create and visualize process maps (cf. [13]).

3.2 Design Science Research Process

The research approach pursued for deriving the functional reference model for MES in the automotive industry follows the guidelines of DSR (cf. [14]). Consequently, the design process is based on the principles of the DSR Methodology [23, p. 54], postulating a sequential design process comprising multiple iterations of design and evaluation cycles. The design process of the functional reference model for integrated manufacturing in automotive with its two iterations is visualized in Figure 2. As described in the previous chapter, the functional reference model of this paper was developed in two iterations. In a first step, it was grounded in the current scientific and practical literature (including MES standards) representing the theoretical knowledge base. The second design cycle comprises the practical knowledge base as it incorporates the findings from the case studies.

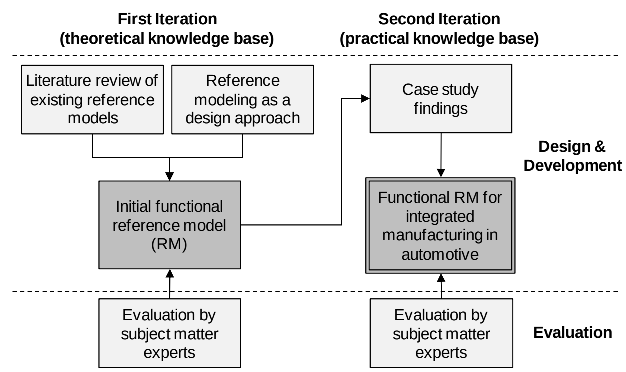

Figure 2: Design process of the functional reference model for integrated manufacturing

Basically, case study research can pursue two different goals: firstly, case studies can examine, describe and explain phenomena in a given (business) context in an explorative manner, secondly, case studies allow to test and develop new theories [9, p. 533, 30, pp. 11-12]. As our study aims at the former, the case studies can be defined as explorative (cf. [32, 36]) describing and investigating a complex research area [21, p. 21] and trying to identify and explain interdependencies or cause effect relations [36, p. 15]. The study design is characterized by multi-case studies as a total of four different OEMs are examined with regard to the same topic, MES [36, pp. 38ff.]. This leads to increased generalizability of findings, compared to single case studies [7, p. 58].

The workshops were carried out as semi-structured on-site focus group interviews [8, pp. 153-159] with varying numbers of participants from both IT and manufacturing departments in order to gather the necessary information. Additionally, we analyzed documents provided by the workshop participants which complemented the information gathered during the interviews. The workshop participants are listed with their roles and affiliations in Table 1 (see following page).

Table 1: Characterization of OEMs and workshop participants

Name	Unit of analysis	Roles and affiliations of workshop participants	Number of participants	Workshop date and duration
Audi	Assembly and component manufacturing plants	• Head of "Process and System Integration" (corporate IT) • Senior IT managers from Audi Hungaria Motor (plant IT)	5	April 29, 2009 – one-day June 3, 2009 – half-day
BMW	Mainly component manufacturing plants	• Heads of Centers of Competence for MES / shop floor systems (corporate IT) • Plant managers	9	May 19, 2009 – one-day
Daimler	Assembly and powertrain manufacturing plants	• Heads of Centers of Competence for MES (corporate IT) • Senior IT Managers for assembly / component manufacturing (corporate IT)	4	June 5, 2009 – one-day
VW	Component manufacturing plants	• Senior Managers for IT and processes in component manufacturing (corporate IT)	3	April 28, 2009 – half-day May 20, 2009 – one-day

The duration of the workshops varied among the OEMs (see Table 1). The researchers analyzed the data gathered during the interviews for each OEM before consolidating the results in a cross-company comparison. After each analysis run, the results were conjointly discussed with the workshop participants in order to guarantee correctness of the analysis.

Validity of the derived model as a reference was further enhanced by carrying out structured interviews with subject matter experts having substantial experience with MES projects in the automotive industry. Two interviews were conducted with the Director of Industry Solutions of SAP Deutschland AG and three interviews with a Solution Manager for Production IT and MES from HP.

3.3 Case Study Overview

The case studies involved the four automotive manufacturers Audi, BMW, Daimler and VW. The case study at Audi did not focus on a single plant, but instead covered both vehicle and component manufacturing at the manufacturing plants in Ingolstadt, Neckarsulm and Audi Hungaria Motors Kft. (AHM) in Györ, Hungary. Within the AudiGroup, AHM takes a unique role, as here both high-volume engine manufacturing and vehicle assembly represent core business processes. Partly, these diverging processes require specific IT solutions on the ERP layer as well as on the MES layer.

At BMW it was jointly agreed to do a comprehensive, cross-plant analysis in contrast to the original intension of focusing on one single plant only. This allowed us to obtain a more comprehensive view on the issue of MES within BMW and to identify and discuss differences between different plants of the company. Similarly, at Daimler we conducted a cross-division analysis with the goal of identifying standardization potentials and synergies between different plants and manufacturing process. The case study covers three different divisions of production within Daimler, namely manufacturing of complex components (engines, gears) for automobiles (so-called Powertrain), assembly of automobiles, and van production. The case study at VW focused on the component manufacturing plants of the company. Components in this case cover the whole spectrum and include simple components, such as pressed or foundry parts, as well as complex components, such as gears or engines.

4. REFERENCE MODEL DESIGN

4.1 First Design Cycle

In a first step we carried out an in-depth review of established MES standards, such as ISA S95 [15] and MESA [20]. As MES standards specific to the automotive industry do not yet exist, we were obliged to draw on these cross-industry specifications accepting the trade-off that these standards try to cover the whole breadth of production requirements of the discrete as well as the process industry at the expense of considering industry specifics. Additionally, we analyzed MES related white papers of regional standardization bodies, namely the National Institute of Standards (NIST, [2]) in the USA as well as the directive 5600 of the VDI [33] and a guideline published by NAMUR [22] in Germany. Again, utilization of standards such as NAMUR that is tailored to the specific needs of the chemical industry results from the lack of MES standards for the automotive industry. Although requirements on MES functions differ significantly between different industries, we used the aforementioned specifications to document the whole spectrum of possible MES functions and establish a uniform terminological basis for our reference model.

From the specifications of the presented standardization organizations we derived a synthesis of relevant MES functions (see Table 2 on the following page). Within its S95 standard, ISA specifies four core functionality categories of MES (Production Management, Inventory Management, Quality Management and Maintenance Operations Management). Each of the four categories is further subdivided into eight function groups [15] and can serve as a basis to define the functional scope of the MES layer. However, the ISA standard focuses more on interfaces and the vertical integration between the ERP, MES and shop floor layer. As it does not provide concrete functional definitions, we do not include it in our synthesis of MES functions.

Considering its experience in MES as well as its cross-industry composition MESA represents the most comprehensive standard with a very detailed specification of twelve MES functions. The wide support that MESA has gained by both industrial enterprises and software vendors in the past, suggests good quality of the specification. The VDI guideline 5600, in turn, has experienced wide acceptance in Germany-based companies. Analysis of the guideline shows, that the specification of the eight MES functions varies significantly concerning its degree of detail. While

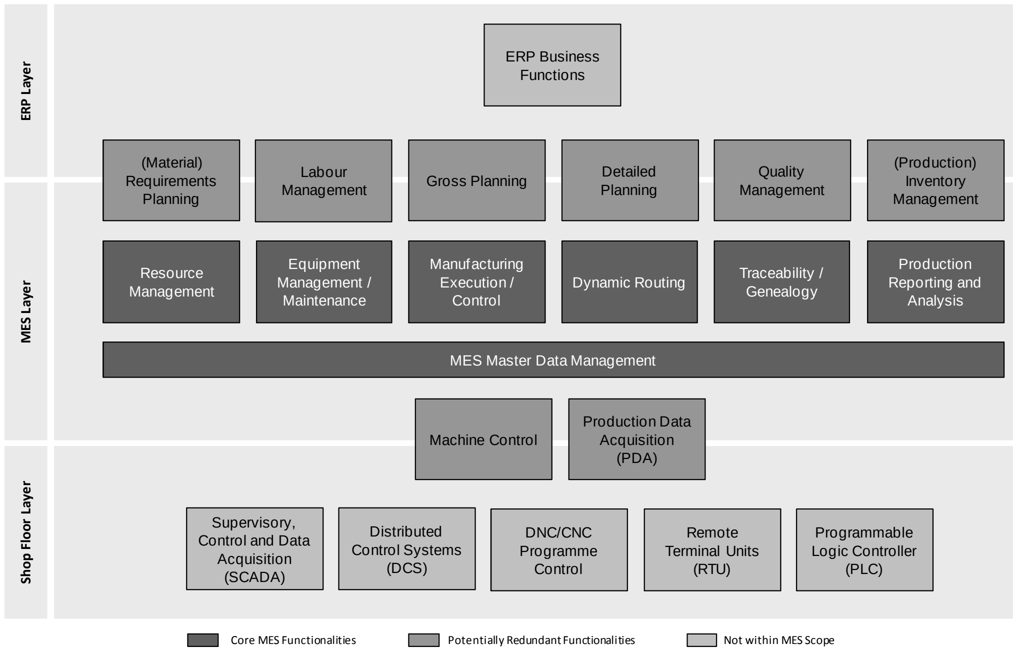

Figure 3: Initial functional reference model (after first iteration)

functions such as Detailed Planning and Resource Management are elaborated in great detail, Quality Management and Production Reporting and Analysis are specified rather superficially or incompletely (e.g. the backtracking of parts is only described on the level of lots but not for single parts which is insufficient for the requirements of the automotive industry).

Table 2: MES functions specified by different standards

	MESA [20]	NAMUR [22]	VDI [33]	NIST [2]
Labour Management	X		X	
Requirements Planning		X		
Gross Planning		X		
Detailed Planning	X	X	X	X
Quality Management	X	X	X	X
Prod. Inventory Management	X	X		X
Resource Management	X		X	X
Equipment Management	X		X	X
Manufacturing Control	X	X		
Traceability/ Genealogy	X			X
Production Reporting	X		X	X
Machine Control	X			
Production Data Acquisition	X		X	X
Master Data Management	X	X	X	X

With regard to our goal of deriving a functional MES reference model for the automotive industry, we have used the specifications of these standards as well as further scientific publications on MES as a starting point for a more detailed definition of MES and related functions, which later resulted in the initial MES reference model. The initial reference model depicted in Figure 3 comprises the three layers already specified, namely ERP, MES, and Shop Floor. It visualizes different business and manufacturing functionalities and assigns them to one (or more) of the three layers, or, more precisely speaking, to the corresponding applications assigned to these layers. The functional reference model can serve two objectives: firstly, it can be used as a means for communication (as done in our project during the data collection workshops); secondly, when instantiated the functional reference model can be deployed to design or refine the application architecture assigning software components to the function mapped.

The MES layer comprises typical functions for production planning and manufacturing control, such as Product Traceability and Genealogy, or Dynamic Routing. Dynamic Routing was added although it is not an element of the MES standards investigated, as it has recently been a much propagated function offered by commercial MES software vendors. The function provides algorithms to route, in real-time, intermediary or work-in-process material to appropriate stations and, hence, achieve real-time load balancing in order to increase manufacturing performance with regard to throughput, workload balance and work in process queues. The initial MES reference model was evaluated and slightly amended based on interviews with MES experts from the automotive industry.

In addition to the map we provided detailed definitions for each of the functions and specified the corresponding tasks that we assigned to each function (cf. [29, pp. 32-36]) in order to guarantee a common understanding of what we understand under each function block and, therefore, facilitate the assignment to one or more of the layers during the data collection workshops.

4.2 Second Design Cycle

Table 3 shows a detailed specification for some of the manufacturing-related functions, namely Detailed Planning, Quality Management and Production Reporting and Analysis, with an exemplary assignment of each task to the three layers from one of the investigated OEMs as worked out during the workshops. We selected these functions because they illustrate best how certain tasks of the function are supported by applications from different layers.

Table 3: Detailed specification of manufacturing-related tasks with assignment to the three layers (extract)

General Function	Detailed (Sub-)Function / Task	ERP	MES	Shop Floor
Detailed Planning	Check production restrictions → analyze available resources and conditions	x		
	Conduct detailed planning			
	Plan time and equipment loading	x	x	
	Adjust shift patterns → Optimize production sequence	x	x	
	Optimize current production plans and sequences	x	x	
	Short-time resource allocation	x		
	Sequence scheduling	x	x	
	Convert production requirements into production orders	x	x	
	Concrete production plan (order disposition)	x	x	
Quality Management	Compile quality planning (inspection planning)	x		
	Preliminary registration of samples and notification of samples	x		
	Quality inspection and documentation of quality tests		x	
	Transmission of quality data for production documentation		x	
	Evaluation of analysis results → Create analysis reports	x	x	
	Recommend action to correct problems and generate measures	x	x	
	Determine and control rework		x	
	Manage measuring and test equipment		x	
	Audit trail functionality	x		
Production Reporting & Analysis	Up-to-the minute reporting of current manufacturing operations results → operative target / actual value comparison		x	
	Long-term production analysis / Statistical Process Control (SPC)	x		
	Evaluation report / visualization of reporting data	x	x	
	Trigger alarms when parameters deviate from acceptable ranges		x	x

During the data collection workshops the functional blocks of the initial MES reference model were arranged according to the concrete implementations of the functions by the corresponding application systems. For this purpose, each functional block was first presented to the OEM's MES experts with the concrete tasks for each function. Each task was then assigned to one of the three layers by discussing which application is currently providing or should ideally provide support for this very task. In addition, the OEM representatives were given the possibility to add further tasks to each functional block that they considered necessary.

The resulting functional MES architectures of the OEMs reveal the functional requirements that need to be fulfilled by MES software products. The functional reference model aggregated across all participating OEMs is depicted in Figure 4 (see following page). A major finding from the comparison of the different instantiations is that a generalized statement with regard to the functional requirements across all automotive manufacturers is hard to achieve. The requirements are rather company- and production-specific with the MES layer (and corresponding applications) covering different functionalities which brings about the question whether standardized MES solution support is realistic. Moreover, the heterogeneity leads to the question of the factors influencing the assignment of functionality to the different layers which is addressed in the following chapter.

Nevertheless, based on the total number of assignments across all investigated OEMs the instantiated MES reference model some general trends on functional MES requirements can be identified. For instance, Detailed Planning, Traceability, Direct Routing as well as Manufacturing Execution and Control are mostly seen as core functionalities covered on the MES layer. For other functionalities, such as Production Reporting and Analysis and Quality Management, MES applications need to provide support. As the functions are assigned to multiple layers (i.e. single tasks of the corresponding function are supported by different applications that can be assigned to more than one layer), the topic of integration to applications from the ERP and shop floor layer that cover some tasks of the functionality is predominant.

The functional MES reference model depicted in Figure 4 summarizes the function assignments consolidated across all four case studies and, consequently, represents the revised functional reference model for integrated manufacturing in the automotive industry.

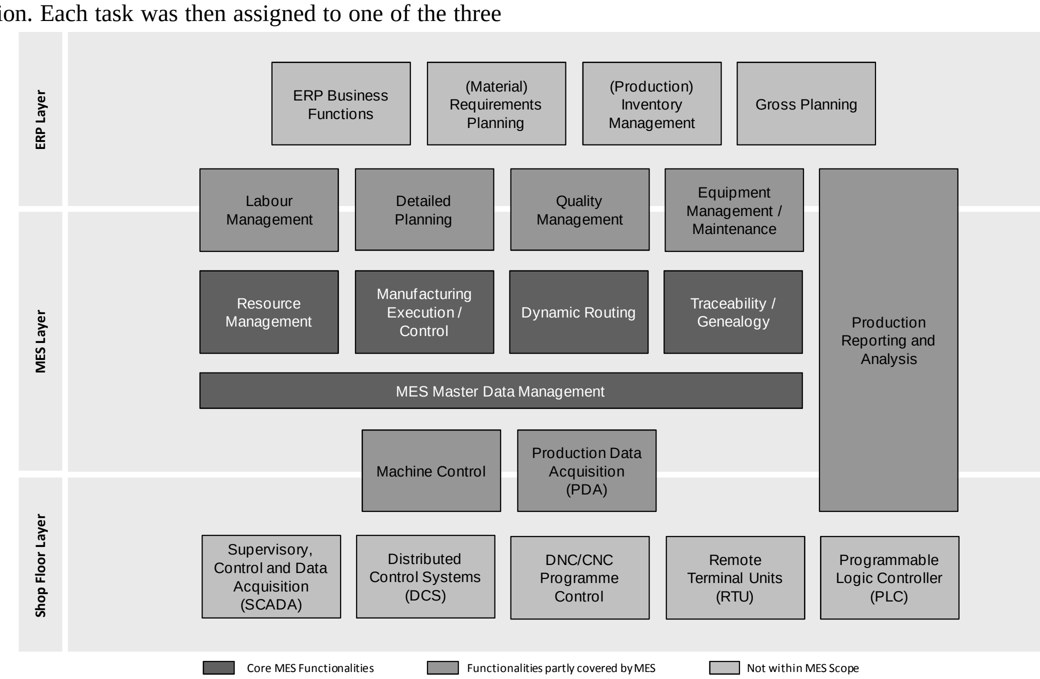

Figure 4: Functional reference model for integrated manufacturing in automotive (after second iteration)

4.3 Configuration Parameters for Reference Model Application

As the previous section has shown, instantiation of the initial reference model may vary significantly. This being recognized, it becomes obvious that it would be helpful to identify parameters influencing instantiation of the reference model. In terms of established approaches for reference modelling they can be interpreted as configuration parameters describing the context of application of the functional reference model for integrated manufacturing [5, p. 27]. They allow for configuration of the model through adaptation principles of aggregation and analogy construction [4, pp. 259-260, 34, pp. 64-68]. In our case, the pre-defined MES functions that were derived from the analysis of MES standards can be positioned within the model or even left out depending on the specific requirements of a certain plant or production site. The requirements should be reflected in the influencing parameters.

Based on the analysis of the instantiations made and on intensive discussions during the data collection interviews, we identified the following parameters (the numbers in brackets denote the number of mentions by the OEMs):

- Production Process Type (4). Component manufacturing (batch production) and assembly (flow production) pose different requirements in terms of functions needed. Additionally, we have to distinguish between casting or pressing plants manufacturing simple components or parts (mainly in batch production), plants for complex components (such as gears or engines, both in batch production and in flow production), and assembly plants (flow production).
- Number of Production Process Variants (4). This parameter is generally dependant on the production process type as component plants are characterized by a larger number of production variants resulting in more sophisticated requirements on prompt mounting of manufacturing equipment or flexible production process adaptation.
- Production Quantity (3). According to the workshop participants, instantiation of the MES reference model largely depends on production quantity, i.e. total amount of items produced (individual vs. series production).
- Vertical Range of Manufacturing (2). The percentage of the manufacturer's own value creation, i.e. the in-house production depth, was also identified as an influencing parameter.
- Degree of automation (2). The specific location of a plant influences requirements on MES functions, as there are considerable differences between manufacturing sites with regard to the degree of automation , e.g. in industrialized and in developing countries. Where the manufacturing process is still dominated by manual activities, required system-based support of functions is much lower than in highly automated plants.
- Production Worker Autonomy (1). An influencing factor on the relevance and assignment of certain MES functions is the degree to which the production worker on the shop floor can autonomously interfere and make decisions during the manufacturing process.
- Green versus Brown Field (1). This parameter accommodates the fact that MES functions can be assigned much more easily and precisely in new plants than in plants in which application landscapes have grown historically, with applications covering a different, but partly overlapping scope of functionality.

Within the study we mainly concentrated on the differences resulting from the production process type, as we had representatives both from component manufacturing and from assembly plants participating in the workshops. The peculiarities of the two production process types lead to specific assignments of some functions and to differing evaluations of their relevance. As a first finding, we recognized a tendency towards a MES layer covering a wider range of functions in component manufacturing plants than in assembly plants. Figure 5 shows the assignment of MES Functions for a component manufacturing plant, which includes both parts and complex component manufacturing (on the left) and for an assembly plant (on the right). The difference is mainly due to the fact that production in the component plants is much more diverse (and, thus, complex): it covers a wider range of products (from pressing parts to engines), it is characterized by a larger number of production process variants (comprising e.g. both batch and flow production) and a more disruptive manufacturing process necessitating rapid respo nse in the production planning and control process. Consequently, planning horizons (e.g. for Detailed Planning) are more short-term and covered by MES applications rather than by ERP systems. In assembly, in turn, production plants have a longer time horizon and bigger parts of short-term activities are directly covered on the Shop Floor layer. Furthermore, the importance of some of the MES-related functions is evaluated differently depending on the

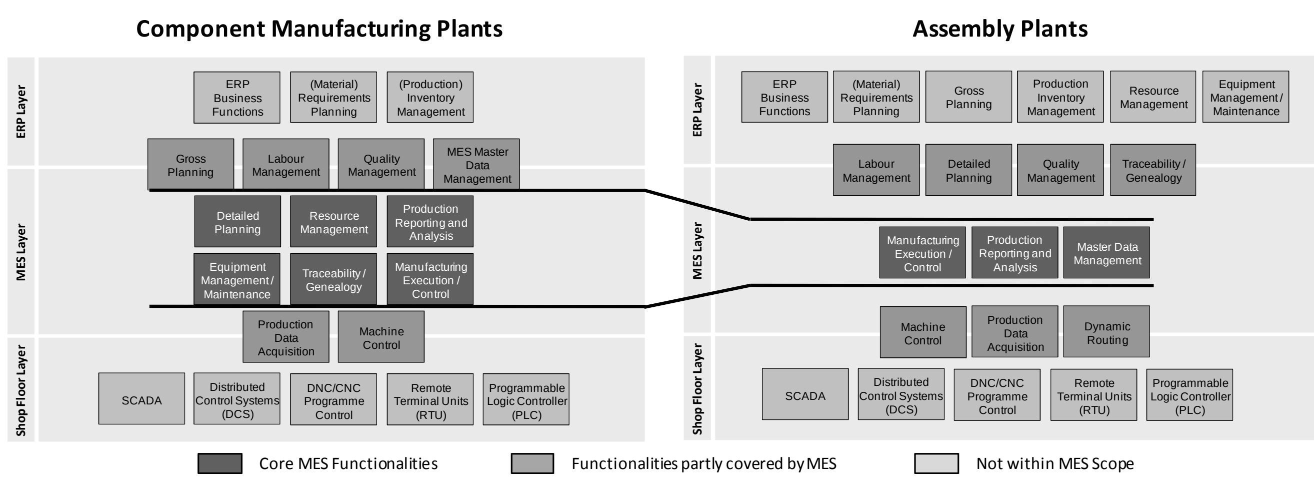

Figure 5: Differences in MES function assignment between component manufacturing plants and assembly plants

plant and production process type. For example, Dynamic Routing is seen as a function of higher significance for assembly than for component manufacturing.

5. REFERENCE MODEL EVALUATION

Playing an active role in designing and adapting the proposed functional reference model as well as applying it within the four case studies, the researcher's ability for inter-subjective evaluation of the artifact is limited. In order to overcome this shortcoming of participatory case study research [3, p. 30], we base evaluation of our functional reference model on established principles and criteria for evaluating reference models, namely the four evaluation perspectives proposed by Frank [12] that incorporate and subsume findings from previous publications on the evaluation of reference models, such as [31] and [10]. The four perspectives are summarized in Table 4.

Table 4: Four perspectives for evaluating reference models (based on [12, pp. 123-136])

Evaluation perspective	**Description**
Economic	Evaluation of costs and benefits with regard to construction and use of reference models
Deployment	Evaluation of usability of reference models including criteria such as comprehensibility, clarity, appropriateness, etc.
Engineering	Evaluation of ability of reference models to fulfill the requirements and purposes which it was developed for
Epistemological	Evaluation of reference models with regard to their scientific value and fulfillment of scientific requirements

By applying these four criteria, evaluation of the functional reference model described in this paper results in the following conclusions:

- *Economic perspective*. Due to the relatively low complexity of the reference model its usage and adaptation does not cause high costs to the potential user. An initial presentation of the reference model and explication of the respective functional blocks of the model at the beginning of the workshops was sufficient to enable the participants to apply the reference model to their specific case. Consequently, the costs for training are negligible. Meanwhile, the functional reference model does not generate direct benefits. However, the reference model fosters inter-company standardization as it supports creation of a unified terminology regarding MES functionality. The ability of the reference model to define an industry-wide common language is further enhanced by its (terminological) compatibility to existing international MES standards, such as MESA. In addition, the concluding multilateral workshop which included the four OEMs as well as MES software vendors showed that the functional reference model does not only foster communication as well as the knowledge exchange between the OEMs but also towards software vendors by providing a mean to express their requirements on appropriate MES tool support.
- *Deployment perspective*. Application of the initial functional reference model in four cases indicates its applicability and comprehensibility. As a general outcome of the case studies, the participants agreed that the MES reference model represents a very useful and appropriate tool for finding common terms regarding production planning and control and for mapping functional requirements for appropriate IT support. Moreover, they approved comprehensibility of the reference model as they were easily able to understand the intention as well as the structure of the model due to the intuitive graphical representation and the detailed specification of the functional building blocks of the model. These findings were further backed by the positive feedback of the two interviewed subject matter experts (see chapter 3.2) that were asked to evaluate the reference model.
- *Engineering perspective*. The intended application domain of the reference model (manufacturing in the automotive industry) as well as its purpose (functional requirements definition of MES) was specified at the very beginning of the project and communicated to all involved stakeholders. The application in the case studies and the resulting findings showed that the functional reference model is suited to fulfil the initially defined goals and that it is flexibly usable in OEM-specific contexts (adaptability of reference models). Furthermore, extensibility of the reference model is ensured as functional building blocks can easily be added or removed on different levels of granularity (functions or tasks).
- *Epistemological perspective*. Application of the reference model as well as the feedback obtained from the reference model users indicated a sound representation of the object world with an appropriate level of abstraction. The requirement of critical distance is fulfilled by precisely defining the reference model type (as done in chapter 3.1) and explicitly specifying the intended application domain. Finally, the explication of the process for designing the functional reference model (as outlined within this paper) ensures fundamental scientific requirements, such as consideration and inclusion of the existing knowledge base, reproducibility of the artefact, etc.

6. CONCLUSIONS AND OUTLOOK

The functional reference model for integrated manufacturing in the automotive industry that we developed in this paper serves the goal of defining automotive specific MES application functions on a conceptual level. This, at the same time, constitutes the basis for a common, industry-wide understanding with regard to essential terms in this domain and allows for a concerted expression of functional requirements on MES software vendors.

The information obtained through the four case studies brought up a number of valuable findings. Firstly, existing MES standards (like MESA, ISA95 etc.) were estimated as insufficient for designing and developing a functional MES architecture for automobile manufacturers. Secondly, a functional reference model for integrated manufacturing that is of general applicability is difficult to develop, as companies assign functions individually to the different layers. For standardized MES application support, the heterogeneity of functional requirements identified for the different companies constitutes a major obstacle. Thirdly, the problem of different function assignments is worsened by a number of influencing parameters. These parameters were identified and described as an additional outcome of the study.

A major research challenge for the future consists in investigating the parameters that influence its instantiation. Based on the analysis of the available instantiations as well as intensive discussions during the data collection interviews we were able to determine some first insights. For obtaining some more substantive findings, adoption of the reference model in further cases will be needed. Therefore, we intend to pursue two directions in the near future. Firstly, we aim at finding further automotive manufacturing companies willing to apply the functional MES reference model presented in this paper. This might also include supplier companies that cover part of the automotive value chain and produce complex parts for the OEMs. Secondly, we plan to deepen our investigation of the current four automotive research partners by examining single plants with regard to their specific MES functions. We will inspect plants producing parts – both complex and simple parts, such as pressed and cast parts – as well as assembly plants. On the one hand this will help us to verify correctness of the content of our reference model, i.e. the functional MES building blocks. On the other hand, it will allow for a more comprehensive evaluation of the precise impact of the parameters on the instantiation and for the identification of functional patterns for different types of manufacturing plants as well as general adaptation and instantiation guidelines for the reference model depending on plant specifics.

Moreover, the functional reference model could serve as a helpful starting point for specifying:

- industry-wide domain models that contain functional components,
- service landscapes defining services for each functional block, or
- a (semantic) information model that unambiguously defines essential information objects as a prerequisite for establishing a common language on MES-related terms and entities.

7. REFERENCES

[1] Albert, C. and Fuchs, C. 2007. *Durchblick im Begriffsdschungel der Business-Software*. Technical Report. Universität Würzburg, Würzburg, Germany.

[2] Barkmeyer, E., Denno, P., Feng, S., Jones, A. and Wallace, E. K. 1999. *NIST Response to MES Request for Information*. National Institute of Standards (NIST), Gaithersburg, USA.

[3] Baskerville, R. L. 1997. Distinguishing Action Research from Participative Case Studies. *Journal of Systems and Information Technology* 1, 1, 25-45.

[4] Becker, J., Delfmann, P. and Knackstedt, R. 2004. Konstruktion von Referenzmodellierungssprachen - Ein Ordnungsrahmen zur Spezifikation von Adaptions-mechanismen für Informationsmodelle. *Wirtschaftsinformatik* 46, 4, 251-264.

[5] Becker, J., Delfmann, P., Knackstedt, R. and Kuropka, D. 2002. Konfigurative Referenzmodellierung. In *Wissensmanagement mit Referenzmodellen*, J. Becker and R. Knackstedt, Eds. Physica, Heidelberg, 25-144.

[6] Becker, J. and Schütte, R. 2004. *Handelsinformationssysteme*. Redline, Frankfurt am Main, Germany.

[7] Benbasat, I. 1985. An Analysis of Research Methodologies. In *The Information Systems Research Challenge*, F. W. McFarlan, Ed. Harvard Business School Press, Boston, USA, 47-85.

[8] Cavana, R. Y., Delahaye, B. L. and Sekaran, U. 2001. *Applied Business Research - Qualitative and Quantitatvie Methods*. Wiley, Milton, USA.

[9] Eisenhardt, K. M. 1989. Building Theories form Case Study Research. *Academy Of Management Review* 14, 4, 532-550.

[10] Fettke, P. and Loos, P. 2003. Multiperspective Evaluation of Reference Models - Towards a Framework. In *Conceptual Modelling for Novel Application Domains*. Springer, Berlin et al., 80--91.

[11] Fettke, P. and Loos, P. 2004. Referenzmodellierungsfor-schung. *Wirtschaftsinformatik* 46, 5, 331-340.

[12] Frank, U. 2007. Evaluation of Reference Models. In *Reference Modeling for Business Systems Analysis*, P. Fettke and P. Loos, Eds. Idea Group, 118--139.

[13] Heinrich, B., Henneberger, M., Leist, S. and Zellner, G. 2009. The process map as an instrument to standardize processes: design and application at a financial service provider. *Information Systems and E-Business Management* 7, 1, 81-102.

[14] Hevner, A. R., March, S. T., Park, J. and Ram, S. 2004. Design Science in Information Systems Research. *Management Information Systems Quarterly* 28, 1, 75-105.

[15] ISA 2000. *ANSI/ISA-95.00.01-2000 Enterprise-Control System Integration Part 1: Models and Terminology*. Technical Report. Industry, Systems, and Automation Society (ISA), Pittsburgh, USA.

[16] Kletti, J. 2006. *MES - Manufacturing Execution System: Moderne Informationstechnologie zur Prozessfähigkeit der Wertschöpfung*. Springer-Verlag, Berlin/Heidelberg, Germany.

[17] Klimm, B. 2008. *Welchen Nutzen bietet ein MES-Cockpit? - Steuerung der Fahrzeugproduktion vom Presswerk bis zur Werksschlussabnahme*. SALT Solutions, Dresden, Germany.

[18] Louis, J. P. and Alpar, P. 2007. Flexible Production Control - A Framework to Integrate ERP with Manufacturing Execution Systems. In *Proceedings of European and Mediterranean Conference on Information Systems 2007 (EMCIS2007)*, Valencia, Spain, 24-1--24-10.

[19] Mayring, P. 2008. *Qualitative Inhaltsanalyse: Grundlagen und Techniken*. Beltz, Weinheim.

[20] MESA 2000. *Controls Definition & MES to Controls Data Flow Possibilities*. Technical Report. Manufacturing Enterprise Solutions Association (MESA), Pittsburgh, USA.

[21] Meyer, J.-A. and Kittel-Wegener, E. 2002. Die Fallstudie in der betriebswirtschaftlichen Forschung und Lehre. In *Schriften zu Management und KMU*, Stiftungslehrstuhl für ABWL, Ed., Flensburg, Germany.

[22] NAMUR 2003. *MES: Funktionen und Lösungsbeispiele der Betriebsleitebene (Functions and Examples of Operations Control Level Solutions)*. Technical Report. Normenarbeitsgemeinschaft für Meß- und Regeltechnik in der chemischen Industrie (NAMUR), Leverkusen, Germany.

[23] Peffers, K., Tuunanen, T., Rothenberger, M. A. and Chatterjee, S. 2008. A Design Science Research

Methodology for Information Systems Research. *Journal of Management Information Systems* 24, 3, 45-77.
[24] Peßl, E. 2008. ERP- und MES-Systeme - Einsatz in der Produktionsplanung und -steuerung. *Zeitschrift für wirtschaftlichen Fabrikbetrieb (ZWF)* 103, 4, 271-275.
[25] Sauer, O. 2004. Agent technology used for monitoring of automotive production. In *Proceedings of the International Intelligent Manufacturing Systems (IMS) Forum 2004,* Cernobbio, Italy.
[26] Sauer, O. 2005. Entwicklungstrends von MES am Beispiel der Automobilindustrie. *PPS Management* 10, 3, 21-24.
[27] Schäfer, M., Reimann, J., Schmidtauer, C. and Schoner, P. 2009. *MES: Anforderungen, Architektur und Design mit Java, Spring & Co*. entwickler.press, Frankfurt am Main, Germany.
[28] Scheer, A.-W. and Schneider, K. 2005. ARIS - Architecture of Integrated Information Systems. In *Handbook on Architectures of Information Systems*. vol. 2, P. Bernus, K. Mertins, and G. Schmidt, Eds. Springer, Berlin, Heidelberg, 605-623.
[29] Schmidt, A., Otto, B. and Kussmaul, A. 2009. *Integrated Manufacturing Execution – Functional Architecture, Costs and Benefits*. Technical Report. St. Gallen, Switzerland, BE HSG/ CC CDQ2 / 17.
[30] Scholz, R. W. and Tietje, O. 2002. *Embedded Case Study Methods. Integrating quantitative and qualitative Knowledge*. Sage Publications, Thousand Oaks, USA.
[31] Schütte, R. 1998. *Grundsätze ordnungsmässiger Referenzmodellierung: Konstruktion konfigurations- und anpassungsorientierter Modelle*. Gabler, Wiesbaden.
[32] Specht, G., dos Santos, A. and Bingemer, S. 2004. Die Fallstudie im Erkenntnisprozess: die Fallstudienmethode in den Wirtschaftswissenschaften. In *Fundierung des Marketing: verhaltenswissenschaftliche Erkenntnisse als Grundlage einer angewandten Marketingforschung*, K.-P. Wiedmann, Ed. Deutscher Universitätsverlag, Wiesbaden, Germany, 539-563.
[33] VDI 2007. VDI-Richtlinie 5600: Fertigungsmanagement-systeme - Manufacturing Execution Systems (MES). In *VDI-Handbuch Informationstechnik, Bd. I: Angewandte Informationstechnik* VDI-Kompetenzfeld Informationstechnik, Berlin, Germany.
[34] vom Brocke, J. 2007. Design Principles for Reference Modeling: Reusing Information Models by Means of Aggregation, Specialisation, Instantiation, and Analogy. In *Reference Modeling for Business Systems Analysis*, P. Fettke and P. Loos, Eds. Idea Group Publishing, Hershey, USA, 47-75.
[35] Wannenwetsch, H. H. and Nicolai, S. 2004. *E-Supply-Chain-Management: Grundlagen, Strategien, Praxisanwendungen*. Gabler, Wiesbaden, Germany.
[36] Yin, R. K. 2002. Case Study Research. Design and Methods. Sage Publications, London, UK.