Implementation of MES at small EMS providers

M.B. Becks
University of Twente
P.O. Box 217, 7500AE Enschede
The Netherlands
m.b.becks@student.utwente.nl

ABSTRACT

Manufacturing execution systems (MES) are widely adopted by electronics manufacturing services (EMS) providers to optimize production activities from order launch to finished products. An MES system is often integrated with ERP as well as machinery. Manufactures often lack a good understanding of MES functionalities and benefits that will become available after implementing an MES system. This makes justifying the investment in MES a hard task for managers. This paper intends to describe how small enterprises in the electronics manufacturing services (EMS) industry could benefit from implementing an MES system. According to the case study conducted at an SME in the EMS industry, quality management, document control and product tracking and genealogy are the most important functions for small EMS providers.

Keywords

Manufacturing Execution Systems (MES), Discrete Manufacturing, Manufacturing Operations Management (MOM), Small and medium-sized enterprises (SME), Printed Circuit Board (PCB), Electronics Manufacturing Services (EMS)

1. INTRODUCTION

The concept of a Manufacturing Execution System (MES) was developed in the early 1990s when the Manufacturing Enterprise Solution Association (MESA) attempted to clarify the definition. An MES enables the optimization of production activities from order launch to finished products[8]. It fills the gap between shop floor information and control systems and other enterprise information systems [12]. In 1997, the MESA-11 model was constructed, indicating the 11 core functions of MES. Over the years several models followed, but the 11 core functions remained the same. Every functionality of an MES system can be categorized as either a functionality for production, quality, or personnel allocation [4]. Companies operating in the Electronics Manufacturing Services (EMS) industry have been widely adopting MES systems to improve quality, throughput, customer service, compliance, asset utilization, and inventory. Electronics manufacturers are especially focused on successful new product introductions and responding to customer demands. All this, while ensuring consistent product quality [9].

Manufacturers often lack a good understanding of MES functionalities and benefits that will become available after implementing an MES system. Uncertainty is often experienced when it comes to validating the applicability, expected benefits, and practical implementation of an MES [4]. Furthermore, problems are often faced when an attempt is made to justify the return on investment (ROI) of implementing an MES, which is found the most difficult task for many executives of electronics manufacturers [7][9]. Reasons for this challenge may include lack of alignment of financial and performance metrics, lack of manufacturing improvements measurements, and little confidence in software improvement projects. The processes of an electronic manufacturer are often unique to their business. Therefore, they cannot buy an MES 'off the shelf' [4] and expect it to work. Instead, an MES needs to be carefully aligned to unique business processes. However, as a rule of thumb, the electronics manufacturer should aim at selecting an MES system that provides at least 80% of the needed functionalities out of the box. Therefore, prior to implementing an MES, the different expectations and requirements need to be investigated. Additionally, small electronics manufacturers often have existing IT systems and databases in place. Integration of MES can be difficult because each system communicates using its own interface and especially the manufacturing equipment is often unique [12].

As a result, it becomes more difficult for decision-makers of electronics manufacturers to see the benefits of implementing an MES.

This paper attempts to sketch out the core functions that an MES should ideally have when implemented at small enterprises in the EMS industry. Additionally, a single case study is conducted at a small enterprise in the EMS industry. This case study seeks to examine the relevancy and potential benefits of each MES function. Also, the extent to which an MES system can be integrated within current information systems is investigated.

An overview of MES functions that are relevant to small electronics manufacturers can help managers to prioritize the implementation of functionalities and improves decision-making in the selection and implementation of an MES system.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.
35^{th} Twente Student Conference on IT July. 2^{nd}, 2021, Enschede, The Netherlands.
Copyright 2021, University of Twente, Faculty of Electrical Engineering, Mathematics and Computer Science.

The goal of this paper is to investigate how MES systems can benefit small enterprises in the EMS industry. In particular, the following questions will be investigated:
Main research question:

- How can MES benefit small enterprises in the EMS industry?

Sub research questions:

- What are the core functions of MES?
- Which core MES functions are relevant to small enterprises operating in the EMS industry?
- How can MES systems be integrated with current information systems at small electronics manufacturers?

To examine the core functions of MES, a literature review is conducted and described in Section 2. Secondly, a use case scan made within project PERISCOP, which is a project in Industry 4.0 for SMEs, is carried out to classify the use case company as well as to identify common needs and interests. Thirdly, an attempt is made to identify the relevant MES core functions for small enterprises by doing a single case study which is described in Section 4. In this case study, semi-structured interviews are conducted to get insight into the relevancy of different MES functionalities and the current situation. The functionalities are prioritized using the analytic hierarchy process (AHP) method[10]. The results of the case study are presented in Section 5 and the conclusions of this research are described in Section 6.

2. LITERATURE REVIEW

2.1 Definitions

Manufacturing Execution Systems (MES)
Manufacturing Execution System (MES) is an enterprise information system that facilitates the information flow between the production floor (people and machines) and the office floor using enterprise information systems like ERP. A definition of MES that is often cited in the literature is proposed by Manufacturing Enterprise Solutions Association (MESA). MESA International is a global organization focusing on improving business results and production. While a variety of definitions of the term MES have been suggested, this paper will use the definition first suggested by MESA. MESA defined the term MES as follows:

> Manufacturing Execution Systems (MES) deliver information that enables the optimization of production activities from order launch to finished goods. Using current and accurate data, MES guides, initiates, responds to, and reports on plant activities as they occur. The resulting rapid response to changing conditions, coupled with a focus on reducing non-value-added activities, drives effective plant operations and processes. MES improves the return on operational assets as well as on-time delivery, inventory turns, gross margin, and cash flow performance. MES provides mission-critical information about production activities across the enterprise and supply chain via bi-directional communications.[8]

Small and Medium-sized Enterprise (SME)
In this paper, the categorization procedure of the EU recommendation 2003/361 is used to define a small and medium-sized enterprise (SME). The factors 'Staff headcount' and 'turnover or balance sheet total' are used to classify an company as an SME and shown in Table 2.1 [1].

Table 1. Definition of an SME

Size	Staff headcount	Turnover	Balance sheet total
Medium	<250	≤€ 50 m	OR ≤€ 43 m
Small	<50	≤€ 10 m	OR ≤€ 10 m
Micro	<10	≤€ 2 m	OR ≤€ 2 m

EMS Industry
Electrical Manufacturing Services (EMS) providers operate in the EMS industry. EMS can be defined as follows:

> Contract manufacturing integrates a wide array of productive functions pertaining to circuit board and hardware assembly, as well as product engineering at the board and systems-level, component design, process engineering, parts procurement, product fulfilment, logistics and distribution, and after-sales services and repair or sometimes installation services. [6]

Printed Circuit Board (PCB)
The PCB manufacturing and sales account for a total of about 1 trillion USD in electronics each year. One of the services an EMS provider provides is PCBa, which refers to the assembly of PCB. In this paper we use the following definition of PCB:

> The printed circuit board (PrCB), the platform upon which components such as semiconductor chips and capacitors are mounted, provides the electrical inter-connections between components. [5]

2.2 MES

In this section, the core functions and informational items of MES are explained.

The concept of MES has been around since the early 1990s. [4] MES can be used for production, personnel, and quality assurance matters. In the discrete industry, MES is more an online information system, a feedback and control system for production. Whereas in the process industry, a greater part of MES functionalities is in the machine and plant control systems. [4] Basic functions of an MES can be described as the collection of software functionalities that are separately available of a singular product. Additionally, it enables the dependent products to be developed as far as possible using the same modules and with a uniform structure. An MES "1) provides a real-time look at manufacturing operations, and 2) makes it possible to integrate the real-time data with other information systems such as production planning and distributed control systems." [4]

2.2.1 Core functions

In 1997 the Manufacturing Enterprise Solutions Association (MESA) published the MESA-11 model, which defines the 11 MES core functions. This model was extended in 2004 and 2008 due to developments in the manufacturing industry. The 11 MES core functions stayed the same. The core functions are defined as follows[8]:

1. **Operations/Detailed Sequencing:** A planning functionality to provide all the detailed sequences of operations. Finite capacity scheduling can be used to take the limits of resources into account while making the schedule, resulting in more accurate final production schedule [3]. The function provides improved production activity control (PAC) for real time production control. PAC allows scheduling, controlling, measuring, and evaluation of the effectiveness of production operations.

2. **Dispatching production units:** A production dispatching functionality to oversee the flow of production by issuing work to available resources. The production flow is determined by jobs, orders, batches, lots, and work orders. When unforeseen events like rework and salvage processes occur, dispatch information is updated in real-time.

3. **Product tracking and genealogy:** A product tacking and genealogy function to provide visibility in the current status of a product. Information about who is/was working on the product, components materials by the supplier, lot, serial number, current production conditions, and any alarms, rework, or other exceptions related to the product are tracked. A historical record of each product will become available.

4. **Labor Management:** A labor-management functionality to give insight into the status of personnel by reporting of time and attendance, certification tracking, and tracking of material preparation and tool room work. These insights can improve the accuracy of activity-based costing.

5. **Quality Management:** A quality management functionality that assures product quality control by real-time analysis of collected production measurements. Problems can be identified and corresponding actions are suggested. This function could be shaped by statistical process control (SPC) or Statistical Quality Control (SQC) tracking and management of off-line inspection operations. Also, analysis in laboratory information management systems (LIMS) could be part of the quality management function.

6. **Maintenance Management:** A maintenance functionality that assures availability of equipment and tools. The function "tracks and directs the activities to maintain the equipment and tools". Periodic or preventive maintenance events are scheduled and operators are notified about immediate problems. Problems are diagnosed by keeping a history of past events and issues.

7. **Resource allocation and status:** A resource management functionality to assign and schedule available resources effectively. Available resources may include people, materials, machines, documents, and tools. To meet operation scheduling objectives, resources can be reserved and dispatched. The functionality also provides a detailed historic overview of resources.

8. **Document control:** A document control functionality to control "records/forms that must be maintained with the production unit, including work instructions, recipes, drawings, standard operation procedures, part programs, batch records, engineering change notices, shift-to-shift communication, as well as the ability to edit "as planned" and "as-built" information. It sends instructions down to the operations, including providing data to operators or recipes to device controls. It would also include the control and integrity of environmental, health, and safety regulations, and ISO information such as Corrective Action procedures. Storage of historical data."

9. **Performance Analysis:** A performance analysis functionality to provide reporting and comparison of expected and actual manufacturing results. MES data gathered by different core functions can provide a lot of useful insights for a manufacturer company[11]. Stassen provided an overview of informational items that could be extracted from MES data and investigated which information was most relevant. These informational items were categorized into the 4 areas of Manufacturing Operation Management as described by ISA 95. Theses areas include operations management of production, quality, inventory, and maintenance [11].

10. **Process Management:** A process management functionality to monitor and control production using decision support or automatic actions for correcting in-process activities. Machines and equipment are monitored and controlled and operation flow is tracked. Integration interfaces are present between equipment and MES. Optionally alarm management is included by this process management function.

11. **Data Collection and Acquisition:** A data collection and acquisition functionality that "provides an interface link to obtain the intra-operational production and parametric data which populate the forms and records which were attached to the production unit. The data may be collected from the factory floor either manually or automatically from equipment in an up-to-the-minute time frame."

2.2.2 Integration

The integration of MES with a higher-lever ERP is a critical factor [4]. Standardized interfaces are crucial to make the information flow between MES and ERP possible.

Interfaces

Interfaces

Interfaces can be described as the communication devices that can be used by systems to exchange data. Standardized interfaces is crucial. For example to integrate the MES system with an ERP system. The relevant data of the MES can be made available in the ERP.

The IEC 62264 standards often referred to as ISA 95 is an international standard which focuses on the integration of enterprise and control systems. In ANSI/ISA-95.00.02.2013, also referred to as IES 62264-3 there are 4 manufacturing operation management areas defined. These 4 areas include production management, inventory management, maintenance management and quality management. Each of these areas are present within small electronics manufacturers.

In part 3 of ISA 95, the activity models of each area is defined enabling enterprise and control system integration. Applying ISA 95 for MES implementation has several advantages. The standard makes it possible to work in a structured way, makes clear communication possible, offers possibilities for future development, a good basis for interfaces, and makes sure applications stay independent. It is however considered time consuming to learn applying

the ISA 95 standard and in some cases it might be too big of a solution.

An MES can be integrated both vertically and horizontally with current systems in a company. Vertical integration includes integration with higher level systems, such as ERP and PLM systems at ISA level 4. Or integration with lower level automation systems such as programmable logic controllers and supervisory control and data acquisition (SCADA) systems at ISA level 2. Horizontal integration with MES includes the integration with systems that are also operating within ISA level 3, such as laboratory information management system s (LIMS) or statistical process control (SPC) systems.

2.3 Electronics Manufactures

Electronics manufacturers have a strong focus on responding to customer demands, ensuring product quality, and successful new product introduction [9]. Electronics manufacturers often struggle to justify the investment in MES

2.3.1 Top goals and objectives

The top goals and objectives of electronics manufacturers have been compared to all other industries in a survey by LNS Research [9]. LNS research is an industry analyst firm "focused on best practices in Industrial Transformation for Operations and Technology leaders".Three operational objectives that were most critical to electronics manufacturers are identified.

The objective of *fast new product introduction* had significantly higher priority than in other industries. This can be explained by the fact that the electronics industry is consumer-focused and product life cycles are short with a lot of product variation.

Responsiveness to customer order demands was another top priority amongst electronics manufacturers, which had higher priority for electronics manufacturers than in other industries.

Furthermore, *assuring quality* was in the top three priorities of electronics manufacturers. Strategic initiatives that can be undertaken to prevent quality and supply chain issues include "Operational Excellence, Lean, and Six Sigma, collaborative manufacturing, deploying global MOM, software supporting production execution, quality execution, and analytics".

Increasing production capacity and capabilities as well as global alignment and standardization of manufacturing processes and reporting were also top objectives, but significantly less prioritized than the top three objectives [9]

2.3.2 Challenges

Respondents from the LNS Research's survey were also asked about their operational challenges. One of the biggest challenges electronics manufactures face is the justification of ROI for improvement investments. This challenge of ROI justifications is found 50% more in electronics industry than in other industries. Causes of this challenges might be lack of alignment between financial and performance metrics, not being able to measure improvement in manufacturing, lack of confidence that MES will be implemented in time, and according to budget. Electronics manufacturers are "extremely consumer focused and these industries have some of the shortest product life cycles, often six months or less with a tremendous amount of product variation."[9]

3. METHODOLOGY

Firstly, a literature review is conducted to examine the core functions of MES using secondary data2. Secondly, a single case study is conducted to gain a more in-depth understanding of the relevancy of core MES functions and system integration possibilities for small electronics manufacturers.

Within this case study, a use case scan made within project PERISCOP, which is a project in Industry 4.0 for SMEs, is carried out to classify the use case company as well as to identify common needs and interests. The use case scan was performed by filling in an English questionnaire, which consisted of 28 multiple choice questions and 10 open questions. This use case scan included questions about the company's customers and orders, production, production planning, information systems, maintenance, and quality checks, purchasing and inventory control, and main challenges. The questionnaire was filled in with the CEO of the electronics company during an online video meeting. The respondent was defined as a person who knows all areas of the company's operation areas. The respondent had unlimited time to answer the questions and could ask for clarification of questions at any time. Results were used to characterize the company in the single case study.

Furthermore, 4 semi-structured interviews were conducted to investigate the relevancy of the 11 core MES functionalities and get insight into the current situation. The target group consists of employees of the electronics manufacturer. To get insights from multiple perspectives, employees from different job duties were interviewed including work a preparation worker, a shop floor worker, an operations manager, and the CEO. The interviews were conducted in the Dutch language for the interviewees to express themselves to their best ability. All questions and handout sheets were translated from English to Dutch. Interviews were conducted at the company in the case study on the 8th of June according to a schedule with timeslots of one hour between 09:45 AM and 4:45 PM.

The interview guideline was structured into 5 main parts. In the first part, the interviewee was asked for verbal consent to record the interview with an audio recorder. The second part included questions about the interviewee's current function and current knowledge about MES. To make sure, the concept of MES was equally understood, the interviewer explained the term MES how it was used in this research. In the third part, the first three steps of the decision-making methodology Analytic Hierarchy Process (AHP) were applied to compare the MES functions to each other in terms of relevancy for the manufacturer[10]. It will help the electronics manufacturer prioritize its MES functions, which allows better software requirements setting for the MES vendor. A list of the 11 MES core functions 2.2.1 was printed before the interview and given to the interviewee. Interviewees were independently asked to pairwise compare the MES functions by giving weight on the scale of 'equal importance'(1), 'moderate importance'(3), 'strong importance'(5), 'very strong importance'(7), and 'extreme importance'(9). This scale was also handed out on paper. After introducing function X and function Y, the interviewee was asked about the relative importance according to the importance scale and reason for the decision. The degrees of importance were directly logged in an Excel matrix. This step was repeated until all functions were pairwise compared. The fourth part included 1 open-ended question to get insight into functions that are already fulfilled in the current situation, for example by an ERP system. In part 5 of the interview, questions were asked to verify the results. The

results were directly computed in Excel using the AHP calculation method[10] and could be shown in a graph chart. Each graph represented one MES function with its corresponding relative relevancy. To verify the results, interviewees were asked if the results were as expected and realistic to the electronics manufacturer. After all the interviews were conducted, the average of all scores was calculated using Excel and visualized a graph chart, see figure 1.

After the pairwise comparison was completed, the interviewees were shown the results represented in a graph and asked to if the results were as expected, seen as realistic for the electronics manufacturer and if there were any remarks.

Furthermore, a company visit was done to acquire knowledge about the current production processes and information systems. To determine the relative relevancy of MES functions for the electronics manufacturer, the analytic hierarchy process (AHP) was performed during each interview.

Within the case study, modules of selected MES vendors, called Aegis, are explored. Information about the MES implementation and MES modules are retrieved from the Vendors website. This information includes many resources like whitepapers, brochures, infographics, videos, webinars, and case studies [2]. The MES system contains 6 different modules, which have been further explored and described in Section 4.2.

4. CASE STUDY

In this section, a single case study is described that was conducted at a small enterprise operating in the EMS industry. The management of the manufacturer in the case study, hereafter referred to as 'the electronics manufacturer', is exploring the possibilities of MES.

The goal of this case study is to investigate relevant MES functionalities for the electronics manufacturer, the benefits an MES could provide, and system integration possibilities. The electronics manufacturer already selected an MES vendor to further investigate. The CEO of the company is now seeking to justify the investment in the system and possibly develop an implementation plan.

4.1 Characteristics of the use case company

The electronics manufacturer is a full-service EMS provider specialized in the development and production of electronic devices for the automotive, aerospace, machine building, medical and marine markets. The company is a small enterprise, with 20 out of 25 employees being employed in production.

The electronics manufacturer is a high-mix low-volume (HMLV) manufacturing company, which has benefits like improved customization of products and increased responsiveness to customers. Lead times are highly dependent on delivery times of purchased components since the electronics manufacturer follows a make-to-order (MTO) policy.

The electronics manufacturer's EMS has two production lines, one surface mounted devices (SMD) line, and one through-hole (TH) line. Currently, there is a significant level of automation in the SMD-line, whereas the TH-line is a manual operation.

Current bottlenecks are the degree of manual work involved, paper instructions, and quality control. The company is looking to digitize the production process, automate production planning and improve production quality. An important aspect of production is ensuring high quality, efficient walk-through of production steps, and fast access to information necessary for operation. Better capturing of data, a guarantee of certified people working on the job, and documentation can already prevent costly mistakes.

4.1.1 Interview summary

During the interviews, an additional question was asked about the current situation. There was asked whether or not one or more of the 11 MES core functions is fulfilled in the current situation. And if so, to what extend. This section will provide a summary of the answers to this question.

1. Operations/Detailed Sequencing The current production planning functionality in the ERP system cannot easily provide realistic planning. For example, it schedules using the infinite capacity of time in a day and available employees. Also, changing the planning in the ERP system when production takes more time than expected is very time-consuming due to many manual inputs. Therefore, the planning functionality is not used. The electronics manufacturer expects to expand their production lines within 5 years. With this expansion, the current production planning functionality in the ERP might not be sufficient.

2. Dispacthing production units Dispatching production units is currently done by the employees. At the production stage, products are labeled with serial numbers, not at the start. Material management functionality in the ERP system offers the possibility of tracing materials, but might not be used to full extend.

3. Product tracking and genealogy Tracking and history functionality is currently limitedly implemented in the ERP system. The electronics manufacturer is working on tracking lot numbers in the ERP. This will become an important functionality when the electronic manufacturer will be producing for the aerospace and medical market to comply with the rules and medical standards. A paper travel card with barcode is used to track operations. However, when the travel card is scanned after an operation is finished, this will not automatically update the operation as done in the ERP system. People have to walk to a computer to scan their travel card and manually update the system, which is not time efficient. Therefore, the scanning of the travel card is often neglected. With higher numbers of products not all products are scanned but are put in the system as bulk. In the desired situation the electronics manufacturer wants to link serial numbers. Lot numbers of components to products and production order linked to the serial number. The traceability of orders is limited in the current situation. The Automated Optical Inspection (AOI) machine has the functionality to view the history of a product, but this information is not connected to the ERP system. Boxes with goods are labeled by article number, and the amount of pieces is marked on the box. A separate MySQL database is used to track serial numbers.

4. Labor management Shop floor control functionality is present in the current ERP, which allows the electronics manufacturer to plan tasks to people based on production orders. However, due to the complexity of the ERP system, a physical whiteboard is used on the shop floor to plan tasks. A list is present with tasks and corresponding required certification. Some specific operations require certification, but currently workers are not restricted by a system to perform tasks.

5. Quality management The test department is using a custom-developed testing tool. The tool requires a separate MySQL database containing the serial numbers. A test may contain more than a thousand test steps, which are automatically captured in the custom database. Also, the electronics company is using a custom-made Microsoft Power Automate application to register product deviations with a smart phone. Bigger product deviations are also registered in the ERP system using a non-conformance report (NCR).

6. Maintenance management Once a year maintenance service is conducted by an external party for the SMD production. Calibration of measuring instruments is important to ensure quality, which is frequently done.

7. Resource allocation and status Assigning a status to orders is being done in the ERP system using status codes. Every status code is unique and indicates the position of an order in the production process. Although updating the status codes of products is possible in the ERP system, in practice this is not always done at every production step resulting in poor data.

8. Document management The electronics manufacturer is looking for ways to simplify and structure its document management processes. Work instructions are now developed in Microsoft Word, printed, and put in a paper folder. Sometimes work instructions get lost, get full of changes made by a pencil, or are out not up to date. Document Control is done using hyperlinks in the ERP system. The hyperlinks redirect to the right document. Not all documents are integrated into one system. Work instructions are developed and printed on paper. Updating these work instructions with changes is time-consuming, so sometimes operators have to work with outdated work instructions. Currently, people are working on document control in the ERP, to make information more accessible.

9. Performance Analysis Analytics functionality is present in the ERP system. However, it is very time-consuming to get the right data out of the system. Furthermore, data is not complete as not every aspect of production is being tracked or logged. Therefore, analysis of production is hardly done. For production, the most important KPI is whether or not the customer gets what was agreed upon.

10. Process management The ERP system allows the electronics customer to define production steps and work instructions.

11. Data collection/Acquisition Data about the processes, materials and operations are collected by scanning travel card, manual entries in ERP, machines and testing tools.

Work preparation A common problem occurs when a customer proposes a new product with a bill of material (BOM) to make a price calculation. Often additional changes are made to the BOM follow afterward. However, the process of manually making these changes in the BOM is time-consuming when the BOM gets larger, and missing a single change in the BOM leads to issues later on when the product is built. During work preparation, a price quotation is made, for which the necessary production operations are devised and a production time estimation is made. However, expected time versus actual time is not tracked. If the electronics manufacturer can better relate time to costs, the production will get more realistic planning and the customer a more accurate price quotation.

4.2 Aegis modules

In this section, all modules provided by FactoryLogix, a modular MES system developed by Aegis are discussed. Also, the relevancy of these modules to the electronics manufacturer is investigated by combining the results from the interview.

4.2.1 NPI module

The New Product Introduction (NPI) module empowers process engineers to define the manufacturing process. Work instructions can be made by importing ECAD, MCAD, and BOM. Necessary operator certification to perform critical tasks can be added. Also, the machine programs can be developed beforehand. Processes and revisions of instructions can be controlled using electronic sign-off and approval before making it definite.

With adaptive planning functionality, necessary materials can be reserved for production. With the task flow management functionality teams can be created and tasks can be delegated.

4.2.2 Logistics module

The Logistics module manages material flow between the warehouse and the production floor. Materials that arrive from the warehouse on the production floor are first labeled and information is updated in the ERP system. The inspection functionality can automate Acceptable Quality Limit (AQL) sampling for material inspections, before accepting incoming materials. The Logistics module works closely together with the Devices module (Section 4.2.3) and the Production module (Section 4.2.4). The gathered consumption data of materials is shared from the Production module to the Logistics module. This makes sure to keep track of unused materials and move them into storage or replenish materials to the factory stockroom.

4.2.3 Devices module

The Devices module comes with software that can be run on supported devices to scan and guide employees. The Devices module comes with three main functions: inStock, inForce and inCheck. inStock guides labeled material into stockroom locations, guides picking and kitting of jobs, assigns transport orders to shop floor storage and/or production lines. Aegis also offers its process control device called inForce, which acts as the gatekeeper on an assembly line. And the inCheck function will verify the SMT line setup.

4.2.4 Production module

The Production module drives the entire manufacturing process, which was defined by the process engineers using the NPI module (Section 4.2.1).

The developed CAD-aware visual work instructions and documentation can now be displayed in a paperless environment and is automatically available at each workstation under revision control and presents searchable, interactive multimedia documentation.

If during the NPI process critical tasks were indicated, the Production module will make sure that only operators with the right certification can perform these tasks. The Production module will take care of guiding the operator through the sequential build process, capture data like setting values or confirmation that a step was performed. All this data will be part of the unit's build history. In the through-hole line work instructions and guidance are relevant for hand assembly, box-build, quality inspection, and rework guidance.

In some cases, sub-assembly or box build is done at the electronics manufacturer. In this case, the Configure-to-Order (CTO) functionality efficiently processes highly configurable assemblies.

Every unit is tracked by the MES. This makes it possible to see where all work orders and units are located throughout the plant.

4.2.5 Analytics module

The Analytics module allows the electronics manufacturer to create a real-time dashboard and customized HTML or PDF reports. Reports can be scheduled and automatically sent by e-mail. Also, alarms can be set based on conditions. The traceability functionality allows to get insights in the "product's genealogy, the route, the operators and machines and times a unit passed through them, test results, parametric data, quality data, rework and replaced component history, machine data, recipes, packaging records, tooling used, and even the person that approved the release of the production order to the floor" [2]. Also, statistical process control (SPC) reporting is possible, to get more insight into quality-related data. For example, the top 5 defects of the months can be displayed or measurement-oriented histograms and quality charts. Information can be displayed on Apple iOS devices using the inSite app.

4.2.6 Integration module

The Integration module offers three main integration functions. Firstly, the xTend functionality, which enables the system-to-system integration using XML file exchange between Aegis and other systems like ERP, PLM, and time and attendance systems. Secondly, the xStream functionality, which enables third-party solutions to access Aegis data. And lastly, the xLink functionality, which enables data acquisition from machines. Using xLink machine data is turn into standardized XML data. Many protocols are supported such as PLC, DB, OPC, OPC UA, Direct, TCP, Euromap, IPC Connected Factory Exchange (CFX).

4.2.7 Functionalities

Quality management: The quality management functionality is separated over different modules and is based on the three pillars of zero-defect quality. The logistics module automates the process of checking incoming goods. Also, in-process issues are captured and fixed with help of the MES. And root causes can be fixed due to more insights.

Virtual reality headset: An optional function that is provided, is the wireless augmented reality headset with a built-in camera, barcode scanner, headset, and microphone.

5. RESULTS

Figure 1 shows the average results obtained from 4 conducted interviews. By looking at this data, the relative importance scores between MES functions are identified. The MES functions are described in Section 2.2.1. All interviewees regarded their results as expected and realistic for the electronics manufacturer. However, some clear differences could be identified between interviewees.

What stands out in the bar chart, are the 3 core functions quality management, document control, and product tracking and genealogy, which were regarded as the most important core MES functions for the electronics manufacturer.

From the bar chart, it can be seen that maintenance management was found the least important core function of MES with a score of 2.97% and with the highest rating of 4.56%.

Performance analysis appeared to be the second-to-last important core function of MES. However, there were some clear differences between important scores identifiable under interviewees. The shop floor worker, NPI worker, and operations manager rated performance analysis with 2.43% on average, whereas the CEO rated it 10.43%.

Comparable to the results of performance analysis, there were some clear differences between important scores identifiable under interviewees for data collection/acquisition. The shop floor worker and NPI worker gave it an average score of 2.72% importance, whereas the operations manager and CEO gave it an average score of 16.42%.

All interviewees answered that they found the results realistic for the electronics manufacturer and the outcome was as expected. Together these results provide important insights into the relative relevancy of MES functions for the electronics manufacturer.

Table 2. Core functions in Aegis modules

Core function	Present in module
Operations/Detailed Sequencing	NPI/Production
Dispatching production units	Production/Logistics
Product tracking and genealogy	NPI/Production/Logistics
Labor Management	NPI/Production
Quality Management	NPI/Production/Logistics
Maintenance Management	Logistics
Resource allocation and status	NPI/Production/Analytics
Document control	NPI/Production
Performance Analysis	Analytics
Process Management	NPI
Data Collection and Acquisition	NPI/Production/Logistics

6. CONCLUSION

This paper presented a literature review of manufacturing execution systems to identify the core MES functions. Furthermore, a single case study was conducted at a small enterprise operating in the EMS industry to investigate the relevant MES functions for the electronics manufacturer, the benefits an MES system could provide and system integration possibilities.

The 11 MES core functions are Operations/Detail Scheduling, Dispatching Production Units, Product Tracking and Genealogy, Labour Management, Quality Management, Maintenance Management, Resource Allocation and Status, Document Control, Performance Analysis, Process Management and Data Collection/Acquisition.

For the electronics manufacturer in the case study, three most important functions were identified which included quality management, document control and product tracking and genealogy. Maintenance management was the least important core MES function.

The MES system can be integrated with machines and an ERP system. The 'data collection and acquisition' MES core function allows integration by providing interfaces needed to communicate with both machines and the ERP system.

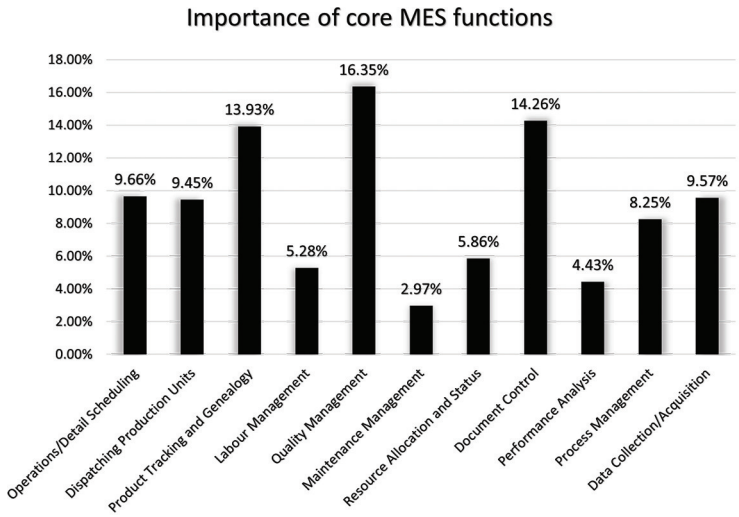

Figure 1. Results

6.1 Limitations and further work

The generalisability of the results in this study is subject to certain limitations. Due to the time frame of this research, only one use case company could be examined. To improve the generalisability, multiple-use case studies at different SMEs need to be conducted. Observations and questionnaires are based on limited people. Potential research includes the investigation of relevant MES functions at multiple small electronics manufacturers considering multiple MES vendors. Doing more use case studies also increases the number of interviews.

To make the comparison of software requirements between small electronics manufacturers more specific, a user requirements specification (URS) document could be composed and compared. The user requirements specifications go into more depth than comparing the relevancies of core MES functions between small electronics manufacturers.

The benefits of MES have not been quantified in this research. To quantify the benefits of MES, a comparison could be made of aspects in the situation before implementation and after implementation of MES. Also, since the company in the use case did not yet implement an MES, it is interesting to perform a similar case study at an SME that already implemented an MES.

Small enterprises might prioritize MES functions differently than medium or large-sized enterprises. Important MES functions for medium or large-size enterprises could be investigated in another research.

6.2 Recommendations

In case the electronics manufacturer decides to not implement an MES, it is recommended, based on the interviews, to investigate the functionalities in the ERP system for finite capacity planning, lot number tracking and labor task management. Also, possibilities to make the data input process in the ERP system more straightforward need to be explored.

In case the electronics manufacturer decides to implement an MES. It is recommended to invest in IT infrastructure at every workplace to enforce user data input and ensure data integrity. Accurate and consistent data is important for the electronics manufacturer to consistently improve current business processes in the long term. An MES will ensure data integrity, by requiring data inputs before the next steps can be performed, which is not required in the current situation. In the interviews, it was mentioned that manual data input and scanning needs to be fast and straightforward.

Quality management, document control, and product tracking and genealogy were found the most important MES core functions. Therefore, it is recommended to further investigate these MES functions. The document control function will also help secure quality. Although the Aegis modules highly complement each other, it is recommended to introduce the modules gradually and start with the modules that are most important [4]. As shown in Table 5, the NPI and Production module will provide functionalities for the three most important functions. Subsequently, the Logistics and Analytics modules can be implemented. The initial digitization of paperwork instructions and training of personnel is a time-consuming task, which should not be overestimated.

Future expansion of production lines and the production of products for the aerospace and medical markets were mentioned in the interviews. And it was mentioned that the current functionalities in the ERP might not be sufficient. Therefore, it is recommended to investigate the functions 'product tracking and genealogy' and 'operations/detail scheduling'.

Furthermore, it is advised to investigate the integration possibilities of the custom test equipment with an MES, which uses the IPC CFX standard. Also, investigate whether the custom Microsoft Power Automate application becomes obsolete after implementing the Aegis Production module.

Additionally, it is recommended to communicate to shop floor workers that an MES is not about surveillance of the workforce, but a tool to improve production processes. From the observations in the interview, a significant difference in importance rating of the 'performance analysis' and 'data collection/acquisition' functions was identified. For instance, it can be communicated that shop floor workers will benefit from a successful implementation of the MES, as meeting deadlines and achieving quality will positively affect their wages [4]. Keep involving all process owners who are directly affected by the implementation of an MES to prevent resistance due to inequality in knowledge.

.

7. REFERENCES

[1] Commission Recommendation of 6 May 2003 concerning the definition of micro, small and medium-sized enterprises (Text with EEA relevance) (notified under document number C(2003) 1422). Technical Report 32003H0361, May 2003. Code Number: 124 Code: OJ L Legislative Body: COM.

[2] Aegis. Aegis Resources Website.

[3] T. Arnold. *Introduction to Materials Management, Ch. 6*. 8 edition.

[4] J. Kletti, editor. *Manufacturing Execution Systems — MES*. Springer, Berlin, Heidelberg, 2007.

[5] J. LaDou. Printed circuit board industry. *International Journal of Hygiene and Environmental Health*, 209(3):211–219, May 2006.

[6] B. Lüthje. Electronics Contract Manufacturing: Global Production and the International Division of Labor in the Age of the Internet. *Industry and Innovation*, 9(3):227–247, Dec. 2002. Publisher: Routledge _eprint: https://doi.org/10.1080/1366271022000034471.

[7] MESA. MESA White Paper #02: MES Functionalities and MRP to MES Data Flow Possibilities | MESA International, 1997.

[8] MESA. MESA White Paper #06: MES Explained: A High Level Vision for Executives | MESA International, 1997.

[9] L. Research. Roadmap for Electronics Manufacturing. Oct. 2014.

[10] T. L. Saaty. How to make a decision: The analytic hierarchy process. *European Journal of Operational Research*, 48(1):9–26, Sept. 1990.

[11] I. Stassen. The informational abilities and opportunities of Manufacturing Execution System data. *Eindhoven University of Technology research portal*, Apr. 2016.

[12] B. S. d. Ugarte, A. Artiba, and R. Pellerin. Manufacturing execution system – a literature review. *Production Planning & Control*, 20(6):525–539, Sept. 2009. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/09537280902938613.