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Integrated Manufacturing Execution – Functional Architecture, Costs and Benefits

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List of Abbreviations

AG	Aktiengesellschaft (Corporation)
AHM	Audi Hungaria Motors Kft.
BDN	Benefits Dependency Network
BMW	Bayerische Motoren Werke
CIP	Continuous Improvement Process
CNC	Computerized Numerical Control
CoC	Center of Competence
DCS	Distributed Control System
DNC	Distributed Numerical Control
EDS	Electronic Data Systems Corporation
ERP	Enterprise Resource Planning
HR	Human Resources
IME	Integrated Manufacturing Execution
IPS	International Production System
ISA	Industry, Systems, and Automation Society
IT	Information Technology
IWI	Institute of Information Management
KPI	Key Performance Indicator
MBC	Mercedes-Benz Cars
MES	Manufacturing Execution Systems
MESA	Manufacturing Execution Solutions Association
NAMUR	Normen-Arbeitsgemeinschaft
NIST	National Institute for Standards
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
PDA	Production Data Acquisition

PLC	Programmable Logic Controller
SCADA	Supervisory Control and Data Acquisition
SPC	Statistical Process Control
VDI	Verein Deutscher Ingenieure
VW	Volkswagen
WIP	Work in Progress

Abstract

One of the challenges in manufacturing companies nowadays is to enable appropriate IT support of production planning and execution. Integrated solutions need to cover company-wide and even cross-company business processes (from order receipt to product distribution) and at the same time live up to the technological complexity of manufacturing processes on the shop floor. The problem is even aggravated in industries, such as the automotive industry, which are characterized by numerous, strongly diverging manufacturing processes and highly versatile products. What such manufacturing companies need is an integrated, consistent view along their entire value chain, allowing for optimal utilization of capacities and closing the gap between business and manufacturing processes.

This final report of the IME study describes essential criteria for further optimizing manufacturing execution and control in manufacturing plants of the automotive industry. Based on case studies carried out at four OEMs, documenting the current status of MES related topics in the respective companies, the study develops a functional reference architecture for MES to be used in the automotive industry as well as a Business Benefits Framework allowing to measure the impact of an integrated MES on the performance of manufacturing processes. From these results, requirements on and recommendations for future, integrated Manufacturing Execution Systems are derived.

1 Introduction

1.1 Motivation

One of the challenges in manufacturing companies nowadays is to enable appropriate IT support of production planning and execution. Integrated solutions need to cover company-wide and even cross-company business processes (from order receipt to product distribution) and at the same time live up to the technological complexity of manufacturing processes on the shop floor. Difficulties result from different levels of detail and accuracy regarding production status information needed on different company levels. The problem is even aggravated in industries which are characterized by numerous, strongly diverging manufacturing processes and highly versatile products. This is the case in the automobile 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. [Klimm 2008, p. 4]. Classical 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. Therefore, a new category of information systems, called Manufacturing Execution Systems (MES), has emerged, allowing to consistently collect and process data on current machine and production statuses. While parallel operation of ERP systems and MES seems reasonable, a number of questions do arise though:

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

system is supposed to cover? How can functionalities be assigned to the layers (ERP, MES or Shop Floor) in order generate minimum overlap [Lampl 2009, p. 99]?

- How can information be smoothly exchanged between the various layers? How can information systems involved be integrated to allow for optimal information exchange?
- How can typical proprietary legacy systems on the shop floor level, which originally were not designed for this purpose, be connected to the other layers [Niemietz et al. 2009, p. 68]?
- How can the impact of an "additional" MES layer on the efficiency and effectiveness of the manufacturing process be measured?
- Are there single "out-of-the-box" software solutions that are capable of covering the diversity of manufacturing-specific requirements, particularly in an industry which is characterized by highly different production processes? How could optimal application support in such an industry look like?

With regard to integration of the ERP layer and the MES layer, the Aberdeen Group in 2006 conducted a benchmark study across 440 manufacturing companies from different industries, revealing that the most urgent goals pursued by integration efforts are seamless data flow from the shop floor layer to the ERP layer, enterprise-wide access to production data, and improvement of product quality (see Figure 1-1).

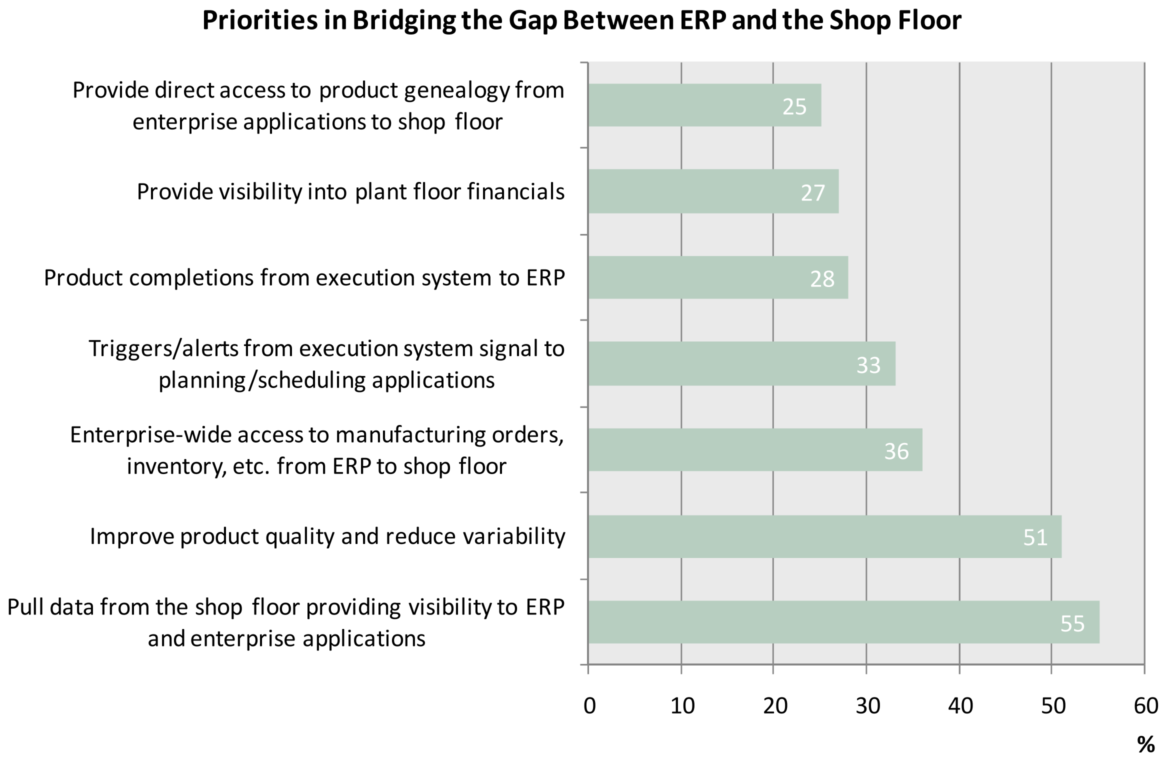


Figure 1-1: Key goals for integration of ERP and shop floor [Aberdeen Group 2006, p. 3]

1.2 Structure of the Final Report

After this introductory section in which the study motivation is expressed, Section 2 is dedicated to the description of the study design including a short presentation of the four participating automobile manufacturers with the corresponding workshop participants. Thereafter, Section 3 provides background information and the conceptual foundation on central topics of the study, most notably MES and the automotive industry.

Section 4 presents the major findings of the study according to the five subject areas that were investigated. The first part (Section 4.1) is devoted to strategic goals, organizational embedding, and application landscape. Section 4.2 then aims at developing a reference architecture for MES functions as one of the pivotal goals pursued with this study. The generic reference architecture (named MES Function Map) is derived from existing MES standards (Section 4.2.1) and then instantiated and refined through the four case studies (Section 4.2.2). The instantiations show functional requirements that the Original Equipment Manufacturers (OEMs) have on IT solutions for production planning and control. Section 4.2.3 then investigates the potential improvement standardized MES solutions could generate with regard to cost, time, and quality. In Sections 4.2.4 and 4.2.5, we discuss some factors influencing the instantiation of the MES reference architecture as well as requirements which are not covered by the MES Function Map (non-functional requirements), but which were explicitly expressed as being important for MES solutions. The fifth subject area, performance measuring, is dealt with in Section 4.3, where we analyze KPIs used by the OEMs for evaluating their manufacturing processes in order to illuminate possible effects of integrated MES solutions on the performance of the manufacturing processes.

Finally, Section 5 summarizes the key results of the study and provides an outlook on future challenges for the automotive industry as well as for research.

2 Study Design

2.1 Research Approach

The basic intention of the study is to describe essential criteria for further optimizing manufacturing execution in assembly and component manufacturing plants of the automotive industry. Based on the identification of a functional MES reference architecture (including adoption criteria for its application), the study aims at formulating requirements on and developing recommendations for future integrated Manufacturing Execution Systems. A reference architecture, or more generally speaking a reference model, is a generic model of a unit of analysis that is applicable as a template for similar cases in the same domain by adapting predefined configuration parameters to the particular situation in which it used. We will describe reference models and their adaptation mechanisms in more detail in later sections of this report when we present the functional MES reference architecture and parameters influencing its instantiation (Section 4.2). In addition, the study evaluates potential benefits of an integrated Manufacturing Execution System by developing and applying a framework of business benefits consisting of MES-related KPIs.

The pivotal element of this study on Integrated Manufacturing Execution (IME) in the automobile industry is the recording of case studies for the four participating automobile manufacturers, namely AUDI AG, BMW Group, Daimler AG and Volkswagen AG[1]. 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 [Eisenhardt 1989, p. 533, Scholz/Tietje 2002, pp. 11f.]. As the IME project aims at the former, our case studies can be defined as explorative [Yin 2002, Specht et al. 2004] describing and investigating a complex area of science [Meyer/Kittel-Wegener 2002, p. 21] and trying to identify and explain interdependencies or cause effect relations [Yin 2002, p. 15]. The study design is characterized by an multi-case studies approach as a total of four different companies are examined with regard to the same topic (MES) [Yin 2002, pp. 38ff.]. This leads to increased robustness and generalizability of findings, compared to individual case studies [Benbasat 1985, p. 58].

Each of the four case studies documents the current status regarding MES for the respective OEM, taking into account five subject areas to be investigated: strategic goals, organizational embedding, application landscape, functional architecture, and performance measuring. In addition, the individual case studies and the findings made therein serve as a basis for the present study report.

[1] The companies participating in the IME study are presented in the following section.

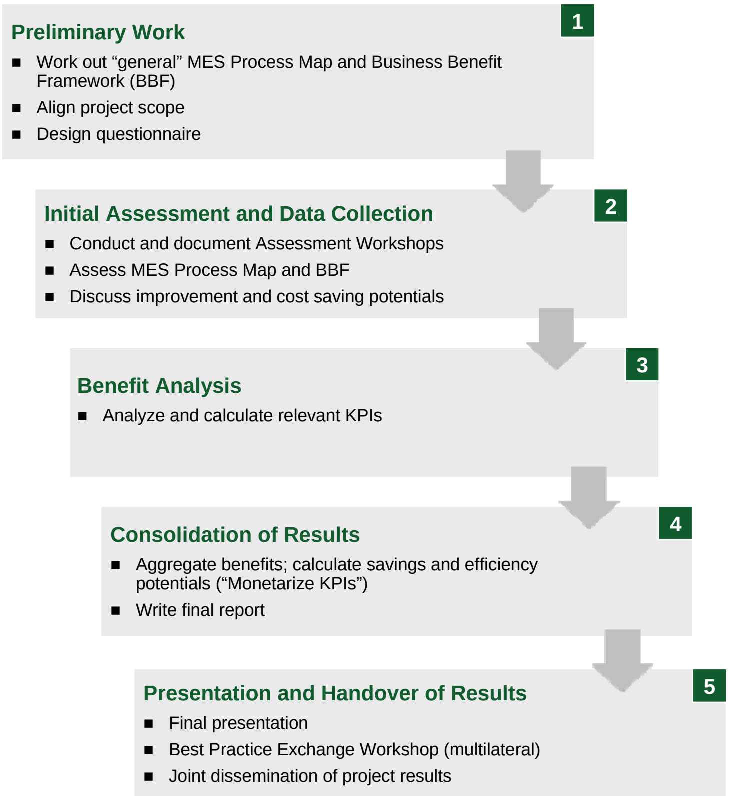


Figure 2-1: Research approach of the IME Study

Figure 2-1 shows the overall research process pursued by the IME study. Based on extensive literature review we designed a questionnaire consisting of both open and closed questions serving as a guideline for the assessment workshops. The questionnaire was reviewed and refined through multiple interviews with experts having substantial experience in MES projects. The interrogated subject matter experts are named in Table 2-1.

Name	Company	Department / Role
Michael Schlecht	SAP Deutschland AG	Director Industry Solutions
Tony Aschwanden	SAP Schweiz AG	Head of EMEA Presales for Manufacturing Execution
Dieter Wormuth	EDS, an HP Company	Consultant for Production IT and MES

Table 2-1: MES experts interviewed for questionnaire design

The workshops were carried out as semi-structured on-site focus group interviews [Cavana et al. 2001, pp. 153-159] with varying numbers of participants (between 3 and 12) from both IT and manufacturing departments (e.g. plant managers). Additionally, we analyzed documents provided by the workshop participants, which complemented the information gathered during the interviews.

2.2 Participating Automobile Manufacturers

The following chapter presents the four OEMs that participated in the IME study as well as the objects of investigation (plants, divisions etc.). In the rest of the paper we refer to these OEMs as automobile manufacturers.

2.2.1 AUDI AG

2.2.1.1 General Information

AUDI AG is a German automobile manufacturer headquartered in Ingolstadt, Germany. It has been an almost wholly-owned subsidiary (99.7 %) of the Volkswagen Group since 1964. The company employs about 57,000 employees, generating a revenue of more than 34 billion Euros (2008). The Audi Group itself is subdivided in several national subsidiaries and manufactures cars in seven international manufacturing sites (Ingolstadt and Neckarsulm in Germany, Brussels in Belgium, Györ in Hungary, Changchun in China, Bratislava in Slovakia, and Aurangabad in India). The company's key figures for the year 2008 are summarized in Table 2-2.

	AUDI AG
Number of employees	57,533
Annual revenue (in million Euro)	34,196
Number of manufacturing sites	6
Number of countries with manufacturing sites	5
Annuals costs of goods sold (COGS) (in million Euro)	28,848
Manufacturing costs (in million Euro)	28,478

Table 2-2: Key figures of AUDI AG for 2008

2.2.1.2 Object of Investigation and Interview Partners

The case study at Audi did not focus on a single plant, but instead covered both vehicle and component manufacturing. Consequently, the study covers the manufacturing plants of AUDI AG in Ingolstadt (with an output of more than 550.000 cars per year and 32,000 employees in 2008), Neckarsulm (approximately 300.000 cars per year and 13,000 employees in 2008), and Audi Hungaria Motors Kft. (AHM) in Györ, Hungary (almost 2 million engines and 60,000 cars with approximately 5,900 employees in 2008). Ingolstadt, as the headquarter site and the location for both technical development and diverse corporate functions, is Audi's biggest plant with regard to vehicle output. Due to the relatively small floor space of the manufacturing site, Ingolstadt typifies the model of permanent optimization of the plant's manufacturing and logistics processes including the underlying IT. With Ingolstadt and Neckarsulm being the two biggest manufacturing plants of the company (with regard to yearly vehicle production), the important issue of MES process and system integration is centered on these two sites. AHM is mainly a component manufacturing plant. however, there is also a small part of vehicle manufacturing (assembly), producing about 60,000 cars per year. With a total of almost two million engines produced yearly, the plant is one of the worldwide biggest engine manufacturing sites. Due to its size and the fact that it encompasses all business functions (e.g. HR, Research & Development etc.), the Györ location differs from other manufacturing sites of Audi and is of equal importance within the company as the main manufacturing plants in Ingolstadt and Neckarsulm. From AUDI AG, the following representatives participated in the assessment workshops:

- Jörg Graf, head of IT of AHM;
- Christoph Lubkoll, responsible for Strategies of Process and System Integration (Customer Order Process);
- Emese Kosar, head of the Process, Integration and Information Management department within the IT department of AHM; and

- Ambrus Zsolt, responsible for IT solutions supporting core manufacturing processes, most notably the planning production process within the IT department of AHM.

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. For the other Audi component manufacturing plants, the standard MES of Volkswagen, as the parent company, are authoritative, whereas IT solutions at AHM may differ from these standards by partly having installed local, proprietary systems in line with governing IT principles.

2.2.2 BMW AG

2.2.2.1 General Information

The Bayerische Motoren Werke (BMW) AG is a German automobile and motorcycle manufacturing company, which was founded in 1916. It is headquartered in Munich, Germany. The company employs approximately 100,000 employees generating an annual revenue of more than 53 billion Euros (2008). Today the BMW Group is the parent company of the MINI brand as well as Rolls-Royce Motor Cars. BMW manufactures cars in 24 sites covering 13 different countries. The company's key figures for the year 2008 are summarized in Table 2-3.

	BMW AG
Number of employees	100,041
Annual revenue (in million Euro)	53,197
Number of manufacturing sites	24
Number of countries with manufacturing sites	13
Annuals costs of goods sold (COGS) (in million Euro)	44,323
Manufacturing costs (in million Euro)	26,727

Table 2-3: Key figures of BMW AG for 2008

2.2.2.2 Object of Investigation and Interview Partners

In contrast to the original intension of focusing on one single plant only, it was jointly agreed to do a comprehensive, cross-plant analysis of MES related topics. 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. Therefore, we had a wide spectrum of workshop participants with varying backgrounds and from different organizational units. The names of the workshop participants as well as their organizational assignment are summarized in Table 2-4.

Name	Role	Department
Robert Peter	CoC Leiter Anlagennahe Systeme	EZ-24
Harald Scheder	IT PL Neue 3er Baureihe	EZ-203
Ursula Richter	Bebauungsplanung, Q-Systeme	EZ-201
Thomas Priemuth	CoC Leiter Logistische Informationssysteme	EZ-241
Jakob Wersching	Leiter Steuerungs- Einrichtungs- Prozesstechnik Montage	TP-401
Albert Sextl	Leiter Instandhaltung Komponentenfertigung	TA-334
Franz Zurl	Leiter Steuerungstechnik Komponentenfertigung	TA-414
Edmund Zuber	Leiter Anlagentechnik Karosseriebau	TP-221
Gerald Meier	Kompentenzfeldleiter Prozessdatenerfassung	EZ-240LA
Rudolf Hoefler	Programmsteuerung (München)	TM-103
Hubert Pielmaier	Leiter Instandhaltung Oberflächenbehandlung (Dingolfing)	TD-311
Dieter Schels	Produktionsnahe IT Montage (München)	TP-401MU

Table 2-4: Workshop participants of BMW

2.2.3 Daimler AG

2.2.3.1 General Information

Daimler AG is a German automobile manufacturer headquartered in Stuttgart, Germany. The company employs approximately 273,000 employees generating an annual revenue of more than 95 billion Euros (2008). Besides being the world's thirteenth largest automobile manufacturer, Daimler is the world's largest truck manufacturer. Its division Mercedes-Benz Cars (MBC), on which the case study has focused, employs approximately 97,000 people generating an annual revenue of almost 48 billion Euros (2008). Cars are manufactured in 15 sites covering six different countries. The main brands of the company are Mercedes-Benz, Smart, Maybach, and McLaren.

MBC's key figures for the year 2008 are summarized in Table 2-5.

	MBC (Daimler AG)
Number of employees	97,303 (273,216)
Annual revenue (in million Euro)	47,772 (95,873)
Number of manufacturing sites	15 (41)
Number of countries with manufacturing sites	6 (17)
Annuals costs of goods sold (COGS) (in million Euro)	74,314
Manufacturing costs (in million Euro)	---

Table 2-5: Key figures of MBC and Daimler AG (in brackets) for 2008

2.2.3.2 Object of Investigation and Interview Partners

In contrast to the original intension of focusing on one single plant only, it was jointly agreed to do a comprehensive, cross-plant and cross-division analysis of MES related topics. The case study covers three different divisions of production within MBC, namely manufacturing of complex components (engines, gears) for automobiles (so-called Powertrain), assembly of automobiles, and van production. Therefore, the scope of the case study is relatively wide, allowing for comparison of the topics investigated between the different branches and, consequently, identification and discussion of major discrepancies. Accordingly, findings are described for each of the three divisions (Powertrain, Assembly, Van) during the rest of the case study. The workshop brought together representatives from CoCs and plants of all three branches. The names of the workshop participants as well as their roles and organizational assignment are summarized in Table 2-6.

Name	Role	Department
Uwe Haag	Senior Manager	• IT VAN Manufacturing Plants • Head of CoC Manufacturing Control and Logistics • Information Officer for plants Düsseldorf and Ludwigsfelde
Markus Hawickhorst	Manager	• IT VAN Manufacturing Plants • CoC Distribution Systems
Gerhard Schiele	Senior Manager	• IT Assembly Plants • CoC Manufacturing Control
Thomas Kampfmann	Manager	• IT Assembly Plants • CoC Manufacturing Control (mainly Sindelfingen)
Stefan Rosenwald	Senior Manager	• IT Management Powertrain (component plants) • CoC Manufacturing Control and Logistics

Table 2-6: Workshop participants of MBC

2.2.4 Volkswagen AG

2.2.4.1 General Information

Volkswagen (VW) AG is a German automobile manufacturer headquartered in Wolfsburg, Germany. With an annual revenue of 113.8 billion Euros and a total of approximately 370,000 employees in 2008, the Volkswagen AG currently ranks among the top three automobile makers in the world and is the biggest European automobile manufacturer. It unites numerous automobile brands, among them Audi, Bentley, Bugatti, Seat, and Skoda. Volkswagen AG currently operates 61 manufacturing sites in 21 different countries. The company's key figures for the year 2008 are summarized in Table 2-7.

	Volkswagen AG
Number of employees	369,928
Annual revenue (in million Euro)	113,808
Number of manufacturing sites	61
Number of countries with manufacturing sites	21
Annuals costs of goods sold (COGS) (in million Euro)	96,612
Manufacturing costs (in million Euro)	---

Table 2-7: Key figures of Volkswagen AG for 2008

2.2.4.2 Object of Investigation and Interview Partners

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. Within the company, the ITP Components department is responsible for IT development and maintenance of all component plants. From this department two representatives participated in the assessment workshops:

- Hans-Christian Heidecke, head of ITP Components;
- Ingo Höfer, software engineer at ITP Components.

3 Background

3.1 Manufacturing Execution Systems

Manufacturing Execution Systems 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 [Louis/Alpar 2007, 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 3-1. The three layers can also be referred to as Company Management (for which ERP systems are the most common tools), Production Management (done by MES), and Production (supported by systems for machine control and acquisition of manufacturing data) [Günther et al. 2008, p. 37]. The latter usually contains hybrid hardware/software systems, such as Distributed Control Systems (DCS), Programmable Logic Controllers (PLC), Distributed Numerical Control (DNC), Supervisory Control and Data Acquisition (SCADA) systems, and other control systems designed to automate the way in which products are being manufactured [MESA 2000, p. 1].

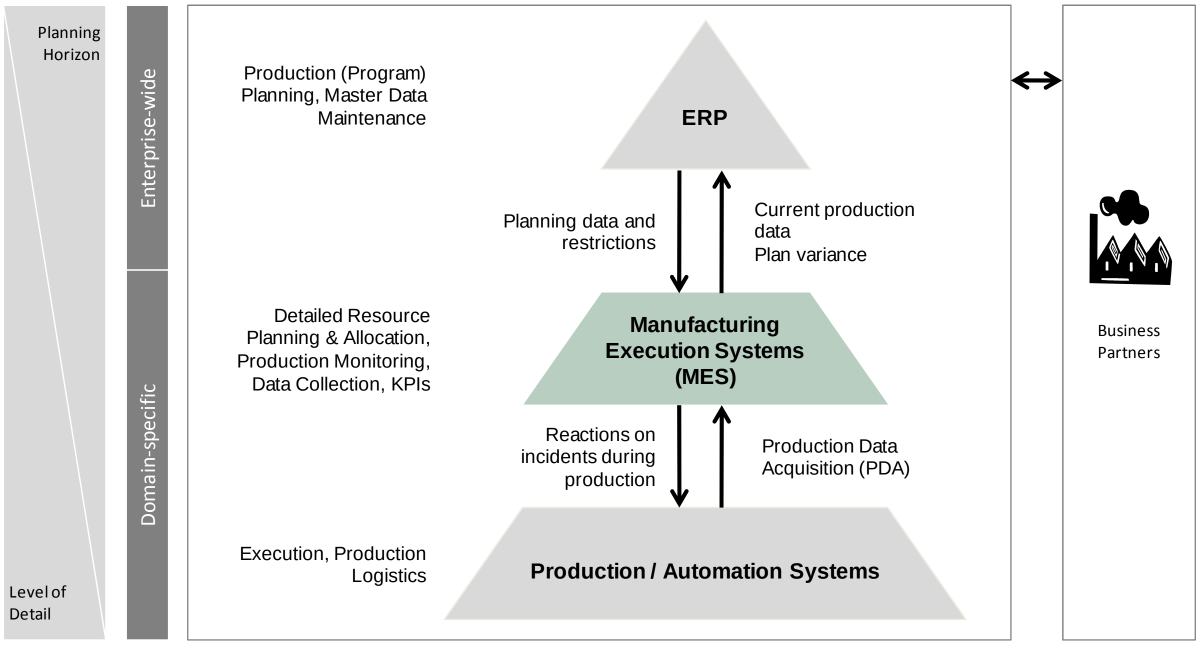


Figure 3-1: MES as connector between ERP and shop floor (based on [Albert/Fuchs 2007, p. 11, Louis/Alpar 2007, p. 24-6])

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 (reactive detailed planning). 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 [Wannenwetsch/Nicolai 2004, 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 (e.g. with regard to the modelling of the production process) [Louis/Alpar 2007, p. 24-3]. It is this gap that MES are trying to fill.

As MES in the past have not been subject of extensive scientific research (some exceptions being the recent works of KLETTI [Kletti 2006], SAUER [Sauer 2004] and SCHÄFER ET AL. [Schäfer et al. 2009]), 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 (cf. [ISA 2000, ISA 2005] and [MESA 2000, MESA 2004]).[2] 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." [MESA 2000, 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).

The ultimate goal of MES can therefore be described as increasing transparency on the manufacturing process and, as a result, establishing horizontal and vertical (closed) control loops [Kletti 2006, p. 11]. These control loops allow for prompt reaction to incidents on the shop floor as information is directly fed back to overlying planning systems (such as ERP) to trigger respective measures as well as to subsequent manufacturing steps (horizontal integration).

[2] A more detailed presentation of the standards is included in the following section.

A major challenge with regard to the model shown in Figure 3-1 lies in a clear demarcation of the three layers[3]. This is a difficult task, as certain enterprise functions may be supported by a number of information systems located in more than one layer (e.g. quality management by ERP and by MES applications, production data acquisition by control systems on the shop floor and by MES applications), leading to a high degree of interconnection between the systems. Nevertheless, a clear distinction appears useful, as the systems differ regarding the degree to which they support functionality for manufacturing planning compared to manufacturing execution. We comply with the above given definition by distinguishing the three layers ERP, MES, and Shop Floor mainly based on two parameters (see Figure 3-1): the planning horizon, i.e. the period of time for which different tasks are scheduled, and the level of detail of the information managed. By rule of thumb, ERP systems cover the mid- and long-term planning for a time horizon of at least one day (up to several weeks or months), MES handle production planning information ranging from one hour up to one day, and on the Shop Floor layer time intervals scale down to the level of several minutes. As every minute of production stop due to machine or tool failure directly leads to loss of money, rapid, ad-hoc decisions need to be supported in production management and execution [Kletti 2006, p. 11].

We would like to emphasize that our understanding of the term "MES" is not limited to the generic term for a type of commercially available or self-developed software, but also includes the functions that are necessary for (more) efficiently managing the manufacturing process and for establishing the link connecting commercial order processing at enterprise management level (ERP) with the

[3] The problem of demarcating the three layers with regard to their functions is also addressed in this study and discussed in more detail with the help of the MES Function Map in chapter 4.2. This part of the study aims at assigning functionality to the different layers and contributes to a more clear differentiation of ERP, MES and Shop Floor in the automotive industry.

operation management level (Shop Floor) [NAMUR 2003, p. 6]. For the remainder of the report we therefore explicitly differentiate between MES functionality and MES applications, the latter referring to software operated to support MES related tasks.

3.2 Existing MES Standards

As mentioned in the previous chapter, several standardization organizations have put some effort into finding a common definition and specifying generic MES functionality. The standardization organizations and the resulting specifications are briefly summarized in the following sub-sections serving as a conceptual foundation for further work (see Section 4.2).

Within its S95 standard, ISA specifies four core functionality categories of MES: Production Management, Inventory Management, Quality Management and Maintenance Operations Management [ISA 2000]. Each of the four categories is further subdivided into eight function groups and can serve as a basis to define the functional scope of the MES layer. However, the ISA standard focuses more on the data models of and interfaces between the three layers depicted in Figure 3-1, i.e. on vertical integration. As it does not provide concrete functional definitions, we do not include it in our synthesis of MES functions.

3.2.1 Manufacturing Execution System Association (MESA)

The Manufacturing Execution System Association is an American industry association headquartered in Chandler, Arizona. Being established in 1992 by different software companies, MESA is maybe the most experienced organization in the field of MES with its standards having reached worldwide acceptance. However, MESA's guidelines are still strongly influenced by the MES software vendor's perspective.

Manufacturing Execution System Association (MESA)	
Foundation	1992
Headquarters	Chandler, Arizona (USA)
Relevant industries	All manufacturing industries
Scope	International; MES only
Members	Software companies, user companies, and manufacturing professionals
Homepage	www.mesa.org

Table 3-1: Organization profile of MESA

The MESA Guidelines, as the most comprehensive MES standard, follow a pragmatic approach and identifies eleven standard MES functions on a fairly coarse-granular level [MESA 2000, p. 1]:

- Resource Allocation and Scheduling,
- Operations/Detail Scheduling,
- Dispatching Production Units,
- Document Control,
- Data Collection/Acquisition,
- Labour Management,
- Quality Management,
- Process Management,
- Maintenance Management,
- Product Tracking and Genealogy,
- Performance Analysis.

Moreover, with the new concept of a Collaborative MES, MESA is actively propagating the vision of MES as a company's central data and information hub [MESA 2004].

3.2.2 Normen-Arbeitsgemeinschaft (NAMUR)

NAMUR is a European organization for users of automation technology in the process industry ("Interessengemeinschaft Automatisierungstechnik der Prozessindustrie"). Its main focus is on the chemical and pharmaceutical industry. It promotes the exchange of know-how and experience between its members and designs guidelines in the form of recommendations and worksheets. NAMUR strongly relies on the ISA S95 standard.

Normen-Arbeitsgemeinschaft (NAMUR)	
Foundation	1949
Headquarters	Bad Neuenahr (Germany)
Relevant industries	Process industry (chemical and pharmaceutical industry)
Scope	European (German at its origin); not limited to MES
Members	User companies
Homepage	www.namur.de

Table 3-2: Organization profile of NAMUR

The main functional blocks defined in detail by NAMUR are:

- Operations-neutral Production Planning,
- Detailed Production Planning,
- Production Management,
- Quality Management,
- Stock Management & Material Flow Management,
- Production Documentation.

3.2.3 Verein Deutscher Ingenieure (VDI)

The VDI is Germany's biggest association of engineers and natural scientists, representing their interests in politics and society. It operates a number of expert panels who work out guidelines for different topics of interest. In 2004, VDI started to develop proper guidelines for MES based on the standards presented before as well as on recent experiences and market trends.

Verein Deutscher Ingenieure (VDI)	
Foundation	1856
Headquarters	Düsseldorf (Germany)
Relevant industries	All manufacturing industries
Scope	Germany; not limited to MES
Members	Engineers and natural scientists
Homepage	www.vdi.de

Table 3-3: Organization profile of the VDI

The 5600 Guideline focuses on an unambiguous definition of the term "MES" and the distinction between different manufacturing types. Functions defined are:

- Detailed Planning,
- Equipment Management,
- Resource Management,
- Personnel Management,
- Data Acquisition and Processing,
- Interface Management,
- Performance Analysis,
- Quality Management,
- Information Management.

3.2.4 National Institute of Standards and Technology (NIST)

The NIST is a measurement standards laboratory as a non-regulatory agency of the United States Department of Commerce. Its mission is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology. In the past, the NIST has actively been working on various issues, such as development of a distributed shop floor control architecture, development of an activity model of the technical aspects of the product manufacturing process for discrete metal parts etc. [Barkmeyer et al. 1999]

National Institute of Standards and Technology (NIST)	
Foundation	1901
Headquarters	Gaithersburg, Maryland & Boulder, Colorado (USA)
Relevant industries	All manufacturing industries
Scope	USA; not limited to MES
Members	Governmental representatives
Homepage	www.nist.gov

Table 3-4: Organization profile of the NIST

Based on the MESA standard, the NIST defines the following MES functions:

- Resource Allocation and Tracking,
- Operations/Detail Scheduling,
- Production Units Dispatching,
- Specification Management,
- Data Collection/Acquisition,
- Labour Management,
- Quality Management,
- Process Management,
- Maintenance Management,
- Product Tracking and Genealogy,
- Performance Analysis,
- Material Management.

3.3 The Automotive Industry

While the definition and illumination of MES in the previous chapter has been rather general and independent of any specific industry, it is important to note that requirements on MES differ significantly depending on the industry and the type of production given (e.g. process manufacturing in the pharmaceutical industry in contrast to discrete manufacturing in the computer industry). We will therefore take a closer look on the characteristics and requirements of the automotive industry.

3.3.1 General Characteristics

The study at hand focuses on the automotive industry. Accordingly, the topic is investigated and analyzed against the background of automotive industry specific characteristics. In general terms, automobile manufacturers currently suffer from enormous cost pressure, which is partly due to strong price competition, but even more to the current economic situation in the automotive market, which is characterized by excess capacities necessitating reduction of production output. This cost pressure has a direct impact on the manufacturing in terms of demanding more efficient and leaner processes. Furthermore, automobile manufacturing is characterized by short delivery times, versatile production (i.e. numerous product variants), and short-term change requests. For the manufacturers this means they need up-to-date status information on the production process in order to be able to react at short notice.

3.3.2 MES in the Automotive Industry

As already suggested in Section 1.1, 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 manufacture of parts and simple components, flow or continuous production[4] in assembly, and a mixture of both in the manufacturing of complex components, such as engines) constitutes a crucial challenge for OEMs. 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

[4] The terms flow and continuous production are used synonymously in this report.

layers. This has to be borne in mind when evaluating currently implemented MES and considering future improvement possibilities.

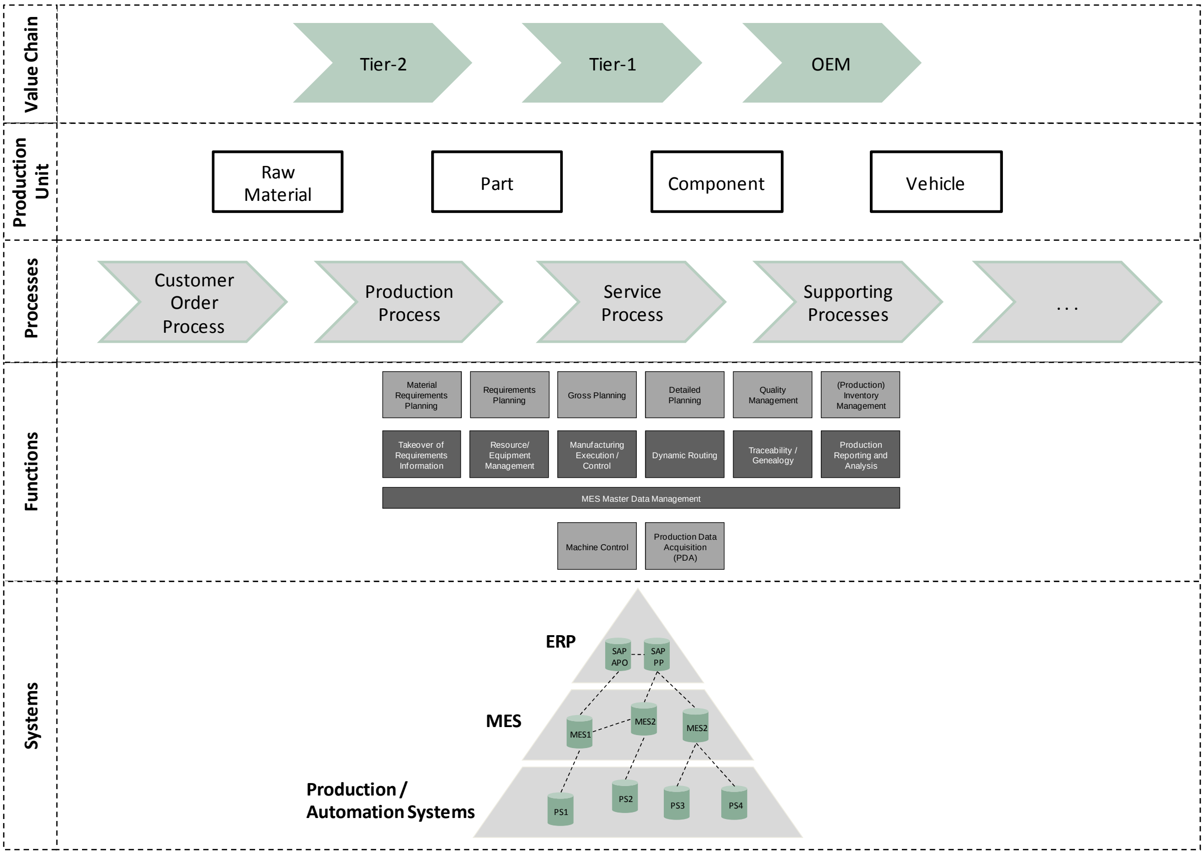


Figure 3-2: Major elements of the automotive value chain

As depicted in Figure 3-2 MES and its functional architecture does not only depend on the type of production and the manufactured product, but is also embedded in a broader architectural framework. It includes most notably the corresponding process architecture, i.e. the (manufacturing) processes in which the functionality is used, as well as the application architecture resulting from the distribution of MES functions to different application systems. The design of MES within the automobile manufacturing companies is in strongly influenced by the interdependencies between these architectural layers.

4 Study Findings

4.1 Current MES Strategy

As described in the previous section, MES is generally considered as an integrated process and IT topic within the automobile manufacturing companies, and is therefore not managed separately but within the overall process and application architecture. Accordingly, explicit MES strategies do not exist. Guidelines for the long-term as well as the mid- and short-term development of MES related processes and applications have been derived from the IT strategy (which is then cascaded to the different core business areas, such as manufacturing) and/or from strategic application maps. The strategic application maps contain the to-be application architecture, indicating which functionality is to be supported by which application, and they also contain the roadmap for all manufacturing related applications (for the ERP layer and for the MES layer). IT departments are urged to evolve their area of responsibility according to these construction plans.

Generally speaking, automotive companies are subject to high cost pressure, mainly due to the economic situation in the automotive market, which is currently experiencing a dramatic downturn. This cost pressure is passed over to manufacturing as well as to IT departments.

4.1.1 Strategic Goals

As discrete MES strategies have not been defined by the automobile manufacturers, the top strategic goals for MES have not been specified explicitly. However, the before mentioned IT strategies and application construction plans do follow general strategic objectives, which also apply for the issue of MES. These objectives include:

- meeting the requirements of the value chain processes (production, customer order);
- achieving operating reliability and ensure robustness to achieve 100% availability of the manufacturing processes;

- reducing complexity and cost (particularly IT cost) by
    a) consolidating the application landscape and decreasing the number of applications;
    b) "intelligent" standardization where possible and profitable, in order to increase reuse of software functionality;
- No per-se "best of breed" approach for MES, but rather case-specific evaluation.

In general, the assessment workshops showed that standardization is pivotal within all companies, particularly with regard to the issue of MES. Here, the challenge is to reach maximum standardization despite a considerable specificity of tasks, which is increasing the nearer these tasks are located to the shop floor. This problem particularly effects component manufacturing, where the production process is characterized by a high degree of variance and complexity, as products often change and the manufacturing process is disrupted quite frequently, making standardization of manufacturing processes and supporting applications more difficult.

4.1.2 Organizational Embedding

As MES is often viewed from a rather technical perspective, focusing on applications that support (parts of) the manufacturing process, responsibility for the subject is generally assigned to IT departments. This is also the case in the four companies examined. However, automobile manufacturers do emphasize the process view by assigning the design and implementation of production processes to the department responsible for MES, allowing them to develop MES solutions according to the specific requirements of the production process.

Moreover, the strategic significance of manufacturing processes entails that the automobile manufacturers aim at managing the issue of MES on a global level in order to achieve maximum homogeneity among all plants worldwide.

Organizational units appointed to deal with the subject are supposed to be commonly responsible for aligning the application landscape to process requirements, i.e. they are expected to develop guidelines for optimal application support of business processes. These guidelines are then implemented by the local IT department of each manufacturing plant. The globally responsible organizational units do not necessarily focus on MES solely, but are supposed to design the application landscape as a whole, including systems on the ERP layer and on the Shop Floor layer. Due to the differences in the production process (batch production versus flow production), in most cases the automobile manufacturers have separate units for assembly and component manufacturing plants.

Some of the automobile manufacturers have implemented so-called Centers of Competence (CoC) or boards, which do not just manage the topic globally but are composed of representatives from various plants, divisions (manufacturing, IT), or even production process types (component manufacturing, assembly). These organizational units aim at fostering standardization and minimizing the gap between component manufacturing and assembly (as far as possible).

4.1.3 Application Landscape and Integration

Concerning automobile manufacturers' applications on the MES layer, current efforts are commonly characterized by the will to consolidate and harmonize existing application landscapes in order to reduce IT costs. An average number of 70 applications being operated on the MES layer constitutes a serious complexity driver for integration and, as a consequence, enhances IT costs. Generally, the study revealed significant discrepancies between assembly and component manufacturing, which can mainly be attributed to the manufacturing characteristics given. Being characterized by a high degree of variance and very specific manufacturing tasks, standardization (of both processes and applications) in component manufacturing is much harder to achieve than standardization in assembly. Component manufacturing ranges from relatively simple components (pressed parts, cast parts etc.) to very complex components (such as engines or gears), and in many cases specialized applications are needed to support complicated manufacturing tasks. Accordingly, MES application landscapes tend to be more heterogeneous in component manufacturing plants.

In the manufacturers' assembly plants one to maximum three proprietary applications cover all core functionalities required on the MES layer (see Figure 4-1), except for very specific tasks, such as screwing technology or testing equipment, that are close to the shop floor. Applications are either self-developed or developed with external partners, and they cover areas such as production logistics and control, quality management, and machine control. In one case the MES solution implemented consists of several functional modules, which can be combined flexibly and allow for tailor-made adaptation to plant-specific requirements. In doing so, this OEM is able to reuse MES functionality across different plants, thereby increasing the degree of standardization and at the same time reducing costs for software development and maintenance.

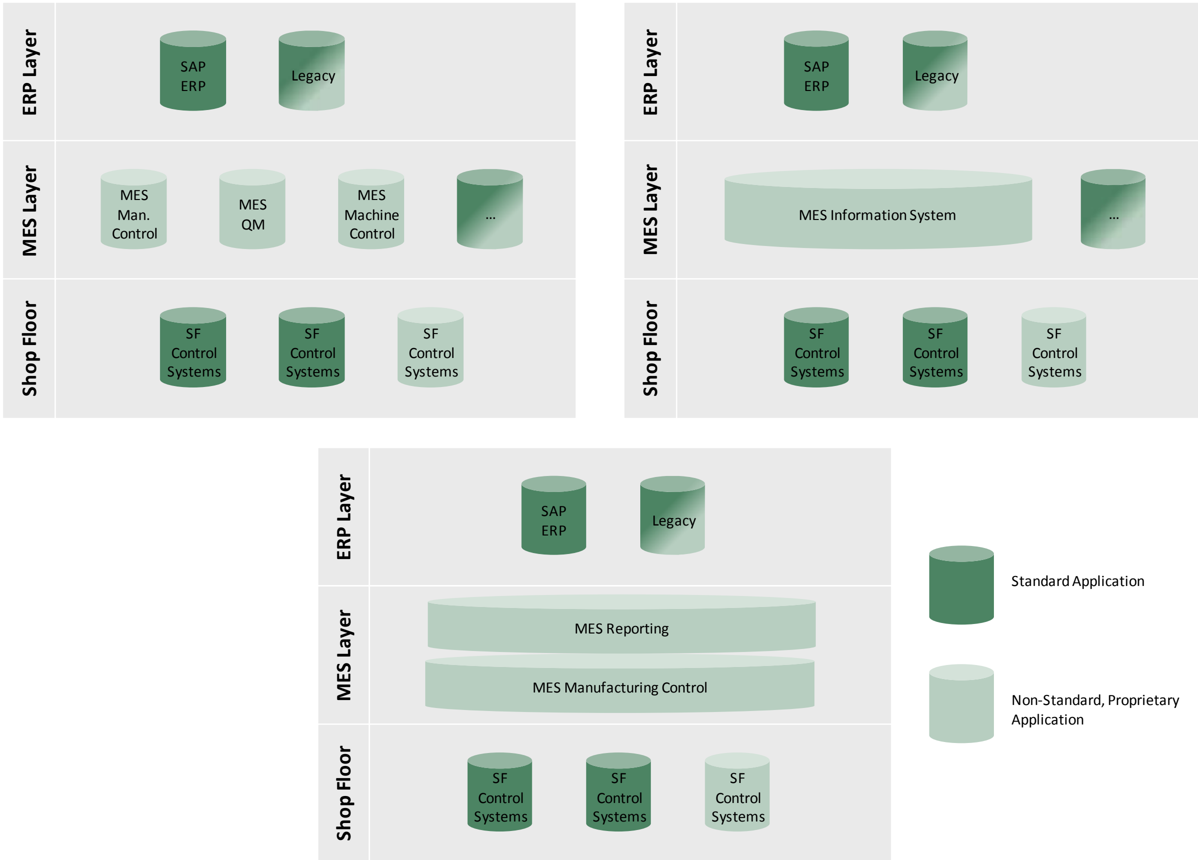


Figure 4-1: Simplified application landscapes in assembly plants

In automobile manufacturers' component plants, four to six self-developed systems are operated, covering different functionalities (see Figure 4-2). For example, there are separate applications to support the (detailed) planning process, connection to the control system on the shop floor, quality management, or production reporting. By this the possibility of accomplishing integrated MES is aggravated, as data is kept separately and in different formats. Furthermore, a large number of applications generally leads to higher operating IT costs. Only in one case a newly implemented MES (to which new functionality is constantly added) covers all core MES functions and can be described as integrated.

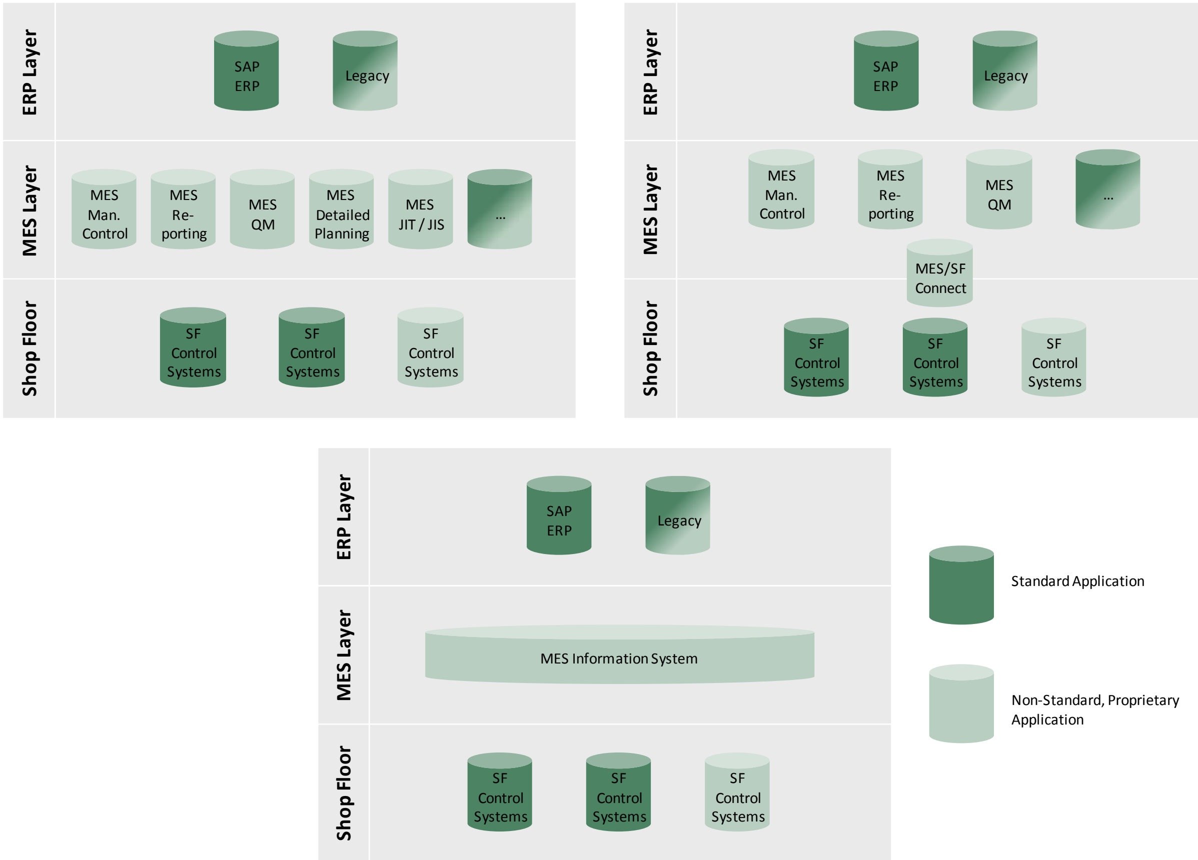


Figure 4-2: Simplified application landscapes in component manufacturing plants

In most of the automobile manufacturing companies integration of different MES applications is accomplished through so-called telegrams (i.e. message-based), which are standardized with regard to format and structure. Specification of the corresponding interfaces is mandatory for integrating newly acquired, additional applications (e.g. from commercial software vendors).

As can be derived from the findings described, MES applications are mostly non-standardized, proprietary. They were either self-developed or developed in close collaboration with external software partners (marked in light green in Figure 4-1 and Figure 4-2). This can be explained mainly by the automobile manufacturers' desire to support the manufacturing process with its specific requirements in the best possible way and to integrate with the existing, historically grown application landscape. Moreover, in most cases the applications currently operated were developed several years ago leaving the potential of new, up-to-date technologies unexploited.

Commercial software vendors, in turn, have ignored the need for software support between the ERP layer and the Shop Floor layer for a long time, which is why the automobile manufacturers have begun to develop appropriate applications on their own. Although all four OEMs have always recognized the advantages of a standardized and integrated MES (which is most notably characterized by reduced effort for integration and maintenance as well as increased flexibility), they have often expressed their scepticism regarding feasibility.

On the ERP layer the degree of standardization is considerably higher. Legacy systems are being increasingly substituted by standardized, commercial ERP systems, with SAP being the dominant software provider (ERP, APO).

4.2 Functional MES Reference Architecture

Reference models (and consequently architectures as specific models as well) are characterized by three attributes [Fettke/Loos 2004]: 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 again by simply applying pre-defined adaptation mechanisms reducing the effort for redevelopment. Finally, reference models contain best practices providing recommendations for conducting business. 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 [Becker et al. 2002, p. 49]. In our study, we pursue the first approach based on the four case studies. The functional MES reference architecture is represented by the so-called MES Function Map.

4.2.1 Generic MES Function Map

The MES Function Map visualizes different business and manufacturing functions and assigns them to one of the three layers, namely ERP, MES, and Shop Floor, or, more precisely speaking, to the corresponding applications assigned to these layers. It can serve two objectives: firstly, it can be used as a means for communication (as done in our project during the assessment workshops); secondly, when instantiated the Function Map can be deployed to design or refine the application architecture by assigning software components to the function mapped.

The Function Map was initially developed on the basis of a literature review of MES related journal and conference articles from both research and business practice as well as established MES standards (see Section 3.2), such as ISA S95 [ISA 2000] and MESA [MESA 2000, MESA 2004]. Additionally, we analyzed MES related white papers of more regional standardization bodies, namely the National Institute of Standards (NIST, [Barkmeyer et al. 1999]) in the United States of America as well as the 5600 Directive of the VDI [VDI 2007] and a guideline published by NAMUR [NAMUR 2003] in Germany.

From the specifications of the standardization organizations presented we have derived a synthesis of relevant MES functions, which are depicted in Table 4-1. The footnotes refer to terms used by the standards that deviate from the function names used within the IME project.

	MESA [MESA 2000]	NAMUR [NAMUR 2003]	VDI [VDI 2007]	NIST [Barkmeyer et al. 1999]
Labour Management	X		X	
(Material) Requirements Planning		X[1]		
Gross Planning		X[1]		
Detailed Planning	X	X	X	X
Quality Management	X	X	X	X[2]
Production Inventory Management	X	X[3]		X
Resource Management	X[5]		X[4]	X[5]

	MESA [MESA 2000]	NAMUR [NAMUR 2003]	VDI [VDI 2007]	NIST [Barkmeyer et al. 1999]
Equipment Management / Maintenance	X[6]		X	X[6]
Manufacturing Execution/Control	X	X		
Traceability/Genealogy	X			X
Production Reporting and Analysis	X[7]		X	X[7]
Machine Control	X			
Production Data Acquisition	X		X	X
Master Data Management	X[8]	X[8]	X[9]	X

[1]Operation neutral Production Planning
[2]Quality Analysis
[3]Stock Management
[4]Material Management
[5]Resource Allocation and Tracking
[6]Maintenance Management
[7]Performance Analysis
[8]Document Control
[9]Information Management

Table 4-1: MES functions as specified by different standards[5]

Beyond a mere definition of MES tasks, the VDI 5600 Guideline also identifies and characterizes objects to be managed on the MES layer (such as resources or data) and not on the ERP layer or the Shop Floor layer.

For the design and development of an MES functional architecture in the automotive industry the investigated standards were uniformly estimated as inexpedient due to the insufficient degree of detail of the provided definitions and the lacking focus on specific requirements of the automotive industry by the interviewed experts.

With regard to our goal of deriving a functional MES reference architecture, we have used the specifications of these standards as a starting point for a more detailed definition of MES and related functions, which later resulted in the MES Function Map. The generic MES Function Map, as illustrated in Figure 4-3, comprises the three layers already specified, namely ERP, MES, and Shop Floor. To each layer, corresponding processes or functions are assigned. The first cluster of functions is

[5] A more detailed description of the functions with single tasks for each of the standards can be found in Appendix B.1.

the category of typical business functions, such as sales and distribution or materials management, which is assigned to the ERP layer. To the Shop Floor layer we assign functions that are directly concerned with the control of machinery, such as Distributed Control Systems, Remote Terminal Units and Programmable Logic Controller.

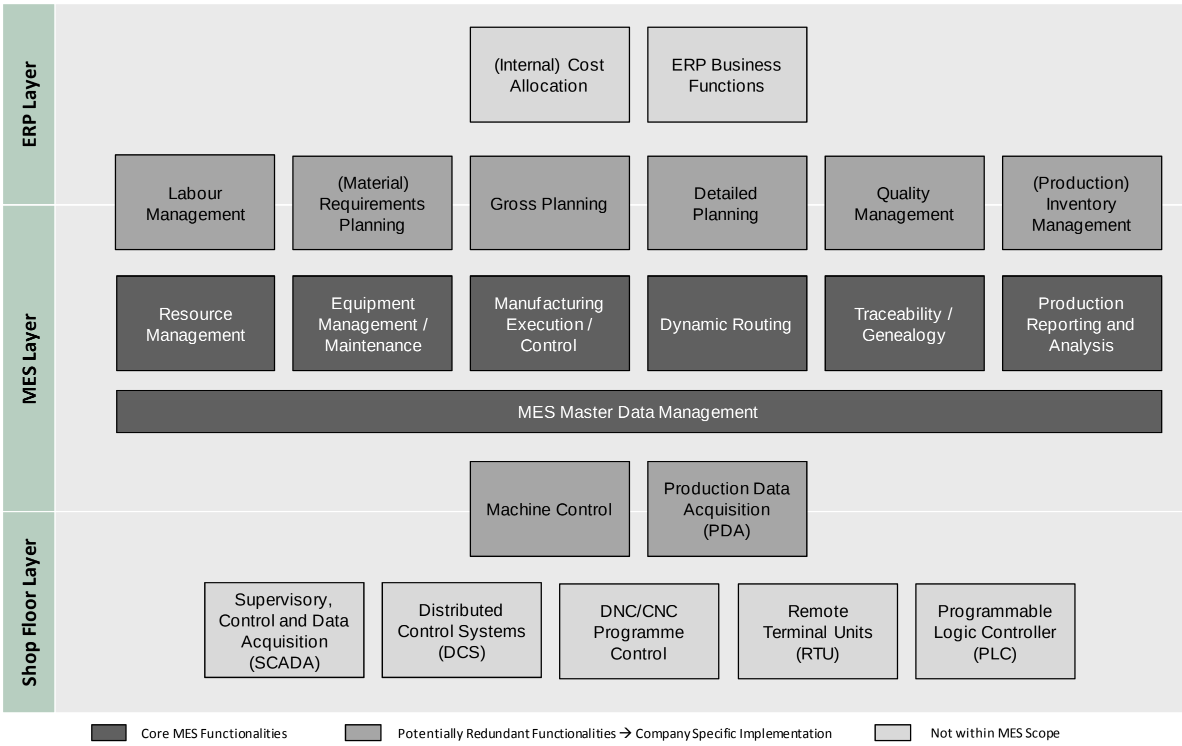


Figure 4-3: Generic MES Function Map

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, such as SAP. Moreover, our initial expert interviews carried out to verify the MES Function Map (see Table 2-1) confirmed the potential of this function for cost and time savings in the manufacturing process.

The main functions are shortly described in the following. More detailed definitions for each function are provided in Appendix B.

- *Labour Management* provides information on the status of personnel in an up-to-the-minute time frame including time logging, attendance reporting, qualification documentation, and staff scheduling.
- *Gross Planning* derives primary requirements from the total customer orders received and from forecasts made during sales and requirements planning. It is also referred to as Rough Production Planning.
- *Detailed Planning* takes over the production requirements from Gross Planning and derives production orders under consideration of production restrictions with detailed time scheduling (sequencing) and job sizes (concrete production plan/schedule).
- *Quality Management* provides timely analysis of product and process measuring taken from manufacturing operations in order to ensure product quality control, including quality/inspection planning, inspection execution and documentation, and management of test equipment.
- *Production Inventory Management,* also referred to as Stock Management, documents all current and available stocks of material (input material, intermediate and final products) including their location.
- *Resource Management,* or Material Management, aims at need-based supply with and disposal of material on schedule within the manufacturing process, including management of work-in-progress (WIP) material, i.e. resources that are currently outside central stock-keeping. The function is often referred to as Material and Production Logistics.
- *Equipment Management / Maintenance* ensures availability of machinery equipment on schedule and, therefore, manages all equipment information including maintenance and repair required.
- *Manufacturing Execution and Control* guarantees production and material flow according to the detailed production schedule (production monitoring) and

sends back information on the actual process. It can also alter the production schedule and provide Electronic Control Station (ECS) and Planning Table functionality.

- *Traceability and Genealogy* provides transparency as to the production status including localizing of manufactured goods at any time during the manufacturing process. Moreover, it tracks, collects and verifies information about sub-components being assembled to parent components. This record allows for traceability of components and usage of each end product.
- *Dynamic Routing* 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 function is often included in Manufacturing Execution and Control.
- *Production Reporting and Analysis* allows for up-to-the-minute reporting and analysis of actual manufacturing. The function allows for Statistical Process Control (SPC), i.e. to compare planned manufacturing and actual manufacturing using performance indicators which can be graphically visualized.
- *Machine Control* constantly monitors the status of all machinery collecting machine data (Machine Data Acquisition).
- *Production Data Acquisition* ensures event-driven acquisition, storage, and update of data from the production process, including manual acquisition, data pre-processing, and automated data transfer. Usually, this function provides initial plausibility checks are provided in order to minimize entry errors.
- *Master Data Management* is a synthesis of the two functions “Information Management” (defined in the VDI standard) and “Production

Documentation" (defined both by MESA and NAMUR), as these tasks are fairly similar, allowing to manage records (of product or equipment master data) that preferably should be kept within the production unit.

Some functions have been deliberately positioned in between the layers. Although some MES standards do assign these functions to the MES layer, in practice they are not always implemented on one layer or the other unambiguously. Implementation of these functions often is determined by company specific or production site specific factors. Quality Management, for example, can be assigned to either ERP systems or to MES; in some cases even overlapping implementations on both layers exist. If this is the case there has to be a good matching between the ERP system and the MES, as the entire process is running across systems [Lampl 2009, p. 99]. Therefore, we left this question to be answered by our project partners and the Function Map to be instantiated flexibly.

However, we have provided a basic definition for each function in order to allow for a common understanding, so that assignment to one or more of the layers is facilitated. It is important to emphasize that the functions described are not totally disjunctive but may overlap to some extent.

4.2.2 MES Function Map Instantiations

MES Function Maps as they were instantiated by the automobile manufacturers are enclosed in Appendix A. Due to the fact that in one case study three plants of one OEM with different production process types were examined, Figure A-1 contains six different MES Function Map representations.

During the assessment workshops it turned out that some of the functions had not been sufficiently detailed, preventing unambiguous assignment to the layers. We therefore decided to further specify each MES function in terms of determining sub-functions and corresponding tasks. Again, the above-mentioned standards (see Section 4.2.1) served as a starting point for definition. Appendix B.1 gives a definition for each MES function by listing all tasks defined by the respective standard. Based on this analysis we developed a consolidated list that includes essential tasks of each MES function (see Appendix B.2). The list was validated and slightly complemented with findings from expert interviews and then used to verify the MES Function Maps instantiated during the assessment workshops, enabling us to more precisely assign MES functions and related tasks to the three layers. Figure 4-4 shows an exemplary MES Function Map with assignment of the tasks defined in Table B-2. Each of the letters denotes a single task of a MES function with tasks belonging to the same MES function having the same letter.

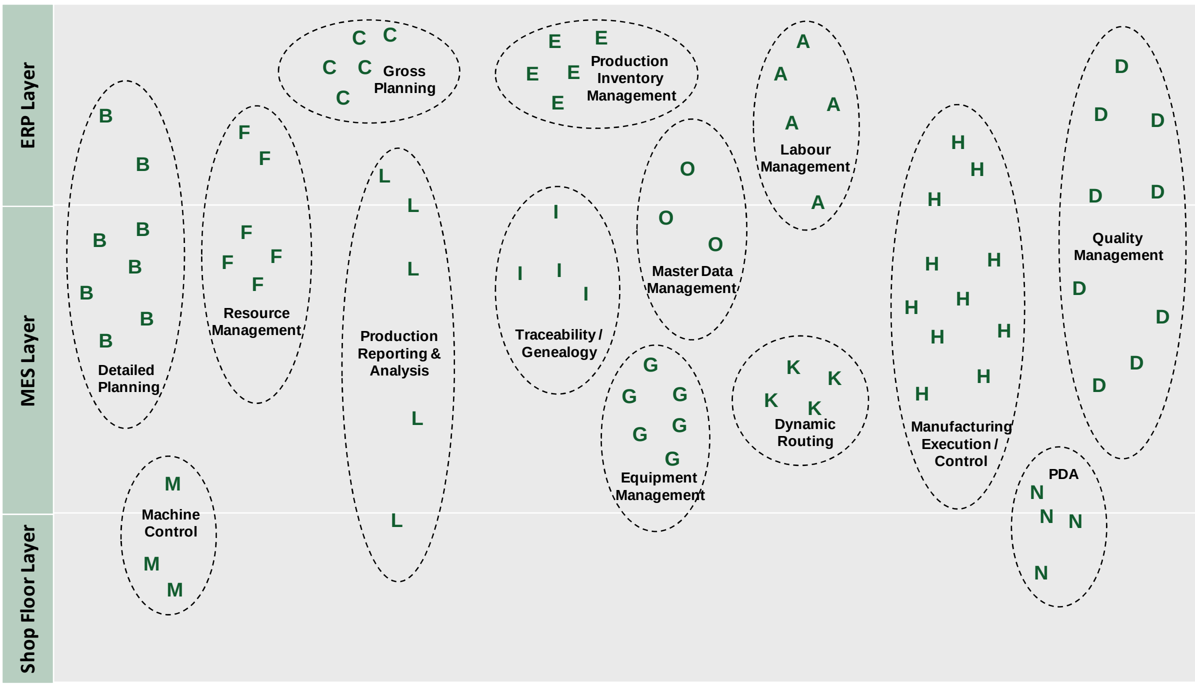


Figure 4-4: MES Function Map as instantiated with detailed tasks

The automobile manufacturers' functional MES architectures illustrated by the respective MES Function Maps have revealed some functional requirements that need to be met by MES software products. One major finding from the comparison of the different instantiations is that a generalized statement with regard to functional requirements across all automobile manufacturers cannot be made. Requirements are rather company specific or production specific, with the MES layer (and corresponding applications) covering different functions, raising the question whether the notion of standardized MES solution support is realistic at all. Moreover, the heterogeneity identified leads to another question about the factors influencing the assignment of functions to the different layers. This topic is addressed in more detail in Section 4.2.4.

Nevertheless, based on the total number of MES Function Map instantiations some general trends on functional MES requirements could be identified (see Figure 4-5). For instance, Detailed Planning, Traceability and Genealogy, Dynamic Routing, Production Reporting and Analysis as well as Manufacturing Execution and Control are mostly seen as core functions to be addressed on the MES layer[6]. For other functions, such as Resource and Equipment Management, and Quality Management, MES applications need to provide support. Here, the topic of integration with applications from the ERP layer and the Shop Floor Layer, covering some of the tasks of these functions, is predominant. Evaluation of MES functions from an integration perspective is discussed in more detail in the following section.

Figure 4-5 shows the frequency distribution of all functions of the generic functional reference architecture with regard to being assigned to the MES layer.

[6] These conclusions are made independently from the importance of each function for each OEM investigated. The topic of relevance is discussed separately in chapter 4.2.3.

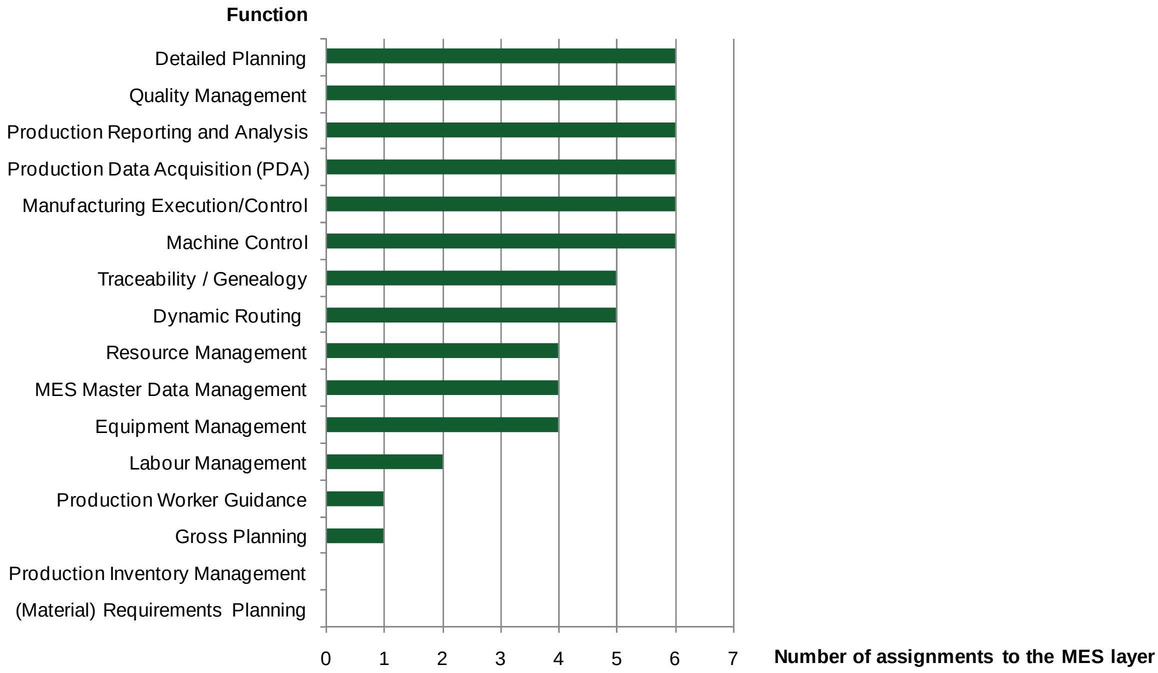


Figure 4-5: Functions to be covered by MES applications

4.2.3 Prioritization of MES Functions

Beyond the goal of achieving terminological clarity, the MES Function Map served for prioritizing MES functions, depending on their relevance for the respective Company as well as on their estimated contribution for improving the manufacturing process. Although the automobile manufacturers revealed a rather heterogeneous picture here, the assessment workshops yielded some findings that can be generalized.

Firstly, a general tendency could be identified that MES applications should first and foremost support basic MES functions, such as Detailed Planning, Manufacturing Execution and Control, Production Data Acquisition, or Production Reporting. Although the potential for efficiency gains of functions such as Traceability and Genealogy or Dynamic Routing has been recognized and even first positive experiences with corresponding implementations have been made in some of the plants (most notably the component manufacturing plants), these functions are assessed rather as supplementary "nice to have" functions by the majority of the workshop participants. More importance is attached to non-functional requirements such as guaranteeing sufficient integration with existing applications (be it on the MES layer or on the ERP and the Shop Floor layer). This point was a typical example for the importance of non-functional requirements, which in many cases were valued more highly than purely functional requirements. They are discussed in more detail in section 4.2.5.

Secondly, there seems to be a significant potential for improvement with regard to functions provided by several applications on different layers. A large number of functions was assigned to more than one layer, implying that application systems of different layers and with different planning horizons support execution of these functions (see also instantiated MES Function Maps in Appendix A). This leads to the need for effective integration of these systems in order to enable continuous planning and control. Consequently, the MES functions can be prioritized with regard to the need for being integrated depending on their assignment to one, two or, all three layers (see Figure 4-6).

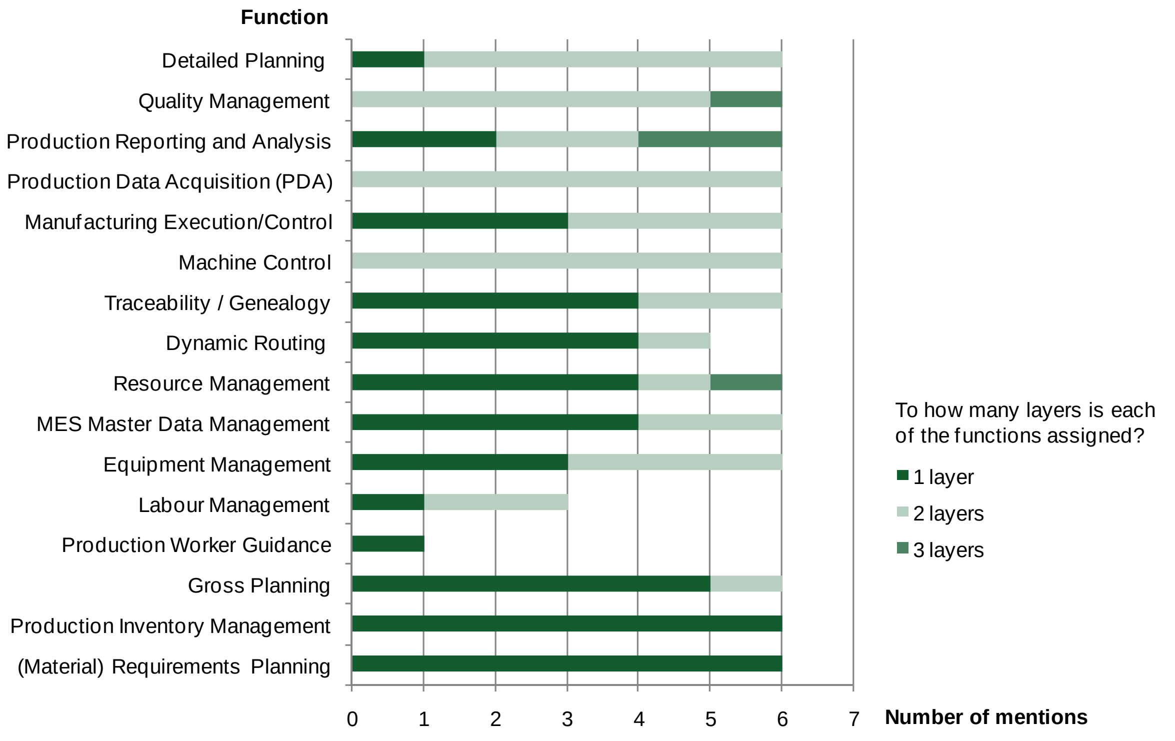


Figure 4-6: MES Functions prioritized depending on number of assigned layers

The graphic reveals that Quality Management as well as Production Reporting and Analysis are typical functions that strongly require vertical integration of application systems on the different layers. Depending on the time horizon, for example, sub-tasks are provided either by ERP systems, by MES applications, or directly on the Shop Floor layer, leading to increased demand for integration of the layers. As far as Quality Management is concerned, inspection planning, preventive quality management, and long-term documentation are often assigned to the ERP system, while MES applications take care of the actual testing (including determination of the inspection scope), the blocking of parts for testing, or the management of rework. Here, an integrated MES covering the entire set of tasks based on a consistent data basis would considerably improve the quality of planning processes and manufacturing execution, and, consequently, would lead to time and cost savings. In individual cases, these savings were estimated to be as high as 10 % of current lead times or manufacturing process costs.

Thirdly, a major point on the agenda for departments being responsible for the issue of MES is the challenge of ensuring an integrated and consistent manufacturing database. This requirement refers to the area of MES Master Data Management and, based on this, affects Production Analysis and Reporting. Due to isolated, autonomously working applications, data is recorded and stored redundantly and in different formats and structures, impeding data exchange along the manufacturing process (horizontal integration) and aggravating aggregation of data for production reporting purposes (vertical integration). Here, a MES application that is built on an integrated, common database representing a "Single Version of the Truth" would provide significant benefits, such as higher data quality (less redundancy), faster generation of reports (time savings), and reduction of work and effort (cost savings).

Finally, potential for improvement was identified with regard to accurateness of planning. Transferring information from the Shop Floor layer more promptly to overlying planning systems (be it on the MES layer or on the ERP layer) would allow for more flexible and precise planning of materials, production parts and equipment (Gross and Detailed Planning), and human resources (production worker planning). As a result, utilization of resources and machinery would be increased, saving costs by reducing non-productive capital.

Based on the workshop participants' evaluation of the MES functions regarding their potential for improvement of the manufacturing process (regarding time, costs, and process quality), we have developed a radar chart summarizing the results discussed in the previous paragraphs (see Figure 4-7). The radar chart allows for visualizing multivariate data in a two-dimensional diagram, in our case the quantitative improvement potentials for the three dimensions costs, time and quality for each of the MES functions (depicted on the axis of the diagram). While we initially aimed at obtaining concrete numeric values for evaluating the potential for improvement each function is expected to yield, the general conclusion of the majority of workshop participants was that any kind of quantification was hard to make here. Due to increased efforts undertaken by the automobile manufacturers in the past years for enabling improved IT support of manufacturing processes and increasing their efficiency, further potential for improvement with regard to time, costs, and process quality was assessed as rather small. As a consequence, the database for quantitative analysis of the potential for improvement turned out to be quite weak. The charts resulting from the assessments were not developed on the basis of concrete figures but rather on rough estimates given by the workshop participants. The radar chart in Figure 4-7 follows a numeric scale, with “1” indicating a possible improvement of up to 5 percent, “2” of up to 10 percent, and so on. In one of the cases, experience values of the already introduced integrated MES were included in the diagram. The value “0” indicates that a function was unanimously assessed as having no potential for improvement if a standardized, integrated MES solution is used. As Figure 4-7 indicates, the average improvement potential across all case studies did not exceed scale “1”, signifying improvement potentials of less than 5 percent.

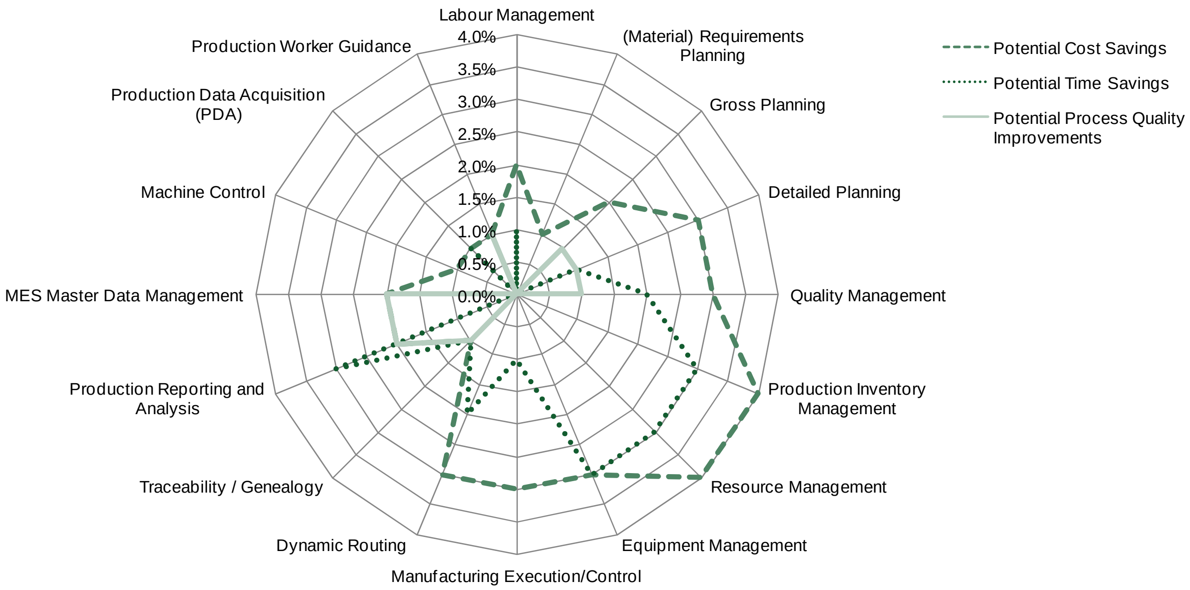


Figure 4-7: MES Functions’ potential for improvement of manufacturing process

The chart reflects quality optimization potentials resulting from improved Master Data and Quality Management as well as possible cost savings arising from reduced material stocks and more efficient equipment utilization (Inventory and Resource as well as Equipment Management). Potential benefits are discussed in more detail in chapter 4.3.2.

As a final, more general remark concerning the functional scope of MES, the comments of several workshop participants with regard to the degree of IT support for manufacturing tasks were contradictory. While some representative consider increased automation as positive, others expressed a demand for reducing IT functionality, thereby freeing the production worker from too complex and too rigorous worker guidance and giving him more autonomy in decision-making. Rather than automating every task of production control, the role of MES applications is to support the production worker in autonomously taking decisions during the manufacturing process.

4.2.4 Parameters Influencing Instantiation of the MES Function Map

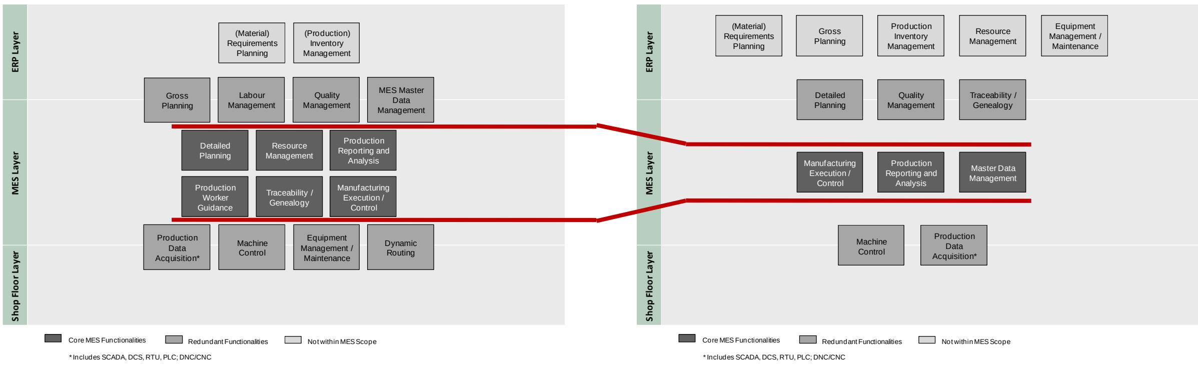
As the previous section has shown, instantiation of the generic MES Function Map may vary significantly (see Section 4.2.2). This being recognized, it becomes obvious that it would be helpful to identify parameters influencing instantiation of the MES Function Map. In terms of established approaches for reference modelling they can be interpreted as configuration parameters describing the context of application of the functional MES reference model [Becker et al. 2002, p. 27]. They allow for adaptation of the model through adaptation principles of specialisation and analogy construction [Becker et al. 2004, pp. 259-260, vom Brocke 2007, pp. 64-68]. Based on the analysis of the instantiations made and on intensive discussions during the assessment interviews, we have identified the following parameters:

- *Plant Type (Manufactured Product).* Component manufacturing (batch production) and assembly (flow production) pose different requirements in terms of functions needed (see Figure 4-8). Additionally, we have to distinguish between foundry 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.* This parameter is generally dependant on the production process type as component plants are characterized by a larger number of production variants (including different production process types, such as batch and flow production, individual and series production) resulting in more sophisticated requirements on prompt mounting of manufacturing equipment or flexible production process adaptation.
- *Production Quantity.* According to the workshop participants, instantiation of the MES Function Map largely depends on production quantity, i.e. the total amount of items produced (individual production vs. series production).
- *Vertical Range of Manufacturing.* The percentage of the manufacturer's own value creation, i.e. the in-house production depth, was also identified as an influencing parameter.
- *Location.* 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 and feasible system-based support of functions is much lower than in highly automated plants.
- *Production Worker Autonomy.* 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 Field vs. Brown Field.* 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 plant type (depending on the product manufactured), as we had representatives both from component manufacturing (production of parts or simple components as well as complex components) and from assembly plants participating in the workshops. The peculiarities of the two plant types lead to specific assignments of some functions and to differing evaluations of their relevance. Figure 4-8 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). Although not generalizable to all companies, there is a tendency towards a MES layer covering a wider range of functions in component manufacturing plants than in assembly plants. This 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 response 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.



Component Manufacturing Plants **Assembly Plants**

Figure 4-8: Differences in MES function assignment between component manufacturing plants and assembly plants

Furthermore, the importance of some of the MES-related functions is evaluated differently depending on the plant and production process type. For example, Dynamic Routing and Production Worker Guidance are seen as a function of higher significance for assembly than for component manufacturing.

Future research will be necessary to validate the impact of the above-mentioned influencing factors/parameters. This would include instantiation of the MES Function Map in more manufacturing plants that clearly differ with regard to these factors/parameters in order to allow for more comprehensive evaluation.

4.2.5 Non-Functional Requirements

With the assignment of the different functions to the three layers (ERP, MES, and Shop Floor) discussed in the previous sections, functional requirements which are or should be provided by MES (standard) software can be derived. Beyond that, the assessment workshops revealed a number of non-functional requirements that are summarized in Table 4-2.

Requirement	Description
Adaptability / Extensibility	The organizational unit responsible should be able to easily make modifications in the MES software according to company-specific or plant-specific requirements. Easily here means the possibility to be able to modify the application's source code without needing external help

Requirement	Description
	and to maintain the system autonomously.
Operating Reliability / Robustness	MES software should be reliable and allow for an availability rate of nearly 100 percent in order to avoid production downtimes and lost units.
Integrability / Connectivity	MES software should provide standardized interfaces or be able to connect to interfaces provided by a) existing applications providing MES functionality, b) existing control systems and manufacturing equipment on the Shop Floor layer, c) existing ERP systems.
Sustainability	MES software should be enduring, in the sense that it can run for a longer period of time in order to avoid frequent changes.
Usability and Simplicity	For the production worker as the main user, MES software should be easy to use and grant decision autonomy in case of need.
Central Deployment	MES software should be centrally deployable, including automatic distribution of system updates and changes instead of requiring multiple individual adaptations.

Table 4-2: Non-functional requirements on MES software

The list of non-functional requirements was consolidated after the assessment workshops and then fed back to the participants for further evaluation. All study participants were asked to, firstly, evaluate the excellence of their currently implemented MES solutions regarding each of the requirements and, secondly, classify the relevance of each requirement for evaluation of alternative MES solutions. For both evaluations we used 5-value Likert scales (ranging from “very poor” to “very good” and from “not important at all” to “very important”, respectively).

Evaluation of the currently implemented MES solution is illustrated in Figure 4-9.

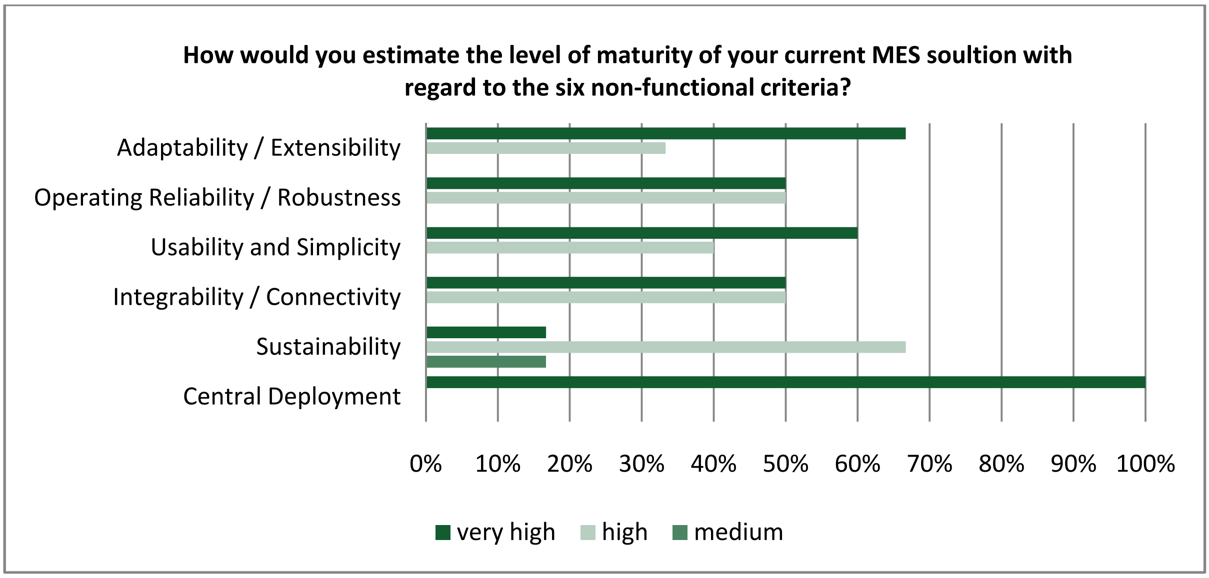


Figure 4-9: Evaluation of current MES solutions regarding non-functional requirements

Although the representatives express themselves positively on the fulfillment of the requirements rating it as "high" or even "very high", the main obstacle remains the insufficient sustainability of self-developed, proprietary MES. Fulfillment of this non-functional requirement is estimated considerably lower compared to the others. It discloses the need for standardized MES solutions that are built on current technologies and that are durable for the long-term replacing currently operated MES software that was developed based on past technologies.

The results of the second investigation concerning importance of the non-functional requirements on alternative MES solutions are depicted in Figure 4-10.

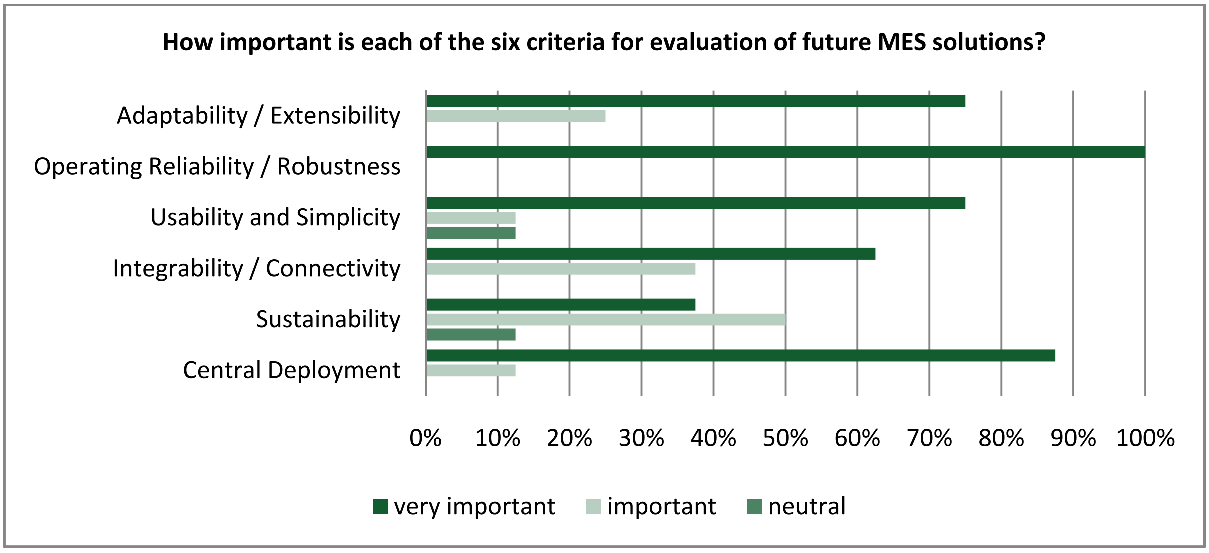


Figure 4-10: Importance estimation of non-functional requirements on MES software

The figure confirms relevance of the non-functional requirements in general as none of them was estimated as not important. However, comparison of the results allows for a prioritization. The almost universal estimation of "Operating Reliability / Robustness" and "Central Deployment" as very important indicates that these requirements are considered as basic prerequisites for deployment of any standard MES solution. Moreover, the participants put a strong emphasis on the ability to easily integrate the software in the existing application landscape and on being able to adapt and extend the provided functionality of the MES solution to plant-specific needs. Here, according to the workshop participants a modular solution consisting of a number of modules of which each one covers specific functions or supports specific manufacturing tasks is desirable. This would foster reuse of application functionality and, hence, reduce software development effort and costs.

4.3 MES Performance Management

For evaluating the potential impact of an improved integration both on the MES layer (horizontal) and between the layers (vertical), we firstly analyzed Key Performance Indicators (KPIs) that are employed by the OEMs summarizing them in a Business Benefit Framework and secondly tried to investigate cause-effect relationships between them.

4.3.1 Initial Business Benefits Framework

The initial Business Benefit Framework for IME was again designed on the basis of a review of existing literature on KPIs. For this purpose scientific papers (e.g. [Mende 1995, Muschter 1999]) proposing metrics for measuring process performance were analyzed as well as white papers from various associations of the manufacturing industry (e.g. [VDMA 2009]) defining production specific KPIs. From this analysis a list of core KPIs was extracted, which were then assigned to the three main benefit dimensions, namely quality, costs, and productivity (which includes the time aspect). The list contains KPIs that are considered relevant for measuring performance of the OEMs' manufacturing processes and that might be positively affected by an integrated application landscape on the MES layer. The initial list of KPIs of the Business Benefits Framework did not intend to be complete, but served as a basis for discussing the automobile manufacturers' specific KPI frameworks. The participants of the assessment workshop were asked to add further relevant, remove irrelevant, or adjust existing KPIs. For every KPI of the Business Benefits Framework a corresponding metric defining how the KPI could be measured was proposed (see Table 4-3).

Benefit Dimension	KPI	Metric
Productivity	Plant Productivity	Revenue per plant
	Output	Total Amount of goods produced
	Machine Load/Asset Utilization	Actual output / Nameplate capacity
	Overall Equipment Effectiveness (OEE)	Availability x Performance Rate x Quality Rate
	Unplanned Downtime	Monthly/weekly amount of unplanned downtime
	Lead Time/Cycle Time	Time from receipt of order to finalization of product

Benefit Dimension	KPI	Metric
	Process Cycle Efficiency	Value-added time / Lead time
	Plant/Production Process Availability (Variance)	Ideal or optimized lead time / Actual lead time
	Employee Productivity	Value added/Sales per employee
	Process Predictability	Overtime hours per week/month
	Adherence to Delivery Dates	Percentage of products delivered in time
Costs	Operational Costs	Costs that can be assigned to production process
	Rework Costs	Costs resulting from producing scrap
	Inventory Costs	Monetary amount of products in stock (inventory)
Quality	Scrap Rate	Number of defected products compared to total amount of items produced
	Scrap Value	Total monetary amount of scrap goods
	Completeness of Data	Percentage of duly completed data input fields
	Accuracy of Data	---

Table 4-3: Initial Business Benefit Framework

4.3.2 Business Benefits Framework Comprising Manufacturing Related KPIs

A summary of major manufacturing related KPIs is provided in Table 4-4. The table also shows different metrics that are used to operationalize the corresponding KPI.

	KPI	Metric
Productivity	Output	• Total amount of goods produced • Actual Output compared to Target Output
	Employee Productivity	• Performance Rate = Output x Allocated Time / Actual Time • Output per employee • Elapsed time or (engineering) hours per unit • Overtime hours per employee
	Overall Equipment Effectiveness	Availability x Performance Rate x Quality Rate
	Machine Load	Actual output / Nameplate capacity
	Unplanned Downtime	Monthly or weekly amount of unplanned downtime

	KPI	Metric
	(Manufacturing) Lead Time	• Time from receipt of order to finalization of product (mainly in car manufacturing plants) • Manufacturing hours per unit
	Adherence to Delivery Dates	Percentage of products delivered in time (mainly in car manufacturing plants)
Costs	Operational Costs (per unit)	Costs per component/vehicle
	Rework Costs (per unit)	Costs resulting from producing scrap
	Quality Costs (per unit)	Preventive Costs + Rework Costs + Scrap Costs
	Inventory or Warehouse Costs	Monetary amount of products in stock (average inventory)
	Lost Units	Number of units (components or vehicles) lost due to system failure
	Sickness Rate	Percentage of people absent due to illness
	Personnel Costs	Direct and indirect costs for personnel in manufacturing
Quality	Scrap Rate	Number of defected products compared to total amount of items produced
	Error Rate	Number of defects/damages or stranded vehicles per 1,000 units
	Rework Rate	Number of units that require rework (due to insufficient quality) → dependent on Error Rate
	First Time Right	Number of vehicles manufactured without rework (=1 – Rework Rate)
	Audit Grades	Grades resulting from internal Quality Management audits (with regard to product quality)
	Customer Product Audit	Product quality evaluated by customers (mainly in car manufacturing plants)
	Complaint Rate	Number of complaints from customers (mainly in car manufacturing plants)
	Plant Incidents	Number of incidents per plant
	Quality of Sequencing	Number of necessary re-sequencing

Table 4-4: Business Benefits Framework comprising manufacturing related KPIs

In general, the most important KPIs used by the automobile manufacturers to measure their plants' performance are Output, Lead Time, Employee Productivity, and, specifically for assembly, Delivery Reliability (i.e. Adherence to Delivery Dates). Another fundamental KPI that is used in the plants of all participating automobile manufacturers is Overall Equipment Effectiveness (OEE), providing an indication of how effectively machine capacities are utilized (machine load). However, due to the fact that OEE is composed of several sub-measures (availability, performance rate, quality rate), this KPI is afflicted with some weaknesses. Most notably, it lacks comparability, since it is not defined unambiguously but rather is based on different parameters that need to be interpreted on a case by case basis. Basically, the large number of product quality related KPIs is striking, which emphasizes the significance of quality conscious manufacturing in the automotive industry. The quality of manufacturing data is not actively and constantly measured in the manufacturing related processes, which is partly due to the huge amount of recorded data.

Figure 4-11 summarizes the manufacturing related KPIs used by the automobile manufacturers in the order of their frequency of being mentioned across all case studies.

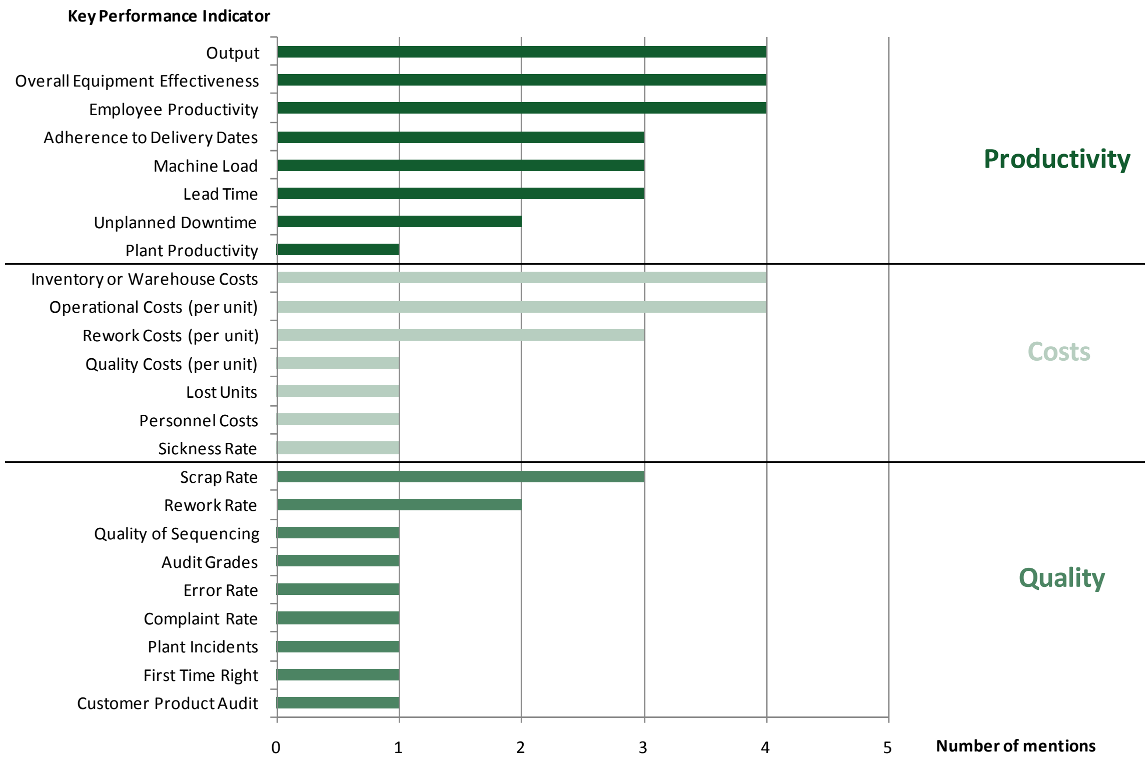


Figure 4-11: Manufacturing related KPIs used by the automobile manufacturers

Additionally, the departments responsible for MES are strongly measured by the level of guaranteed availability of the systems they account for supporting the manufacturing process. This KPI (Availability) is mainly measured by the number of lost units in case of system failures. Lost units are all components or vehicles the manufacturing of which could not be finalized or has brought about defects, and which therefore need rework or are directly rated as scrap.

The Business Benefits Framework presents a number of KPIs that are used to quantitatively measure the performance of manufacturing processes as well as the impact of an integrated MES on such processes. However, it lacks coherent representation of the interdependencies between the KPIs, which is why the impact of an integrated MES on these KPIs remains rather vague. In order to close this gap, we tried to explicate the impact as well as the interdependencies between KPIs. We therefore worked out a cause-effect network visualizing interdependencies based on the KPIs represented in Table 4-4. As a tool for visualization we used the so-called Benefits Dependency Networks (BDN), allowing us to show how innovative IT capabilities (the *means*), in our case an integrated MES, lead to necessary business changes (the *ways*) in order to achieve benefits and long-term goals desired (the *ends*) [Peppard et al. 2007, p. 5].

As already explained in Section 3.1, the essential goal of MES is to increase transparency on the manufacturing process as well as accuracy of manufacturing-related data. It was commonly agreed by the workshop participants that an increased degree of integration on the MES layer (as an "IT Enabler") would enhance transparency on the manufacturing process and accuracy of manufacturing data (as "Enabling Change"), showing, for instance, unused capacities and resources, parts additionally needed, or malfunctioning equipment. Thus, increased transparency has a positive effect on a number of KPIs, which is why "Increase

Transparency" has a central position in the "Enabling Change" layer (see Figure 4-12).

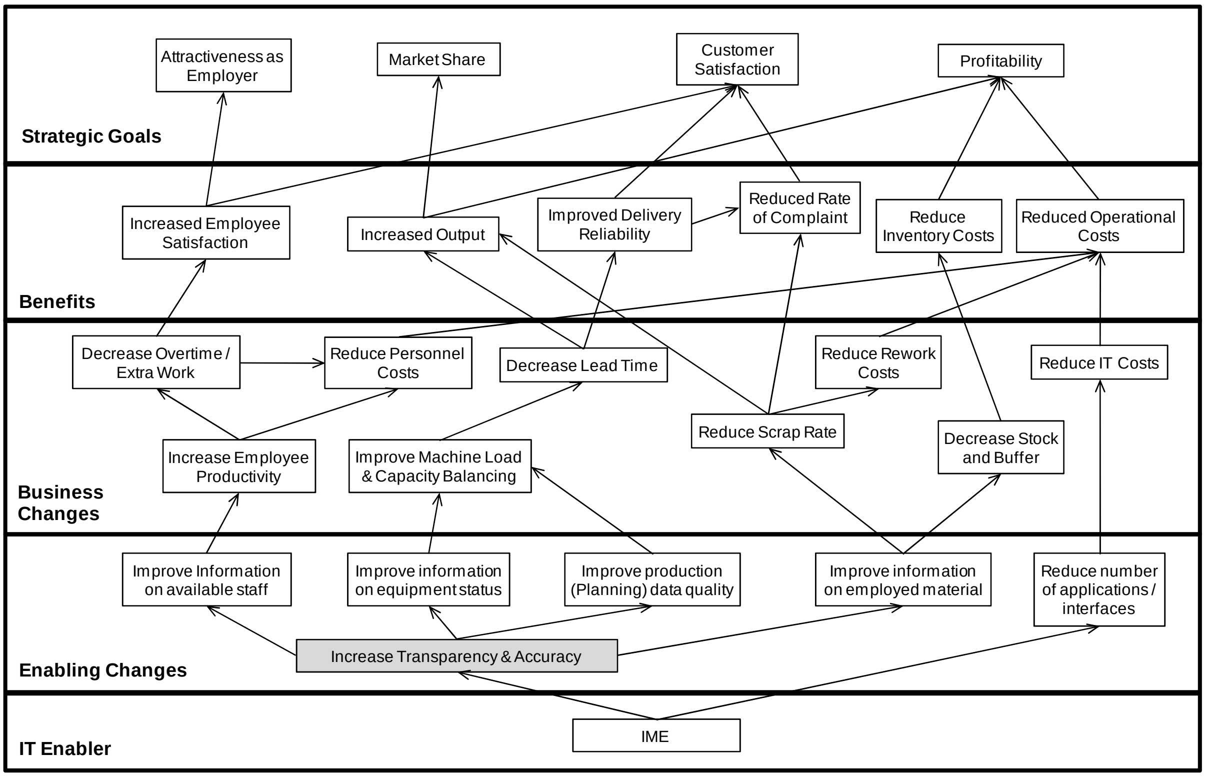


Figure 4-12: Cause-effect network for MES KPIs

In the upper section of Figure 4-12 the impact of different operational KPIs of the Business Benefit Frameworks on strategic goals is depicted. The cause-effect relationships there are rather loose and indirect.

The cause-effect network visualizes business benefits provided by an integrated MES, which were not obvious at first sight but became apparent in the discussion of the Business Benefits Framework during the assessment workshops:

- Based on transparent manufacturing process and accurate manufacturing data, the manufacturing management gets a more precise picture of the current capacity situation with regard to both personnel and equipment. This, in turn, leads to improved load balancing: WIP material and intermediate material can be rerouted to unused equipment, free personnel capacity can be used. As a result, the costs of capital employed are lowered or output is increased.

- Integration of Production Data Acquisition and Resource / Production Inventory Management allows for more transparency with regard to material used. As a consequence, material stock as well as buffers in the manufacturing process is reduced, resulting in lower costs of capital employed. In one of the case studies integration of Production Data Acquisition and Resource Management (based on integrated processes and data between the ERP and the MES system) improved the tracking of material in the manufacturing process, bringing about a reduction of stocked material of up to 50 % as well as a reduction of the material turnover time by almost 60 %, despite an increase in productive part numbers within the plant by one fifth within less than 18 months.
- Transparent and more accurate planning is achieved by integrating Manufacturing Execution and Control and Detailed Planning. In this way, up-to-the minute data from manufacturing is directly included in the production schedules and future production plans. This, again, allows for more efficient capacity utilization (machine load) shorter lead times, and higher output.
- Having personnel planning data and qualification data from Labour Management included in the production planning (Detailed Planning) allows for more efficient deployment of workers in the manufacturing process (according to availability and qualification), increasing plant productivity and satisfaction of employees (e.g. by less overtime work).
- Coupling of Machine Control (including acquisition of machine data) with Equipment Manufacturing and Maintenance fosters transparency regarding the current status/depreciation of machinery and directly triggers

maintenance measures in case of machine failure. This, in turn, improves capacity utilization, reduces (unplanned) machine downtime (which minimizes the lead time of the manufacturing process), and leads to more output.

- Integrated Manufacturing Control and Quality Management / Traceability speeds up identification and localization of faulty material or parts that can be replaced more rapidly. As a consequence, assembly of wrong or defective parts can be avoided and the scrap rate can be reduced, leading to less rework (costs) and higher output of error free components and vehicles.
- As far as Quality Management is concerned, inspection planning, preventive quality management, and long-term documentation are often assigned to the ERP system, while MES applications take care of the actual testing (including determination of the inspection scope), the blocking of parts for testing, or the management of rework. Here, an integrated MES covering the entire set of tasks based on a consistent data basis would considerably improve the quality of planning processes and manufacturing execution, and, consequently, would lead to time and cost savings. In individual cases, these savings were estimated to be as high as 10 % of current lead times or manufacturing process costs.
- Through facilitated aggregation of manufacturing data (resulting from uniformly defined data formats and structures) management information (reports) on production can be derived more quickly and flexibly. Necessary improvement measures can be addressed more precisely, further improving the quality of the production process.

Apart from these business benefits with regard to manufacturing related KPIs, an integrated MES also helps reduce the number of interfaces between applications, cutting IT costs for maintenance.

5 Summary and Outlook

5.1 Study Results

The IME study pursued the goal of describing criteria for further optimizing manufacturing execution in manufacturing plants of the automotive industry. Based on the case studies carried out at four OEMs, documenting the current status of MES related topics in the respective companies, the study aimed at developing a functional reference architecture for MES (MES Function Map) to be used in the automotive industry as well as a Business Benefits Framework allowing to measure the impact of an integrated MES on the performance of manufacturing processes. From these results, requirements on and recommendations for future, integrated Manufacturing Execution Systems can be derived. Although the results cannot be considered representative for the entire automotive or even discrete manufacturing industry but represent a consolidated view of the four OEMs some general trends can clearly be derived.

The case studies conducted revealed that the issue of MES today is considered as highly important and mission critical by all OEMs participating. It is managed as a strategic topic, and it is located in IT sub-departments that have company-wide responsibility in order to develop MES solutions standardized to the maximum possible extent. Although having a strong IT focus, the issue of MES is not considered from an application perspective only, but always together with corresponding manufacturing processes, meaning that the respective organizational units are also in charge of the engineering of MES related processes.

Furthermore, the study disclosed that the specific characteristics of component and car manufacturing processes lead to very different requirements regarding appropriate IT support. The higher degree of freedom in batch manufacturing causes higher variance in and more disruptions during the manufacturing process, requiring shorter response and changeover times. Consequently, the time horizons of production plans for component manufacturing are shorter, and the requirements on MES are significantly higher. While the procedural character of vehicle manufacturing allows for more automation that can directly be executed by the production systems on the Shop Floor, the MES layer in component manufacturing plants generally covers a larger spectrum of functionality. This is also reflected in the present application landscapes on the MES layer, which is more heterogeneous in the component plants due to a higher number task specific applications. Although the application landscapes (irrespective of the production process type given) are dominated by self-developed systems (often developed in collaboration with external software vendors), the OEMs participating have recognized the need for and are willing to implement standard MES solutions. However, the requirements to optimally support the manufacturing processes and integrate with existing applications are opposed to this goal.

The MES Function Map that we developed as an result of the IME study (see Section 4.2) brought up a number of 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, it can be said that a reference architecture for MES 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 further aggravated by a number of influencing parameters. These parameters were identified and described as an additional outcome of the IME study (see Section 4.2.4). In addition to these functional requirements, the study analyzed non-functional requirements on MES software, which are considered crucial by the OEMs examined.

Moreover, the study came up with a prioritization of MES functions depending on their potential for improving performance of the manufacturing process regarding quality, costs, and time. KPIs used for measuring process performance were identified and consolidated in the Business Benefits Framework across all OEMs investigated. In order to illuminate both interdependencies between relevant KPIs and the potential impact of integrated MES solutions on these KPIs, we developed a cause-effect network that allows to visualize and explain possible effects.

5.2 Critical Acclaim

It is important to point out that the findings of the study cannot be generalized. As we are aware of this general shortcoming of case study research, we tried to mitigate the problem by carrying out multiple case studies in one specific industry (automotive) in order to increase the validity of the study's findings. Nevertheless, the findings are not valid to OEMs other than the ones investigated in the study. This is not only due to the limited number of companies investigated but also a result (and this already is one important outcome of the IME study) of a company specific understanding and design of the MES layer (with regard to processes, organizational embedding, and application support). Although general best-practices were identified with the help of the four case studies, applicability of these best-practices in other (specific) cases cannot be taken for granted.

5.3 Outlook on Future Challenges

For the future, the challenge lies in standardizing not only MES application functionality but most notably the underlying processes. Particularly regarding further potential for optimization, significant improvements solely based on the enhancement of IT can hardly be achieved. There has been a common agreement that, instead, improvements can only be achieved by changing and standardizing manufacturing processes. However, this task becomes increasingly difficult the more the processes to be standardized concern manufacturing tasks. With regard to this process optimization, carefully balancing between cross-plant process standardization and a (justified) claim for plant-specific optimization of processes and corresponding IT support represents a major challenge in order to achieve a global, company-wide optimum. Additionally, standardization of the shop floor control systems in the course of standardizing manufacturing tasks will become an increasingly relevant topic for the future.

As mentioned several times during this study report, standardized "out-of-the-box" software solutions are (still) not capable of adequately meeting the requirements of heterogeneous manufacturing processes as they are common in the automotive industry. Consequently, the demand of our OEMs for more innovative solutions optimally supporting production processes has become louder. It is still unclear how such a tailor-made (for specific manufacturing tasks) but still integrated (with little effort) system may look like. The vision of so-called production portals (comparable to portal solutions in other domains, such as process or customer portals) providing each production worker with a role-based view on the information (from different systems) necessary for his specific task is often propagated as a possible solution. However, the portal concept disregards the actual and most critical problems of data and application integration, as it constitutes simple integration on the presentation layer (desktop integration) [Puschmann 2003, p. 27, Heutschi 2007, p. 17]. Therefore, a module-based or component-based solution with reusable software components that can be combined according to plant-specific needs appears more promising. Moreover, a strictly modular application structure would facilitate possible extensions in the future - one of the essential non-functional requirements mentioned in the study report. Such a system could (but does not necessarily need to) be implemented in a service-based way by defining services that encapsulate certain manufacturing functions functionalities. As an architectural alternative the implementation of software agent platforms to integrate existing software systems from different layers has gathered increasing interest in recent years [Sauer 2004]. Although first prototypes have been successfully implemented, the technology is not yet fully proved in manufacturing operations. Therefore, the question is still left open how powerful and efficient such a solution is in operation.

From a research perspective, evaluation and refinement of the functional reference architecture for MES constitutes a challenging task for the future. It will be necessary to validate the impact of the factors influencing instantiation of the MES Function Map. For this purpose, adoption of the reference architecture in more manufacturing plants would allow for more comprehensive evaluation and identification of functional patterns for different types of manufacturing plants.

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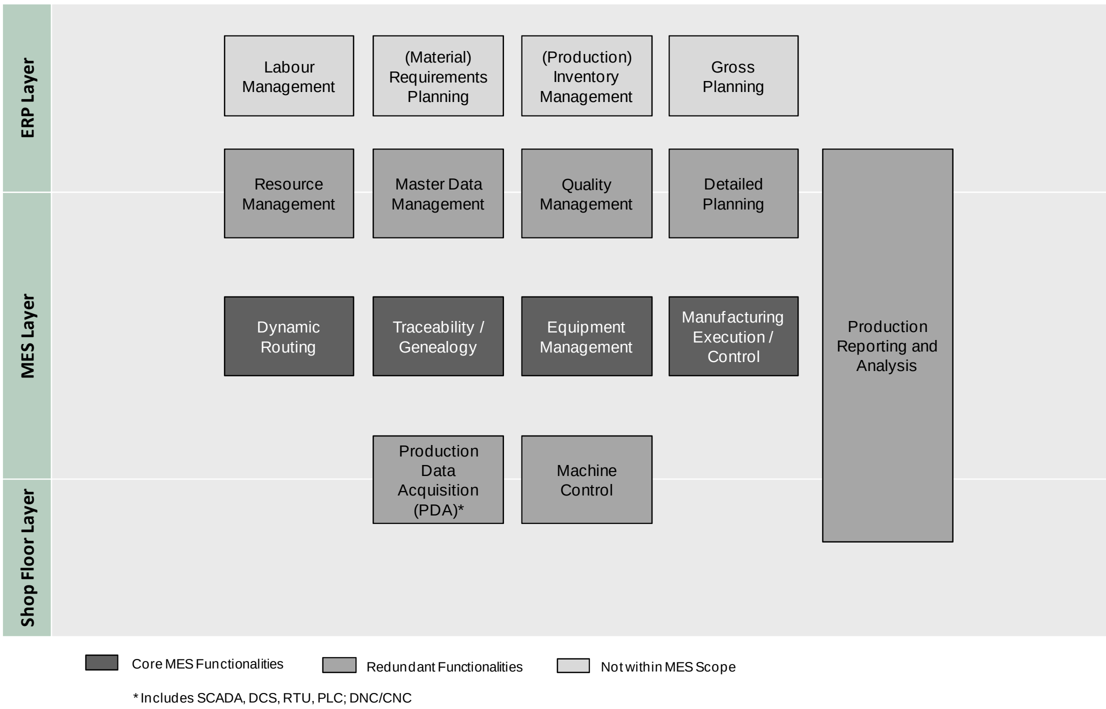
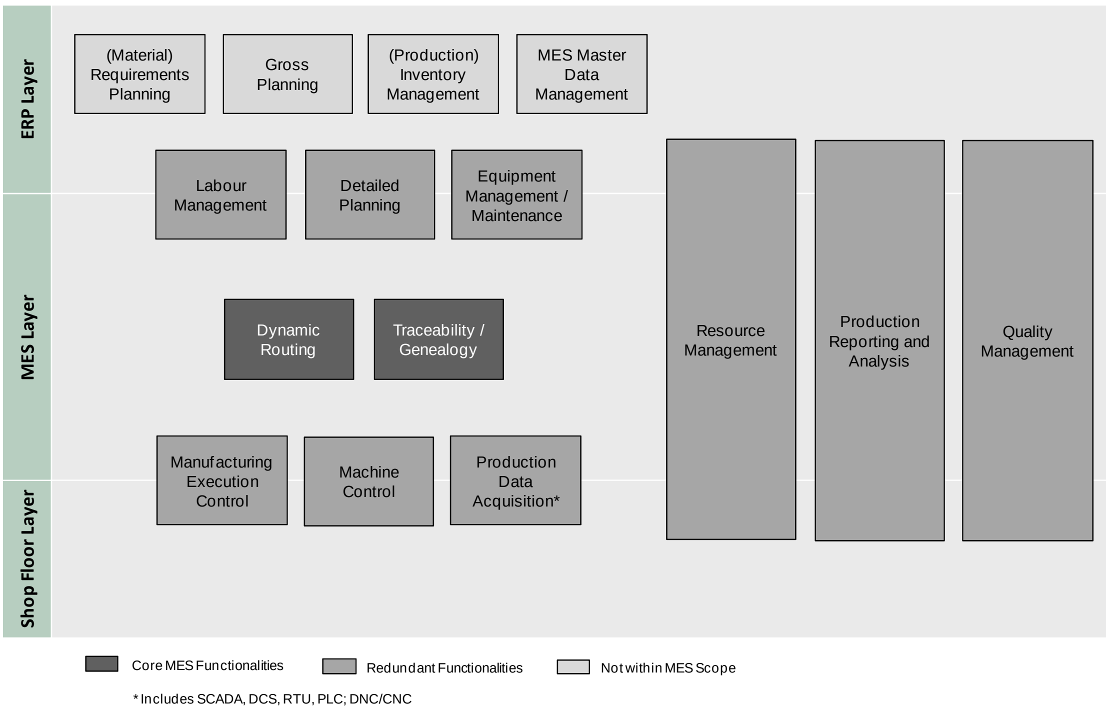
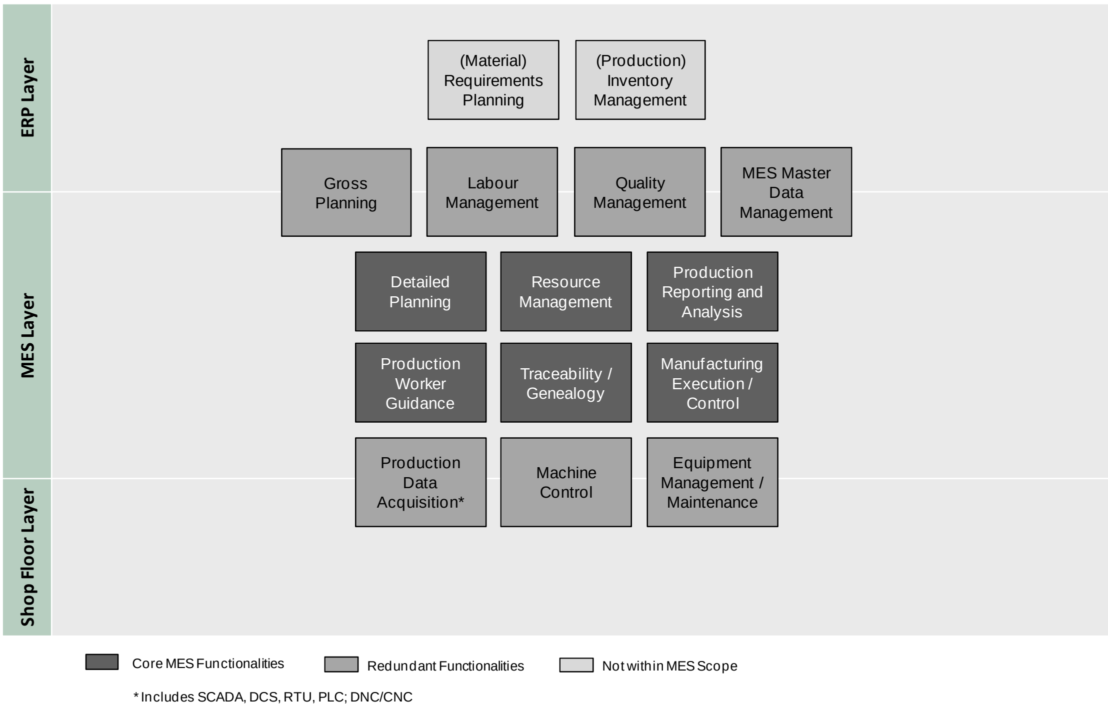
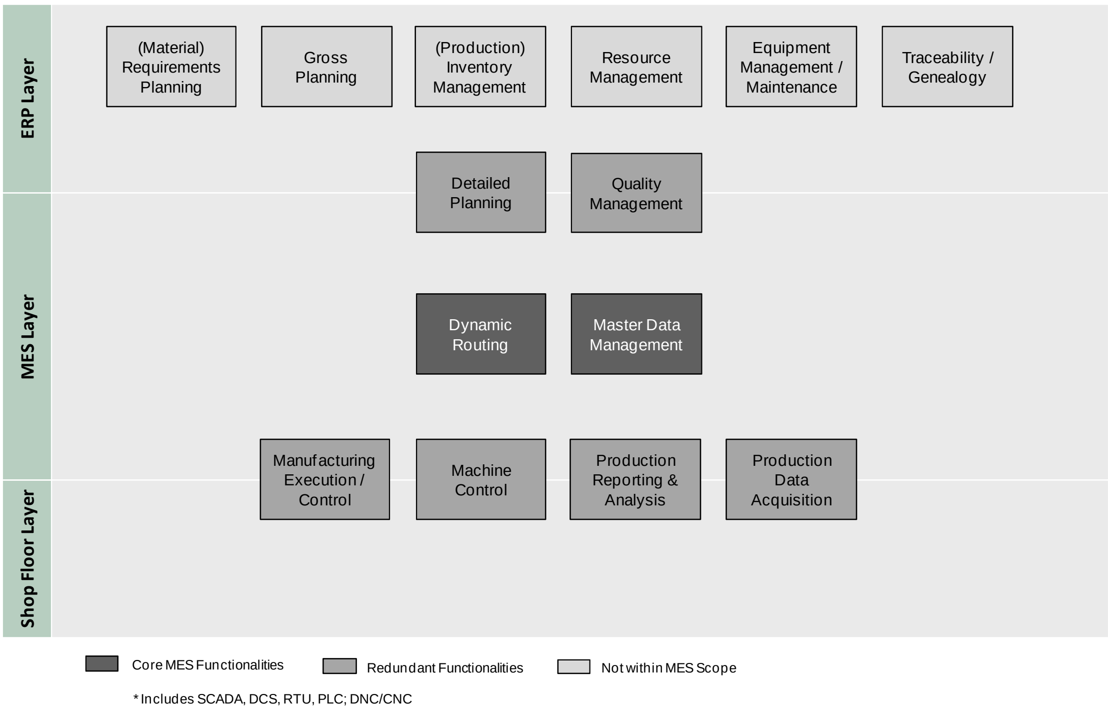
Appendix A: Instantiations of the MES Function Map

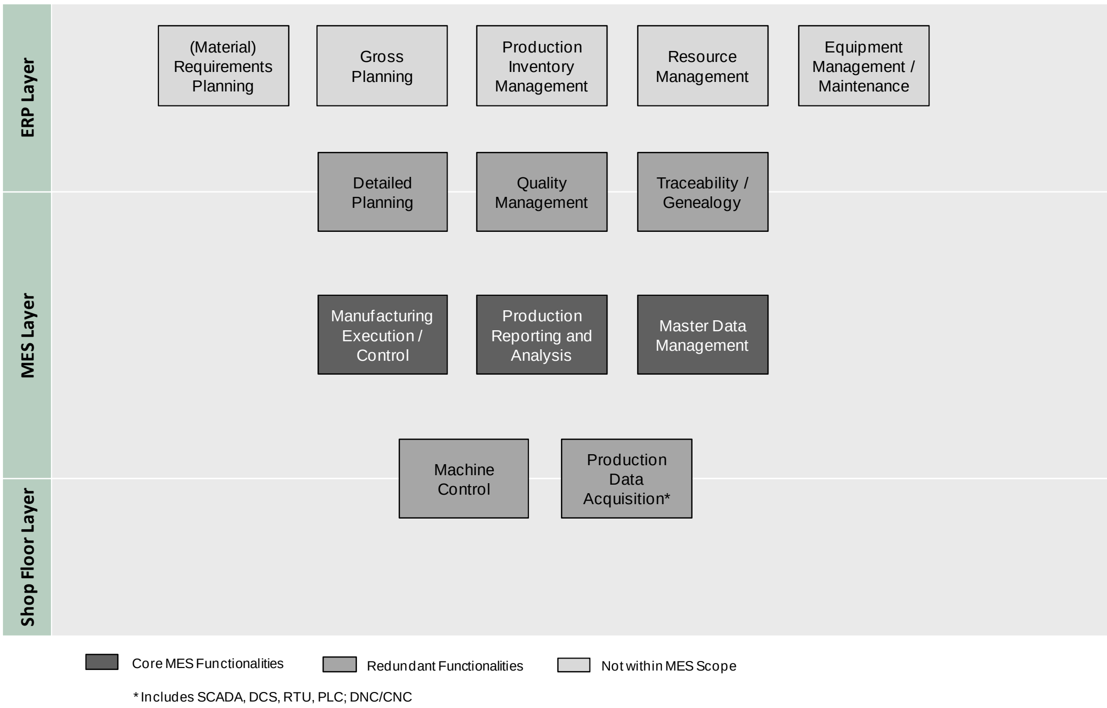
The following figure shows the instantiations of the MES Function Map as a result of the assessment workshops. Due to the fact that in one case study three plants of one OEM were examined, Figure A-1 shows six instantiations in total.






ERP Layer
MES Layer
Shop Floor Layer
(Material) Requirements Planning
(Production) Inventory Management
Gross Planning
Labour Management
Quality Management
MES Master Data Management
Detailed Planning
Resource Management
Production Reporting and Analysis
Production Worker Guidance
Traceability / Genealogy
Manufacturing Execution / Control
Production Data Acquisition*
Machine Control
Equipment Management / Maintenance
Core MES Functionalities
Redundant Functionalities
Not within MES Scope
* Includes SCADA, DCS, RTU, PLC; DNC/CNC


ERP Layer
MES Layer
Shop Floor Layer
(Material) Requirements Planning
Gross Planning
(Production) Inventory Management
Resource Management
Equipment Management / Maintenance
Traceability / Genealogy
Detailed Planning
Quality Management
Dynamic Routing
Master Data Management
Manufacturing Execution / Control
Machine Control
Production Reporting & Analysis
Production Data Acquisition
Core MES Functionalities
Redundant Functionalities
Not within MES Scope
* Includes SCADA, DCS, RTU, PLC; DNC/CNC



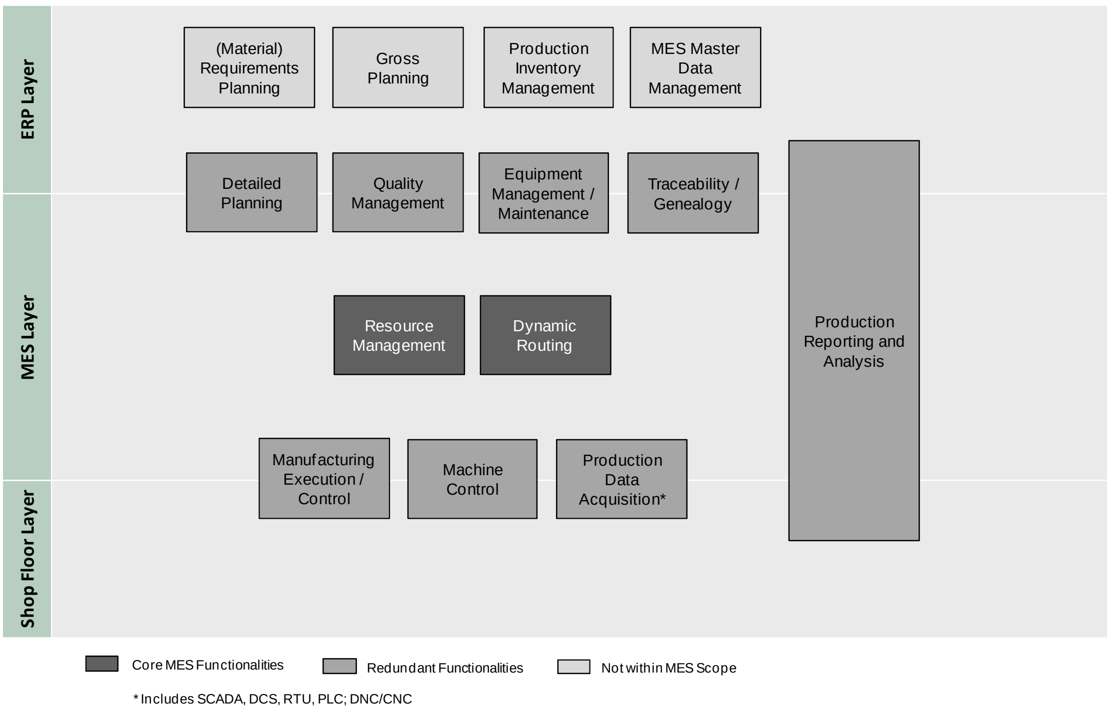


Figure A-1: Instantiations of the MES Function Map

Appendix B: Detailed MES Functionality Definition

B.1. Detailed MES Functionality Definition According to Standards Investigated

Table B-1 contains a summary of detailed MES functions as defined by each of the MES standards investigated.

MES Functions	VDI	MESA	NAMUR	NIST
Labour Management	• Manage and process personnel information • Administrate personnel time accounts • Make staff scheduling and capacity planning • Provide and assign personnel on schedule	• Provide status of personnel • Carry out time and attendance reporting / certification and activity tracking • Determine optimal assignment (in interaction with resource allocation)	-----	-----
(Material) Requirements Planning	-----	-----	•	-----
Gross Planning	-----	-----	• Make rough-cut scheduling with capacitive model • Allocate production requirements to potential plants • Generate material requirement plan	-----
Detailed Planning	• Check production restrictions • Support completion of operational queue • Conduct detailed planning • Analyze current manufacturing situation • Ensure real-time actualization of	• Analyze available resources and conditions • Carry out sequence scheduling of independent activities • Plan time and equipment loading • Recognize alternative and overlapping	• Convert production requirements into production orders • Arrange a detailed time schedule • Put up a detailed capacitive model • Put up a production plan • Record current order feedback • Adapt plan to take	• Sequence independent activities • Recognize alternative and overlapping production activities • Calculate exact time or equipment loading • Adjust plan to shift patterns

MES Functions	VDI	MESA	NAMUR	NIST
	production plans • Develop (conflict-) resolutions • Optimize actual production plans and sequences • Carry out short-time resource allocation • Determe material requirements and availability • Constitute process schedule	operations • Adjust shift patterns • Optimize production sequence	into account delays or interruptions • Generate production plan for in-process checks • Compare planned and actual production situation in the plant	
Quality Management	• Compile quality and test planning • Secure machine and process capability • Carry out quality inspections (effect and document the quality test) • Manage measuring and testing equipment • Generate action plan / measures for process influence	• Make real-time analysis of measurements • Ensure product quality control • Track SPC /SQC and manage off-line inspection operations • Identify problems requiring attention and determine causes • Recommend action to correct problems	• Make preliminary registration of samples by detailed scheduling (order) • Notify samples taken by production control (order) • Register samples with automatic or manual compilation of extent of testing (order) • Manual capture measurement data • Measure data transmission online • Clear orders • Transmit relevant quality data for production documentation • Return information on one sample • Process deviations • Analyze certificates • Evaluate analysis results • Enable version-led master data management • Ensure user management • Provide audit trail functionality • Manage reference samples	• Provide timely analysis of product and process measurements • Evaluate and track product instances across processes • Track SPC /SQC and manage off-line inspection operations • Identify problems requiring attention and determine the cause • Recommend action to find and correct problems • Capture measure-ment data with additional interfaces to process control

MES Functions	VDI	MESA	NAMUR	NIST
Production Inventory Management	-----	• Manage flow of production units (jobs, orders, batches, lots, work orders) • Dispatch information in sequence of workflow • Alter prescribed schedule on the factory floor • Control the amount of work in process (buffer management)	• Collect current and available stock information of all material • Cover input material requirements by in-house production or procurement from outside (input material order) • Take into account in-coming and outgoing deliveries (monitor quantities in stock) • Transport tracking for outgoing deliveries • Monitor material movements and unscheduled material requisitions	• Manage direction of workflow of production units • Dispatch information in sequence of workflow • Alter prescribed schedule on the factory floor • Control the amount of work in process (buffer management)
Resource Management	• Record process quality information, • Schedule production material • Initiate material transports • Manage production charges • Manage and pro-cess WIP stocks • Enable traceability of resources	• Provide detailed history of resources • Ensure properly set-up of equipment for processing • Provide status real-time • Carry out reservations and dispatching	-----	• Track resource status • Maintain detailed resource history • Set up equipment properly • Ensure availability of resources, other entities and documents • Carry out reservations (in support of detailed planning function)
Equipment Management / Maintenance	• Manage and process equipment information • Provide equipment • Ensure need-based availability on schedule and technical functionality of equipment	• Track and direct activities to main-tain the equipment and tools • Ensure availability of equipment and tools for manufacturing • Ensure scheduling for periodic or preventive maintenance • Respond immediately to problems (alarm)	-----	• Track and direct activities to main-tain the equipment and tools • Ensure availability of equipment and tools for manufacturing • Ensure scheduling for periodic or preventive maintenance • Respond immediately to problems (alarm) • Collect historical

MES Functions	VDI	MESA	NAMUR	NIST
		• Collect historical data of past events or problems (aid in diagnosing problems)		data of past events or problems (aid in diagnosing problems)
Manufacturing Execution / Control	-----	• Monitor production and manage flow of production units • Present dispatch information in real-time • Provide and correct decision support to operators (correcting and improving in-process activities) • Alarm management • Provide interfaces between intelligent equipment and MES • Alter prescribed schedule on shop floor	• Execute instructions derived from detailed planning • Return information on the actual status • Notify material movements to inventory control • Send orders for in-process checks to QM • Transmit production data to production documentation	-----
Traceability / Genealogy	-----	• Provide visibility • Provide status information • Enable online tracking (create a historical record) • Enable traceability of com-ponents and usage of each end product	-----	• Track WIP material • Store and manage product and production history data • Manage “as build” data (document control)
Production Reporting and Analysis	• Process evaluation and analysis • Carry out long-term analysis • Compare production targets to actual production	• Provide up-to-the minute reporting of actual manufacturing operations results • Compare actual production to past history and expected business results • Create evaluation reports or on-line presentations of current performance	-----	• Provide up-to-the minute reporting of actual manufacturing operations results • Compare actual production to past history and expected business results • Create evaluation reports or on-line presentations of current performance • Trigger alarms when parameters exceed acceptable ranges

MES Functions	VDI	MESA	NAMUR	NIST
Machine Control	-----	• Monitor machinery status • Collect plant and machine data (Machine Data Acquisition) • Provide ECS functionality	-----	-----
Production Data Acquisition	• Process input data • Provide plausibility checks (helps to avoid errors) • Provide status information • Pre process / aggregate data	• Collect data from factory floor (manually or automatically) in an up-to-the-minute time frame • Provide an interface link to obtain the inter-operational production and parametric data	-----	• Acquire and update production information used for product tracking, maintaining production histories etc. • Collect data from factory floor (automatically / manually) in up-to-the-minute time frame
Production Documentation	• Design, process and document workflows • Edit information and make them available	• Control records / forms that must be maintained with the production unit • Edit “as planned” and “as build” information • Send instructions down to the operations / Provide data to operators or recipes to device control • Control integrity with environmental, health and safety regulations and ISO information • Store historical data	• Capture data continuously (values over time, trending) • Capture discrete event data (alarms, warnings, individual values) • Capture quantities and batches used up and produced • Capture of previous batches or chains of steps for tracking • Visualize trends and plant images • Generate reports • Manually record production data • Provide electronic manufacturing documentation • Enable user management	• Control, manage and deliver information packages associated with the production unit • Send instructions to operators and recipes to device controls • Support of editing “as planned” information • Maintain version histories of specifications • Control integrity with environmental, health and safety regulations and ISO information

Table B-1: Detailed MES functionalities as defined in investigated MES standards

B.2. Detailed Functionality Definition of the MES Function Map

Table B-2 shows a synthesis of detailed MES functions. The list was derived by consolidating the MES functionality defined by the standards investigated (see Table B-1) and verifying the resulting set of tasks through expert interviews.

General MES Function	Detailed MES (Sub-)Functions
Labour Management	Manage and process personnel information
	Administrate personnel time accounts (Time Logging)
	Staff scheduling and capacity planning → Determine optimal assignments
	Provide and assign personnel on schedule
	Time and attendance reporting
Gross Planning	Carry out rough-cut scheduling with capacitive model
	Allocate production requirements into potential production sites
	Generate material requirement plan → Bill of material explosion
	Compose orders → calculate lot size, lead time
	Check feasibility
Detailed Planning	Check production restrictions → analyze available resources and conditions
	Conduct detailed planning
	Plan time and equipment loading
	Adjust shift patterns → Optimize production sequence (delay, split, cancel orders)
	Optimize actual production plans and sequences
	Short-time resource allocation
	Carry out sequence scheduling
	Convert production requirements into production orders
	Create concrete production plan (order disposition)
Quality Management	Compile quality planning (inspection planning)
	Preliminary registration of samples and notification of samples taken by production control
	Quality inspection and documentation of quality tests (test order control and processing)
	Transmission of relevant quality data for production documentation
	Evaluate analysis results → Create analysis reports
	Recommend action to correct problems and generate measures
	Determine and control rework
	Manage measuring and test equipment
	Audit trail functionality
Production Inventory Management	Collect current and available stock information of all material
	Cover input material requirements by in-house production or procurement from outside (input material order)
	Take into account incoming and outgoing deliveries (monitor quantities in stock)
	Monitor material movements and unscheduled material requisitions
	Perform physical inventory (stock-taking)

General MES Function	Detailed MES (Sub-)Functions
Resource Management	Ensure availability of resources for processing → Initiate material transport (material logistics)
	Manage and process WIP stocks
	Track resource status
	Maintain detailed resource history
	Alter prescribed schedule on the factory floor
	Reservation and dispatching of resources (in support of detailed planning function)
Equipment Management / Maintenance	Manage and process equipment information (status management)
	Provide equipment in production process → track and direct activities to maintain equipment and tools
	Ensure scheduling for periodic or preventive maintenance (incl. maintenance planning, execution and documentation)
	Response (alarm) to immediate problems → emergency maintenance
	Collect historical data of past events or problems → maintenance reporting
	Inform responsible maintenance manager
Manufacturing Execution / Control	Monitor production (orders)
	Record current order feedback
	Control and adjust order sequence
	Compare planned and actual production situation
	Real-time actualization of production plans
	Electronic Control Station (ECS), Planning Table functionality
	Correction or provision of decision support to operators
	Lock parts, record waste
	Notification of material movements to inventory control
	Send orders for in-process checks to Quality Management
	Transmit production data to production documentation
Traceability / Genealogy	Provide status information
	On-line tracking of information about components assembled into parent (create a historical record)
	WIP tracking
	Product / production history data storage and management
Dynamic Routing	Deviation / Exception Management
	Storage Planning
	Re-sequencing
	Real-time load balancing and routing of WIP
Production Reporting and Analysis	Up-to-the minute reporting of actual manufacturing operations results → operative target / actual value comparison
	Long-term production analysis / Statistical Process Control (SPC)
	Evaluation report / visualization of reporting data
	Trigger alarms when parameters deviate from acceptable ranges
Machine Control	Monitor machinery status
	Collect plant and machine data (Machine Data Acquisition)

General MES Function	Detailed MES (Sub-)Functions
	Provide ECS functionality
Production Data Acquisition	Pre-processing, verification and aggregation
	Plausibility checks
	Conversion of dimensions
	Provide dashboard functionality (display production data)
	Collect data from shop floor (manually or automatically) in an up-to-the-minute time frame
Master Data Management	Takeover master data from ERP
	Manage records that must be maintained with the production unit → create, maintain and update product and equipment data
	Enable electronic manufacturing documentation
	Maintain version histories of specifications

Table B-2: Detailed MES functionality

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