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Collaborative Systems, Operation and Task of the Manufacturing Execution Systems in the 21st Century Industry

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Abstract

Until the first two decades of the 21st century, as part of the Enterprise Resourse Planning (ERP), the Manufacturing Execution System (MES) and related systems have undergone development in both complexity and efficiency. In the field of production technology, there are many sources of work nowadays to get a detailed picture of the solutions offered by MES. The purpose of this article is to give a comprehensive overview of the MES solutions that currently used in industry. In addition to the general structure of the systems and Holonic MES are briefly described. Special attencion is paid to various collaborative systems that complement the MES. The additional manufacturing tools for MES is also described shematically in this article.

Keywords

Manufacturing Execution System (MES), Computer–Integrated Manufacturing (CIM), Holonic MES (HMES)

1 Introduction

Today, competition among global companies and mutual interdependence among market players has led to a significant increase in competition between companies. For the sake of stability, therefore, individual companies need to increase their economic efficiency and reduce the cost of production. As a result, ERP and MES – like a part of the Computer – Integrated Manufacturing (CIM) System – have become an integral part of manufacturing processes to date in corporate culture. However, there is still much to be done to ensure that MES provides the required vertical and horizontal integration within a company.

This emerging problem with such a complex system can be examined from a number of sides. One of the most important approaches is to review the methods of manufacturing physical products to control costs, efficiency and product quality. However, in order to achieve this, there is a great need for the transformation and acceleration of the information flow during production, to which can be used the Manufacturing Information Bus (MIB) for Cyber Physical Manufacturing System (CPMS) too [1]. With the focus on mobility, portability and flexibility as aspects, wireless Networked Control Systems (NCS) are becoming increasingly important [2]. This is complemented by a variety of solutions used in Smart Manufacturing (SM), which, with professional application, can achieve significant resource savings. At the same time, there is a need to become more and more important in the case of larger – scale, more vulnerable corporate IT systems also cyber security issues.

In addition to the MES in the traditional sense, MES versions that perform more efficiently the various specialized tasks, such as the Holonic MES (HMES), are playing an increasingly important role [3]. Examples of such systems include Holonic Adaptive Plan – Based Architecture (HAPBA) or the use of the Product – Resource – Order – Staff Architecture (PROSA) alongside MES or HMES.

In addition to independently operating MES, there is an increasing number of subsystems with complementary collaborative properties that already contribute to greater flexibility at the design stage [4]. For example, the Systems Modeling Language (SysML), which helps the model – based design process for the early phases of Manufacturing System Planning (MSP). The centralized Scheduling System (SS) can also be applied to the MES as it is suitable for generating a global schedule to be implemented by MES. Since the objectives are different at the different levels of production systems, the Viable System Model (VSM) can be applied to the MES to control tasks and subtasks [5]. By using the collaborative Supervisory Control And Data

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Acquisition (SCADA), an enterprise can effectively filter out manufacturing failures and errors, which can be complemented by the Deterministic Finite Automaton (DFA) calculation model [6]. Last but not least, the integration of lean management principles can be an effective way to reduce certain types of losses in production processes.

In addition to collaborative systems, MES also needs to integrate manufacturing technology tools into controlled processes that are widely used in industry today. Collaborative robots can greatly increase productivity by providing adequate control systems, such as Human – Robot Collaborative (HRC) Monitoring System [7]. Other problems may arise if the work of several traditional industrial robots needs to be coordinated. At this point, the coordination of individual software systems and route – exclusion planning can also be a priority. Another widely used tool for automated processes is Automated Guided Vehicle (AGV). Material handling with in – house AGV can be controlled, for example, by Radio Frequency Identification (RFID), whose efficiency can be tested by theoretical methods such as a Gantt chart [8].

On the basis of the above, it can be clearly seen that MES can be expanded in many ways with modern solutions and tools to increase the efficiency, stability and competitiveness of companies, thereby increasing complacency of employee and customers. These methods and tools are described in detail in this review article in the same order.

2 The structure and practical operation of the MES

Nowadays, the vast majority of companies have already realized that using ERP and MES will increase their competitiveness in the global marketplace. It is also generally accepted among professionals that it would not be possible to obtain the properties of Industry 4.0 without using MES. One of the fundamental tasks of MES is to vertically link the tools and information related to the production of the products and make the relevant data visible to the management. Therefore, it can be defined as an intermediate system between the ERP and the manufacturing systems, with the task of providing ERP with manufacturing, logistics, employee, or for example, quality assurance information.

At the same time, MES is an integral part of production management, as it is in direct contact with the automated process system and communicates with networked elements to control, direct and manage the production. It also has an impact on optimization, as it is responsible for collecting data generated during production processes and for debugging. For this reason, MES enables the flow of information in real time and therefore offers a wide range of options for managing production processes. However, due to the different structure of the companies and the different production processes of the products, the functions and tasks of the MES are often defined by industry, not to mention the special needs of the different corporate culture. This is complemented by the fact that the use of MES may have short – term disadvantages due to the staff training and the high investment costs.

The use of MES and ERP at the shopfloor level of the enterprise is one of the most widely used solution. However, according to Lopes et al. [6], due to the ERP and shopfloor levels, the MES between the two systems may be has greater importance than generally accepted, so software support with advanced modeling procedures and collaborative features is required to support the system. An example of this is the Supervisory Control And Data Acquisition (SCADA) described by the Authors, which is responsible for tracking shopfloor and raising awareness of potential disruptions. This is complemented by the Supervisory Control Theory (SCT), which provides optimal control logic and the Discrete Event System (DES), which a formal way to control and model events.

According to the Authors, the use of MES, ERP and SCADA with SCT integration is detrimental to the need for a common interface for DES control units. As this greatly increases the development time of the system and reduces the flexibility, the study recommends the use of Deterministic Finite Automaton (DFA) in SCT, which is used as a computational model in IT fields. The hierarchy of MES, ERP and SCADA and the relationship between the interfaces and systems are illustrated in Fig. 1.

According to Lopes et al. [6], MES is most comparable to a collection of functions that accompany the value creation operations of the production process from order to finished product. However, this requires a continuous information flow for data collection, optimization and control. The latter is assisted by SCADA, which is a software layer above the hardware layer (PLC, microcontroller, or any other type of programmable controllers). A monitoring system with the most important tasks of managing accesses, worker – machine interface control, trend analysis, monitoring, logging and alerting, but implementation is provided by other systems. However, the study describes that one of the major drawbacks of using SCADA is that the need for simultaneous communication makes use of more than one interface between different systems and levels. This can cause additional difficulties

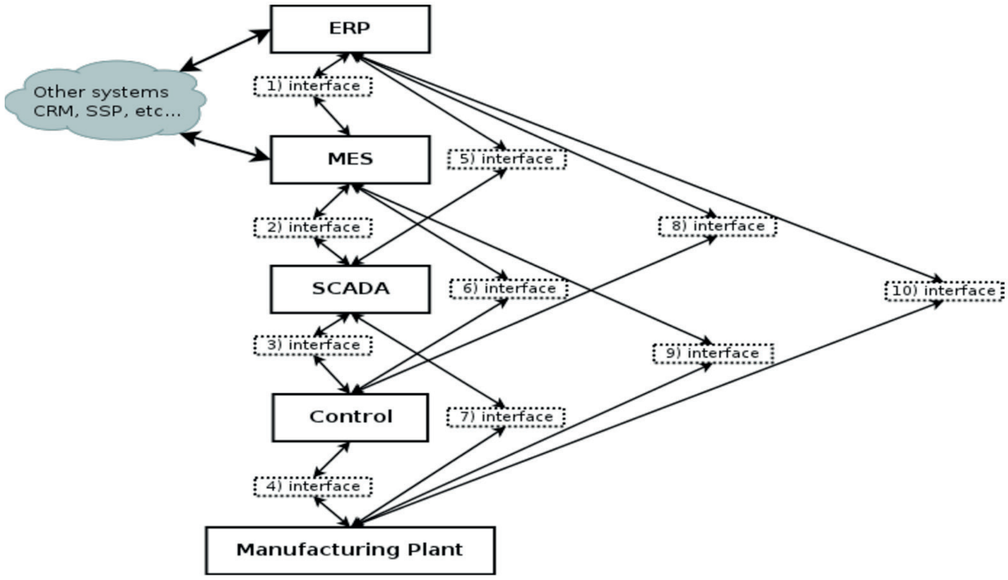

Fig. 1 Interfaces between the ERP, MES, SCADA and manufacturing plant [6]

when data entry is not available for each interface automatic but manual. The Authors consider the manual data entry to be disadvantageous for three reasons:

- there is the possibility of inaccurate data entry;
- the time delay in delivery makes it difficult to monitor production processes in real time;
- data may not be collected properly in all cases.

Lopes et al. [6] also described, that all three features have a particularly negative impact on ERP, alongside SCADA and MES, which is responsible for integrating all corporate processes and centralizing information, but ERP is less suitable for controlling processes due to general instruction sets.

Based on the study, the use of SCADA and DFA in practical production can only be effective if the systems are well – known. However, if the appropriate interface network is deployed, it can increase the transparency and stability of the production system by minimizing manual data entry by using a solution, for example bar code readers.

Representatives of individual industries have made great efforts in many areas and support integrated production methods to reduce losses in order to preserve their position and stability in global competition. One of these is the lean – based manufacturing approach, which for a long time was hardly compatible with the use of various information tools. D'Antonio et al. [9] is looking for an answer to this question, and in their study, examines the benefits of the lean approach in production management systems, and show an example of a case study in the field of aeronautics.

According to the Authors, MES occupies a special place in the manufacturing system of companies, and smaller companies also can successfully apply to improve their competitiveness. The two main tasks of MES are related to the exchange of information, and these are:

- ensuring top – down data flow to meet organizational requirements;
- managing bottom – up data flow for performance measurement and product quality data collection.

Fig. 2 illustrates the position of the MES within an industrial framework.

D'Antonio et al. [9] emphasize that the development of low cost, small and easily expandable sensors and monitoring systems for MES has improved process performance and product quality. Nonetheless, the combination of such IT tools and lean principles has long been seen as a contradiction between companies. The reason for this, according to the study, is the contradiction between *"more is better" information technology* and *"less is better" lean principles*. In the case study, the Authors investigated the production process according to the seven loss types (in Japanese is Muda) separated by the Toyota – method, which are: *overproduction*, *waiting*, *transport*, *extra processing*, *inventory*, *motion* and *defects*. It should be noted, however, that the study does not include the extra one loss type, the unexploited human knowledge. To improve the processes, a three – step test method was introduced and the steps are the follows:

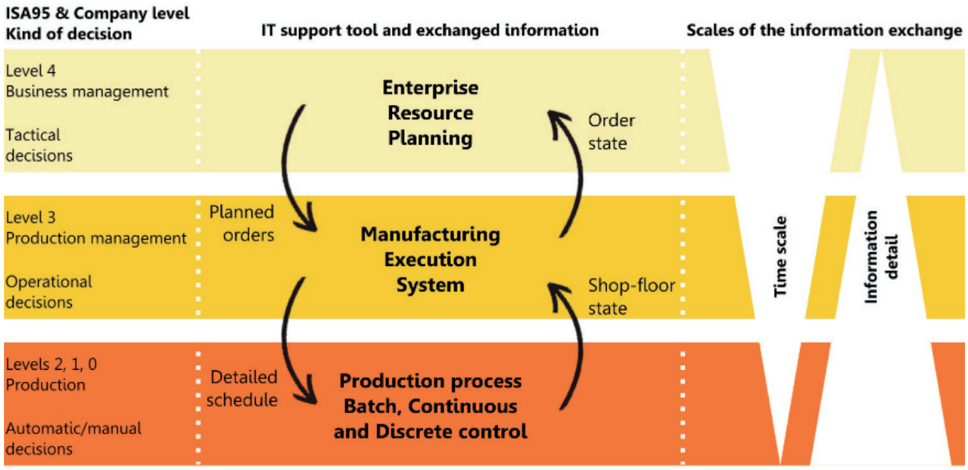

Fig. 2 MES positioning within an industrial framework [9]

1. identification of the waste classes;
2. description of the process;
3. data – analysis for development.

In addition, the process had to be broken down into components and resources, as summarized in Table 1.

In the case study, D'Antonio et al. [9], after completing the above steps, found that with the adaptation of the lean principles, the proportion of scrap components can be reduced by 50 percent, while time and manufacturing costs can be reduced by 40 percent. At the same time, attention is drawn to the fact that without a comprehensive methodology and properly formatted data (for example, the use of the Data – Information – Knowledge Wisdom (DIKW) hierarchy), the implementation of the lean principles alone is not enough.

As described above, the central role of MES in companies often requires collaborative methods, tools and solutions that play different roles in each subsystem. This requires extra investment on the part of the organization, but it can greatly help reduce losses, or in the words of D'Antonio et al. [9], customers are not willing to pay the loss.

According to Li et al. [10], MES is the bridge that connects the top layer of planning and the bottom layer of control. The Authors examined the functions of MES of a steel company operating in Shanghai, which gained

Table 1 Complements and resources of the process [9]

Input components	Output components	Input resources	Output resources
Suppliers: they can be external partners as well as upstream manufacturing processes within the same company to provide raw materials or semi – finished parts to be further processed. *Planning*: consists in information necessary to plan the push or pull production system and control the shopfloor level. Inter – arrival time and variability for the input components must be evaluated. *Design*: related to the instructions necessary to produce the parts: materials, machines, part – programs, parameters or work-piece position in machinig areas.	*Performance*: the process provides the (semi –) finished products and performance indicators to characterize the line: like cycle time, work in process, throughput, queues, average utilization of the machines, their availability or the incidence of failures. *Quality*: information about product quality is getting to be mandatory for manufacturers. It may result from a simple "pass or non-pass" test, or from a more complex monitoring system based on the deployment of sensors.	*Reusable*: includes all the resources that can be re – used in the manufacturing process after the production of a part. *Disposable*: collects the resources which are used for the purposes of the production process and cannot be reused or restored like energy and the fluids (compressed air, lubro – refrigerants) used by the machines, or the tools.	*Reusable*: physical output quantities are the same that were provided in input, but the operations changed their state. *Disposable*: nothing can be collected at the end of the process, except scraps. Information about the consumption of the process must be collected to to evaluate the real impact and cost of the processes.

outstanding economic benefits through the use of the system. The research focused on the production aspects that made special demands on MES functions in the production of steel products. These were complexity, randomicity, restriction, multi – object and continuity.

In Li et al. [10] opinion, the listed functions and the process in the MES software used so far have been significantly simplified. At the same time, inadequate transmission of information contributes to unreasonable process layouts, high work intensity, and difficult variability. However, the Authors note that MES is rarely used in product design, quality control, and dynamic cost control. At the same time, better optimization of the material flow path can reduce material costs and energy consumption, which in the long run increases economic efficiency.

In their study, Yoon and Suh [1] also emphasize the importance of appropriate information transfer to achieve an effective MES. To improve Smart Manufacturing (SM) and Total Performance Index (TPI), the Authors have therefore developed the Manufacturing Information Bus (MIB) architecture to support the Cyber Physical Manufacturing System (CPMS). This allows to replace the As – Is Factory Model with the To – Be Factory Model. The differences between the two models and the benefits of the latter model are illustrated in Fig. 3.

According to the Authors, the replacement can be divided into an eight – step process with the following steps:

1. definition of goal and scope;
2. build a factory model;
3. identify information flow of As-Is factory model;
4. identify information flow required for To-Be model;
5. identify smart factory services;
6. define MIB for smart factory;
7. verify To-Be model information flow;
8. implement service.

Following the introduction, the MIB architecture can be useful in designing intelligent manufacturing systems, identifying appropriate services, and achieving more efficient information flow. At the same time, Yoon and Suh [1] also notes that in the design of the SM to achieve MIB efficiency and to manage the data stream, Smart Agent Technology (SAT), machine learning, complex event processing and distributed database platforms are also required.

According to Papacharalampopoulos et al. [2], Networked Control Systems (NCS) play a major role in MES and generally in corporate information transfer, modeling the efficiency of process control. Therefore, the study presents NCS modeling of a production subsystem, which took into account the delay of signals, routing and packet loss resulting from the applied protocol and the effect of different distortions. The effectiveness of the defined variables and the physical measures described were examined in two production processes: laser welding and robot movements.

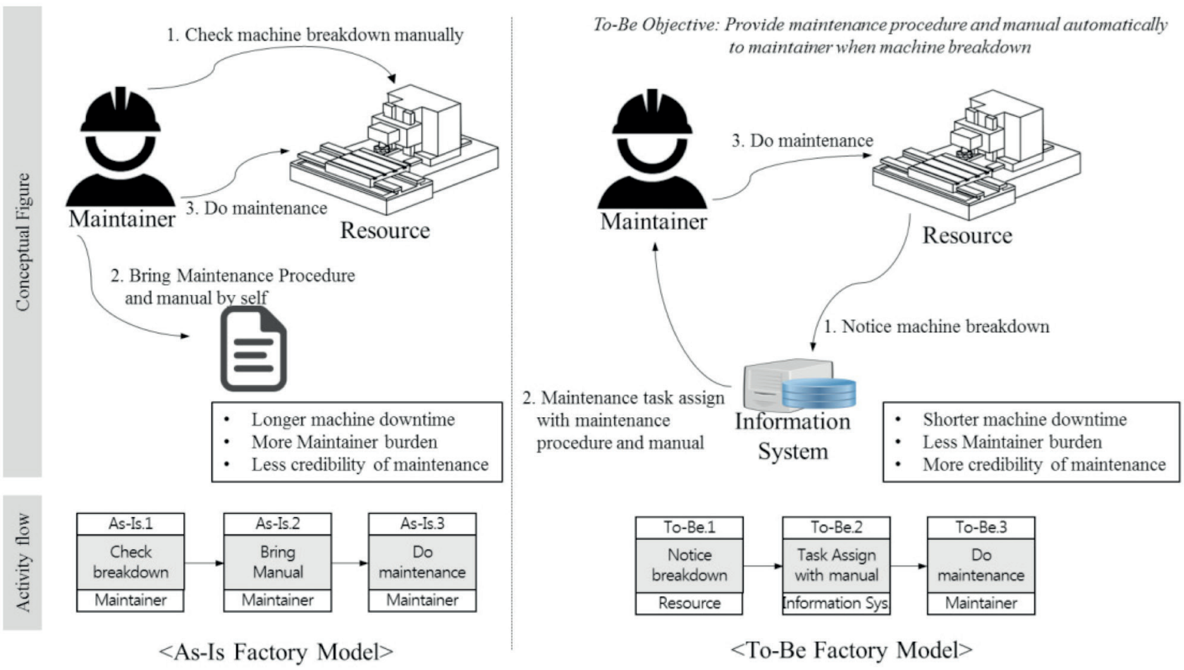

Fig. 3 Differences between the As-Is and To-Be Factory Model [1]

In the opinion of the Authors, better results can be achieved with respect to cycle time and energy consumption, with the help of NCS for control and monitoring of production processes. The network control used to control the manufacturing process often interferes with the operation of the system, which adversely affects the performance of the control. This is further complicated by the fact that modern manufacturing systems generally require more complex loop systems, the simplified structure of which is shown in Fig. 4.

Papacharalampopoulos et al. [2] also note that an appropriate ad – hoc communication network and topology make available the robustness and performance of the production system on a daily basis.

In their study, Larsen et al. [11] note, that special industries often require a combination of new production technologies and innovative materials, and these may also have unique demands on MES. Examples include Carbon Fiber Reinforced Thermoplastics (CFRTP), which allow the aerospace industry to weld thermoplastic matrix systems. Based on the study, Automated Tape Laying (ATL) and Automated Fiber Placement (AFP) machines, which are essential to the manufacturing system, are easily available on the market, but systems for producing special 3D shapes are still missing, making it difficult to customize standard parts. For this reason, the Authors have implemented an integrated work cell illustrated in Fig. 5, with the following main elements:

- preprocessing and production planning apps;
- industrial robot with a gripper for an ultrasonic welder;
- storage system for cut-piece supply;
- the computer vision system;
- collision avoidance app;
- logging system for inline quality control.

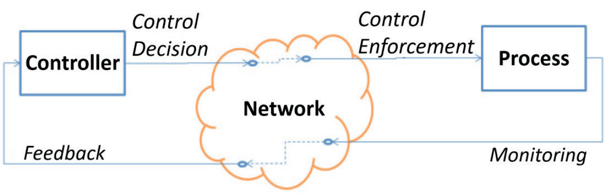

Fig. 4 Simplified structure of the network systems [2]

Larsen et al. [11] focused on two aspects of system creation, which can greatly increase the efficiency of MES when applied systemically in all cells of the production system: Collision Free Path Planning (CFPP) and Grip – Planning and Metainfo Generation (GPMG). By using Computer Aided Technologies (CAx), a reliable Smart Manufacturing (SM) system has been created that measures and records the parameters of the process and takes into account the simulations performed on the raw material, which is an important aspect of pre – processing. The Authors also point out that flexible production for such systems like this, manual training should be avoided as it is time consuming and expensive, and proper cutting detection and flexible program modules are also essential, which also gives the user a better orientation.

By creating a bridge between physical manufacturing, especially Smart Manufacturing (SM) solutions and the digital environment, companies face new challenges besides potential benefits. Examples include IT security in existing industrial and manufacturing systems, or cyber attacks, as illustrated by Tuptuk and Hailes [12]. The study discusses problems such as the weaknesses of existing cyber security systems or the importance of preparing for costly IT infringements.

In addition to discussing individual security issues, the Authors list the most common cyber attacks, including Denial of Service (DoS), eavesdropping, man – in – the – middle, false data injection, time delay, data tampering, replay, spoofing, communication channel, covert – channel, zero day – physical attack and attacks against machine learning and data analytics. In addition to each mode, identifiable attack steps are also discussed. Tuptuk and Hailes [12] also analyzed what tools CIM connects to

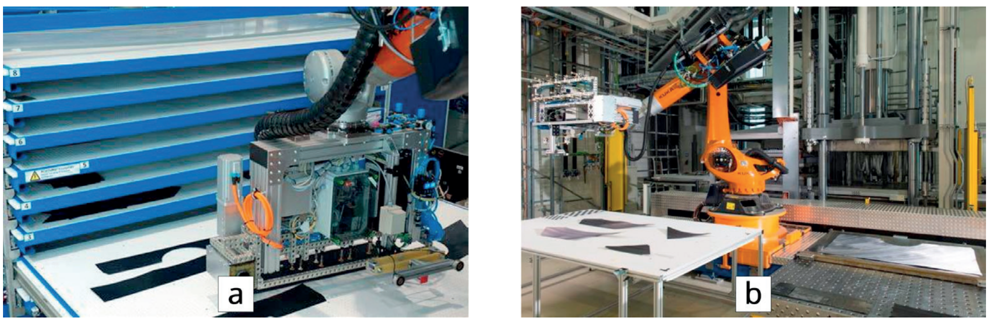

Fig. 5 Mobile drawer unit for the storage of cut pieces (a), Robot in detection position in the integrated work cell (b) [11]

the company at five levels and what network communication it uses. The triangle summarizing these and tools in every company level are illustrated in Fig. 6.

The Authors also point out that without adequate data analysis and learning methods, it is extremely difficult to recognize the long-term effects of damage caused by attacks. Among the protection methods, static methods can be distinguished, which are also found in industrial standards and dynamic methods, which are typically incident management systems. However, the effectiveness of these can be greatly reduced by the large number of subsystems linked to CIM if cybersecurity is considered to be a design principle. Safety is therefore not a product that can be purchased and added to a system, but a process that begins at the design stage or before, and has to transcend all aspects of the system that has been created.

3 The use of the Holonic MES

In addition to increasing the efficiency of production systems, concepts and suggestions have been brought to the forefront of system – oriented production that not only develop some elements of MES, but MES as a system for greater flexibility. One of these system – level concepts is the Holonic Manufacturing Execution System (HMES) that extends the possibilities and capabilities of MES, which is also described by a study of Pascal and Panescu [3].

According to this study, compared to the production and control systems used so far, HMES has outstanding flexibility, which is ensured by the balance between hierarchical and heterarchic architectures. The applied architecture is also called Holonic Adaptive Plan – Based Architecture (HAPBA), and its strength lies in the ability to implement concrete design mechanisms. This is complemented by the appropriate coordination protocols and the Belief Desire Intention (BDI) agent – based architecture. The schematic structure of the system is shown in Fig. 7.

In the case of HAPBA, four basic organizational units (holons) can be distinguished according to Pascal and Panescu [3]: product, resource, order and staff holons. According to the structure, a new element or device introduced into the HMES system must appear as a holon. In addition, only need to establish a communication link in HMES and no other change is needed. If a holon falls out of the network for some reason, BDI will try to replace it, which will increase the flexibility of the production system. At the same time, the Authors also point out that although the HMES set – up plans may be independent, they must be prepared at the level of the design libraries, which means that the same method should be introduced at the holons levels.

The theoretical questions of the application of HMES are also discussed by Verstraete and Valckenaers [13]. The Authors present HMES, which works with the design system, and allows the linking of robustness and flexibility with the optimization done by the system. In the description, the PROSA (Product, Resource, Order and Staff holon) Architecture was used alongside the HMES.

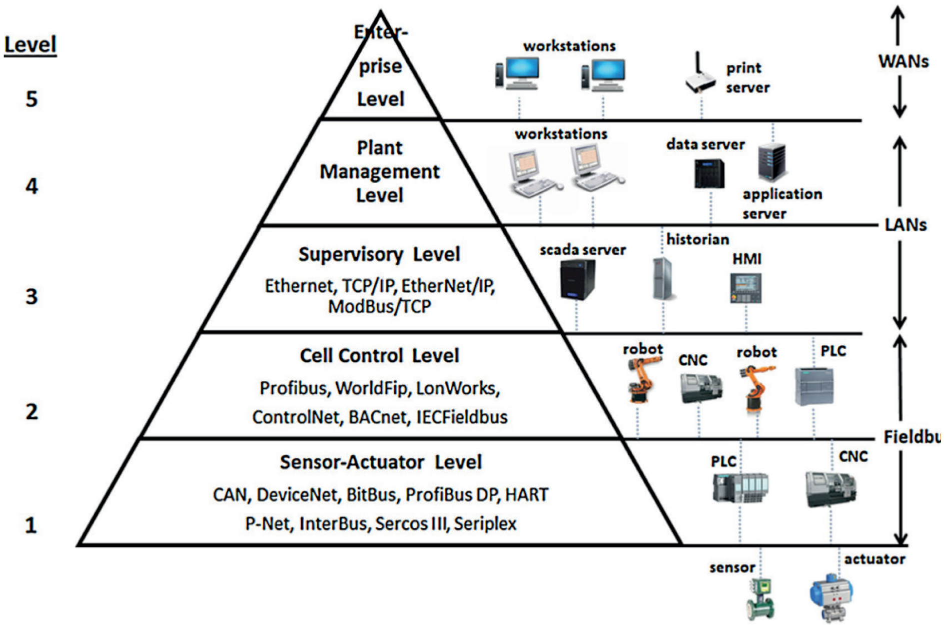

Fig. 6 Company levels triangle, tools, and network communication for Computer – Integrated Manufacturing (CIM) [12]

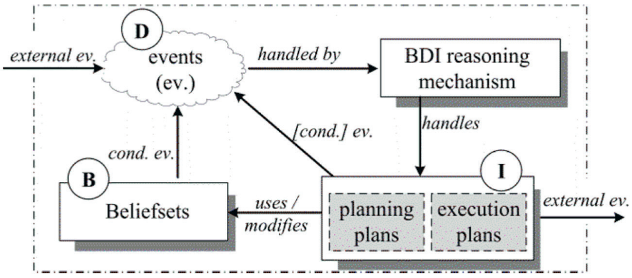

Fig. 7 Diagram of the holonic agent's activity in HAPBA [3]

The HAPBA described by Pascal and Panescu [3] is an instantiation of PROSA reference architecture. In addition, the case discussion includes:

- the challenges of the MES follow the planning;
- the adaptations made to the challenges of these challenges;
- the input and planning used by the MES;
- the output of the combined system.

The study describes that companies primarily have two objectives for the shopfloor operations, and therefore the use of HMES would be particularly justified:

- optimizing production performance for management purposes (cost reduction or customer satisfaction);
- robustness and thoroughness implementation that take into account unforeseen disturbances in production and other parameters that cause uncertainty.

At the same time, Verstraete and Valckenaers [13] emphasize that the introduction of HMES is not a monolithic system capable of solving problems that arise on every production side. In this case, the introduced holons and subsystems could only operate under strict constraints, reducing flexibility. If a particular holon does not find a solution alternative, other holons may have to switch to another solution. Thus, one of the directions of development of agent – based systems is that the problems that have arisen are eliminated at the planning level.

Hadeli et al. [14] also used the PROSA reference architecture to describe their own HMES, and this was supplemented with multi – agent technology. Three types of agents have been defined to describe system processes:

- product agent for product and process – related technological aspects;
- resource agent for resource aspects;
- order agent for logistical aspects.

The location and hierarchy of each agent within the manufacturing system is shown in Fig. 8.

The HMES presented in the study is based on two aspects:

1. Orders received into the system do not have predefined information about the required operations and routes, so the system must identify them and determine the steps and order of manufacturing.
2. Resources do not have information on what order to process in the next step, so HMES should also provide resource allocation.

To coordinate the system, Hadeli et al. [14] had to define three other agent types:

1. feasibility ant agent to indicate the downstream available operations at every exit of the resources.
2. exploring ant agent to virtually navigate through the factory from the start position of the work piece until the last process.
3. intention propagation ant agent to select the best performing route for the work pieces.

The benefits of the described HMES against conventional production systems are summarized in Table 2 by the Authors.

The study by Hadeli et al. [14], besides the benefits available, also highlights that the core of HMES and agents' operation is made up of forecasts that include order paths and the amount of resources needed to produce the items. However, this is somewhat contradicted by the fact that HMES has no explicit scheduling function. It should be mentioned that, the study does not focus on problems related to the use of holons, such as difficulties in solving common tasks, executing orders from higher levels at lower levels, and defining the under- and over-order relations. Fractal systems developed in parallel with the holons are also not mentioned in the study.

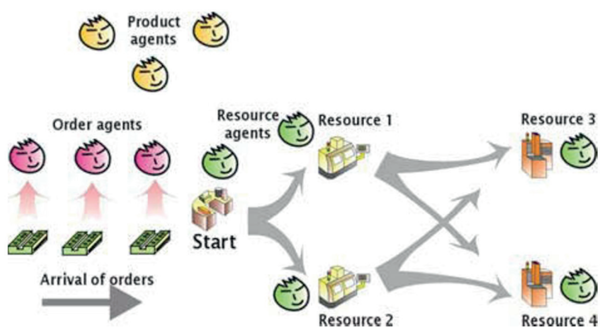

Fig. 8 A manufacturing system and its agents [14]

Table 2 Comparison between the HMES and the traditional approach in a manufacturing system [14]

HMES	Traditional Approach
Given settings	
No prior routing. Flexible process plan. Each order has its own arrival time.	Routing is pre – defined. Pre – defined process plan. Orders presumably to be arrived prior the scheduling process.
Planning aspects	
Each order will self organise itself. Find their own routing. Discover available resource(s). Reserve the resource(s).	Available orders are scheduled based on the current prediction on future resource(s) availability.
Control aspects	
When changes & disturbances appear only affected order takes necessary action. It re-discovers its own route, update its own reservation.	When changes & disturbances appear whole schedule needs to be re – scheduled.

According to the authors, such a system – along with all its advantages and disadvantages – is most reminiscent of a conventional map. A good map has many points of reference, but users are free to choose their route and the way to get there.

4 Collaborative systems that complement the MES

In addition to the methods and tools for solving problems arising from the use of MES on a daily basis, as well as the holonic approach that increases the flexibility of MES, and in many cases, it may be necessary to use collaborative systems that support MES. These systems may include physical subsystems and networks serving some of the functions of MES, or models enhancing the theoretical efficiency of MES.

The latter is also the subject of a study by Steimer et al. [4] describing the Model – Based Planning Process (MBPP) for the early phases of Manufacturing System Planning (MSP). This approach is based on Model – Based Systems Engineering (MBSE) and aims to increase the integration of MSP and Product Development (PD). MBSE – based design supports a modeling scheme that describes system features using System Modeling Language (SysML). The Authors also modeled the production process of a cylinder head as an example for the presentation of MBSE.

According to Steimer et al. [4], a model – based approach to MSP can be extremely beneficial in terms of the ability of MBSE to identify all the tasks required for product – integrated design of a production system. The process structure of the definition then can be divided into two stages: one for early system design and the other for discipline – specific design. This is described by a so-called iterative V – model that allows iterative planning while being divided into four modeling levels, which are:

- Context level: defines the boundary conditions of the production system based on regulations and standards, the management, product development and other stakeholder requirements.
- Manufacturing technique level: includes manufacturing technology requirements, primary (value – creating) and secondary (logical) processes, and elements of flow – oriented structure.
- Structure & control level: basically provides information about the structure of the manufacturing system and the control logic and assigns the necessary resource types to the originating processes from the production technology.
- Technical solution level: identifies the three types of technical subsystems in the production system: subsystems which, without further iteration, are classified as black – box in the production, which can be described as products and whose development is continued during the next design phase.

The iterative V – model and the four levels connection to each other described above are shown in Fig. 9.

Steimer et al. [4] draw attention to the difficulties of using MBSE and SysML due to the system approach, which are summarized in eight points:

1. MPS engineers prefer traditional manufacturing systems and procedures.
2. The use of MBSE and SysML requires expert knowledge.
3. Mostly only abstract system representation is possible, there are no functions for modeling real scale layouts.
4. Modeling and evaluating different design variants is not yet included in SysML.
5. It is difficult to handle large models.
6. There are no libraries for standard production units.
7. MBSE requires a very abstract way of thinking in the early planning phase.
8. System modeling is difficult to adapt to the production and business processes of an enterprise at the same time.

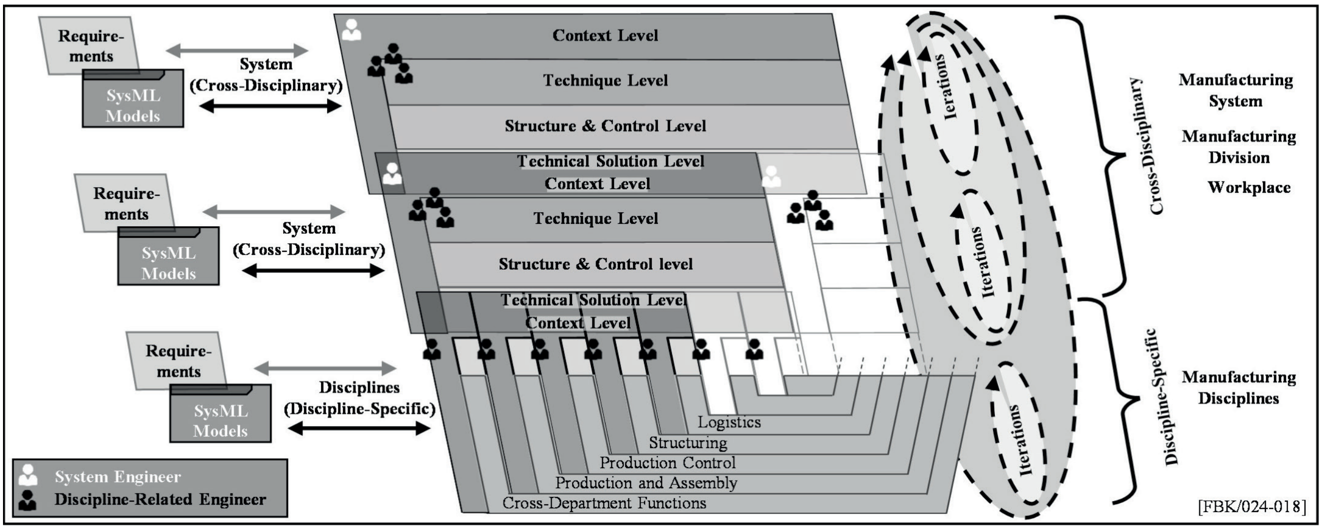

Fig. 9 Iterative V – model and the four connecting modeling levels of MBSE approach for MSP [4]

At the same time, the Authors point out that the modeling procedures pay off in the long run if the above described problems are solved on the research and practical side.

In order to satisfy different orders, the flexible and reliable operation of the production items to be incorporated into the production system has become of paramount importance, as discussed by Novas et al. [15]. The study shows the relationship between a decentralized MES and a centralized Scheduling System (SS) that greatly enhances the performance of the implementation process when using an IBM ILOG environment. At that time, the PROSA architecture described above was applied to MES, and in addition, the Authors used the Delegate Multi – Agent System (D – MAS), which use product, resource and order agents, like Hadeli et al. [14] described.

The SS is based on Constraint Programming (CP) technology, which is responsible for generating a global quality schedule that takes into account the specifics of the MES used in the enterprise. The CP also provides an opportunity to monitor the implementation process and shows the impact of the process on production performance when an unexpected disruption occurs. The main tasks of the SS are to

- optimize execution at the required stability and efficiency level during the scheduling horizon;
- enable performance measurement;
- meet the modeling constraints specified in the program at low CPU times.

According to Novas et al. [15], CP is an excellent tool for these tasks, as it includes computational implementations of algorithms to tackle constraint satisfaction problems. An important advantage of short – term scheduling is that the limitations for CP can be easily and gradually added to the system and can be formulated as interval variables and last but not least domain – based strategies can be developed for the search process, as the modeling language is highly declarative.

The Authors have placed great emphasis on the ability to handle the temporal, assignment and topological constraints on the domains at the last point in the SS they describe. In addition, it was crucial for the SS to be able to process relevant parameters such as transport and storage information in addition to the MES – related manufacturing activities. For the collaborative application of SS and MES, the data exchange process had to be written down and resolved. Because of this, the SS helps MES with a schedule with the required properties, even MES provides up – to – date information to the SS to optimize the schedule. The schematic process of data exchange described is shown in Fig. 10.

In addition to the benefits of collaborative deployment of SS supported by CP technology for shedule, and the MES for implementation, Novas et al. [15] draw attention to the

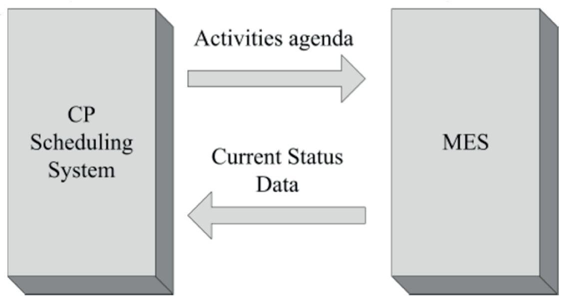

Fig. 10 Schematic representation of the data exchange between SS and MES [15]

tasks that are key to improving the performance of a manufacturing system. These are

- investigating unexpected events in the SS system that may cause deviations from the original schedule;
- run simulations to make the MES deployed flexible in terms of implementation;
- finding that MES or SS is more suitable for system – level data update examining SS – MES interactions for efficiency and stability.

If a relevant solution is found for the tasks described above, the combined use of SS and MES can greatly help to adapt economical and modern production processes.

The rapid change in market demands and the massive shortening of the manufactured products' life cycle also led to the adaptation of companies to the changed circumstances. The complexity of automated production systems and the need to optimize production processes are also increasing. For this reason, besides the MES that responsible for factory – level operations, the Viable System Model (VSM) with collaborative features – and advantages by use the SysML – has been published, which is also the subject of a study by Brecher et al. [5].

The importance of the Viable Manufacturing Execution System (VMES) developed by the two systems, according to the Authors, is that it can handle all the processes at the factory, shopfloor and cell level simultaneously unlike the conventional MES. In practice, this means that a CAD file belonging to a product and the data associated with it, as the production quantity, together describe an order. This order is displayed as an input in the highest level of the system, and even each subsystem can access the appropriate information from the order database. The differences between MES and VMES are shown in Fig. 11.

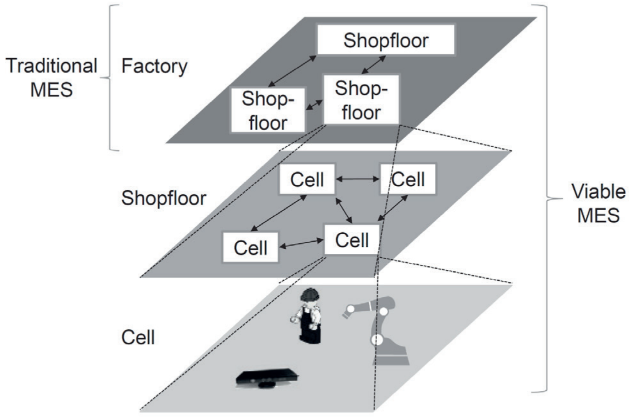

Fig. 11 Activities of a traditional MES and a Viable MES [5]

According to the study, the Viable System (VS) can be used effectively in general, because at different production levels, different goals are usually desirable, so the modeling of a decentralized system can be solved by solving multidimensional problems. Within VS, Brecher et al. [5] distinguish six subsystems:

1. System 5 (Policy) to provide values, norms and politics to develop a stucture and define the identity of a system.
2. System 4 (Planning) to record and diagnose the environment and represent the strategic layer regarding future and outside appearance.
3. System 3 (Control) to optimalise, provide instructions directly to the underlying processes and incorporate an overall model for all processes and ineractions.
4. System 3* (Auditing) to escalate errors and supervise the underlying processes.
5. System 2 (Coordination) to regulate and coordinate subsystems.
6. System 1 (Process) to realise basic activities of the whole VSM.

The Authors also point out that the principles of VSM are

- recursion, that ensures that all levels need only handle specific information;
- autonomy, that increases the degree of decentralization of the system and improves the self – organization and independence of the elements of the system;
- viability, that ensures the invariant structure of the system, making it easier to recognize internal disturbances and react to environmental changes.

The model and the properties of the VSM are illustrated in Fig. 12.

In addition, Brecher et al. [5] compare VSM with a human nervous system, capable of learning and disrupting the learning process in the next cycle of optimization. In addition to the benefits described, the study also shows that further research at some levels of the system would be needed. For example, to focusing on technical components, it would be necessary to examine the interaction between VMES and human operators and last but not least validate the capabilities of the system in industrial practice.

5 Additional manufacturing tools for the MES

Collaborative systems can be highly efficient in controlling and optimizing processes at shopfloor level. At least as important to achieving the goals of companies is that

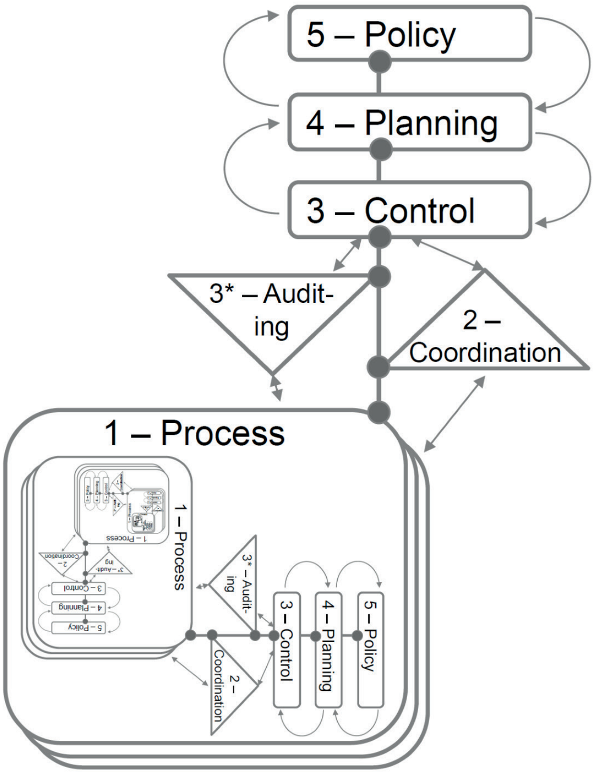

Fig. 12 Structure of VSM [5]

a process can be controlled with the same precision for each cell and subsystems serving the cells. Nowadays, many modern industrial solutions and specialized manufacturing units are available for the economical and large – scale production of a product. However, this also includes the requirement that machining in a Human – Robot Collaborative Cell (HRCC) can be provided with a suitable software background for proper performance and data collection which is also the subject of a study by Argyrou et al. [7].

The Authors describe the application of a software system that can be used in HRC assembly cells to monitor the state of resources and machining stages. The proposed system should also ensure that sensor data can be dynamically and uniformly managed and provide valuable information to the operators. The system described in the study has also been validated by testing in a HRC cell for assembling EURO6 diesel engines.

The HRC Monitoring System used by Argyrou et al. [7] is a device that functions as a data collection point because it provides different data sources and information about the different layers of production. In the case of integration with MES, it can be regarded as an intermediate system that transmits production process parameters to MES and is capable of transmitting data over the Internet. The latter enhances the connectivity of HRC systems and allows connection to other cells, machines, or vehicles. The HRC System consists of three main parts:

1. HRC monitoring system adapters that are responsible for collecting information about the HR environment;
2. HRC Fusion Engine (HRC – FE) that processes information collected by adapters;
3. publishers that transmit processed data to other systems (such as MES).

The adapters include the follows:

- Safety Oriented Execution Controller (SOEC), which provides access to control functions;
- Human Activity Recognition (HAR) module, for monitoring the position of human operators;
- Skillnet Execution (SE) module that controls robots by sending the skills for execution to SOEC.

The practical usage was implemented in Linux Operating System by using Robot Operating System (ROS), and for HRC – FE, the Authors used the C ++ programming language. The structure of the system is shown in Fig. 13.

According to Argyrou et al. [7], in the case of a HRC cell, great emphasis should be placed on the visual presentation of informations (for example, using of the Smartwatch user interface) and the various security solutions that are illustrated in Fig. 14 with the investigated manufacturing cell.

Based on the study, the HRC data fusion system can be considered as a reliable source of information that can provide well – processed data for the coordination of other processes with MES and for the management. During validation, HRC – FE was adjustable for data processing and

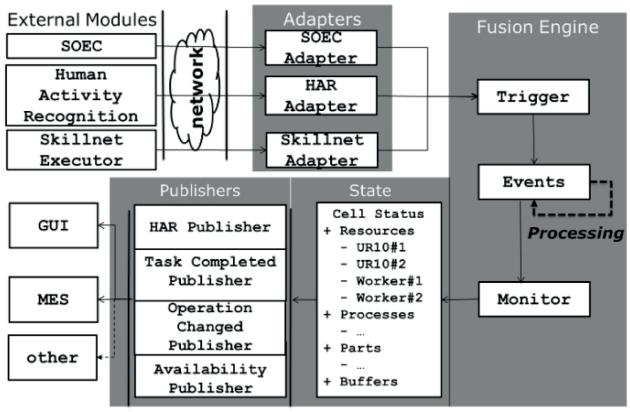

Fig. 13 Architecture of the HRC Monitoring System and the main components [7]

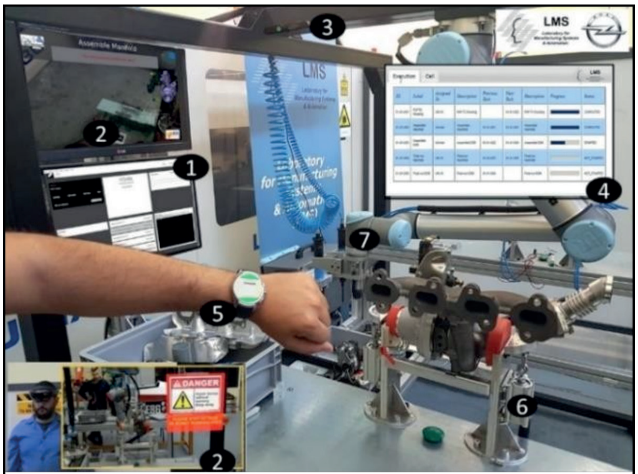

Fig. 14 Visual tools, security solutions and the HRC Cell [7]

the system worked well for compatibility. At the same time, Argyrou et al. [7], on the basis of the tests, note that it would be possible to implement self – learning mode by examining a more complex HRC Cell. Additionally, the performance of the system would be enhanced by collecting human activity data using a laser scanner with a monitoring adapter.

Schuster et al. [16] examined manufacturing problems with production cells used in the aerospace industry. The structures used here have to withstand heavy mechanical stress, which requires the use of special materials such as Carbon Fiber Reinforced Plastics (CFRP) or Fiber Metal Laminates (FML). According to the Authors, in addition to the lack of innovative technologies from the industry that would allow the production of such materials of adequate volume, their processing is much more problematic in integrated systems such as production cells developed for high flexibility.

For this reason, the study examines an autonomous multi – robot pick – and – place process in an airframe manufacturing cell with steps of picking, transfer, dropping and post – drop treatment, that can be apply in MES and ERP for aerospace industry enterprises. According to Schuster et al. [16] for industrial robots, the biggest difficulty is that in the aerospace industry, the diversity of components made of the same material is so large that the time spent on teaching efforts can exceed the production time of parts. The industry already uses advanced solutions such as Delmia Robotic Simulation or Process Simulate software, but they can only be used within certain limits. However, due to the high quality standards, the systems used must be robust, nad that is directly related to CAx, which is needed to eliminate manual teaching of the robots.

Because MES can be used to check the reliability of the process in an enterprise use, the Authors have developed a CPMS – controlled cell for CFRP production that controls two robots mounted on the same linear axes. KUKA Quantec KR210 R3100 type robots are controlled by KUKA Robot Language (KRL) using the Ethernet CRL. The system is structured as follows:

- MES and the Cut Detection Interface (CDI) that handle general metadata and layup information;
- robots and their controllers;
- Multiple Computer Vison Systems (CVS) for detection of the goods being handled;
- Collision Control Simulation Environment (called CoCo) for collision avoidance;
- Hardware Abstraction Layer (HAL), that ensures the triggering of the right cameras and the coordinate transformations between cameras and robots.

Schuster et al. [16] emphasize that cameras can be mounted on a robot, or define a logical relationship between a robot and a camera, which increases the flexibility of the system and facilitates data collection for optimalization for MES and ERP. The overall structure of the system for four robots and cameras is shown in Fig. 15.

Based on the study, validation by hundreds of workpieces, the Authors say the CPMS – controlled cell has performed

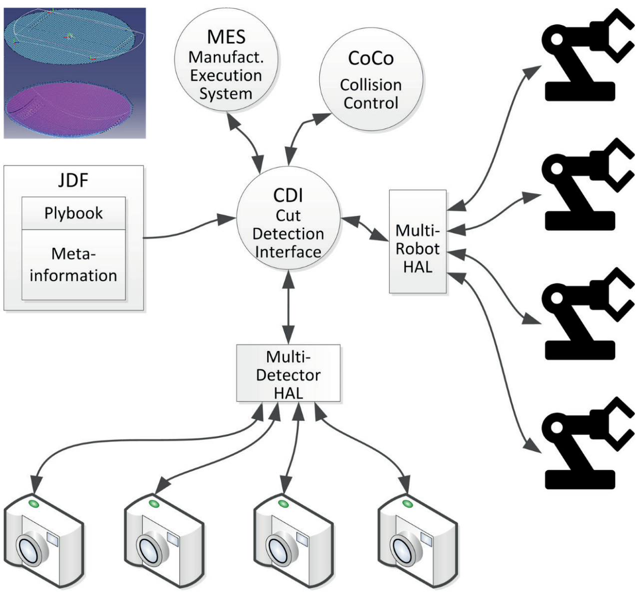

Fig. 15 System architecture for four robots and cameras [16]

satisfactorily for quality and stability. It has been successfully proven, that the system is capable of performing a pick – and – place process independently, while only a general description and a CAD model are available. In parallel, there are still shortcomings in the production system for generating motion paths and collision monitoring. In addition, Schuster et al. [16] suggest the extending of the system to a complete production network for further development that can be an additional subsytem for the MES.

In an increasingly dynamic market, companies need increasingly dynamic and powerful production systems to keep their competitiveness. However, enterprises should be designed to provide permanent information about the state of the system with minimal disruption and loss. The same considerations apply to the production subsystems. One of these is the Automated Guided Vehicle (AGV) subsystem, which is used for tools and material handling, and was developed by Zhang et al. [8].

The study presents an intelligent Production Control System (PCS) in which each component has embedded knowledge of the state of the production process. For dynamic scheduling and material handling, Authors used Radio Frequency Identification (RFID) technology to communicate between heterogeneous hardwares and softwares. In contrast to other identification technologies (such as bar code scanners), RIFD has advantages such as passive, wireless data transfer, dynamic data reading, high data capacity and ability to use distributed control systems.

To create an Intelligent Manufacturing System (IMS), Zhang et al. [8] also include automated material handling, so the agent – based system – defining storage, machine and AGV agents – has been developed to control AGVs. Storage and mechine agents systematise and issue the tasks to the AGV agents, which selects the optimal task for each AGV. Authors have also built a simulation platform for testing the system. The main parts of this platform are:

- AGVs for deliveries;
- RFID Reader for communication between the parts;
- Machine Center to order deliveries;
- Automated Storage/Retrieval System (AS/RS) based on the Advanced RISC Machine (ARM) Controller and is responsible for transporting the work – pieces and storing the raw materials and machined parts.

The simulation platform and main parts of the system are shown in Fig. 16.

Zhang et al. [8] defined four types of products and machines, two AGVs, and two orders to complete the test, and the state before and after optimization was illustrated on a Gantt – chart. Significant progress was made – with the simulation of one AGV repair – to reduce the total time of the optimized process from 289 to 275 seconds. At the same

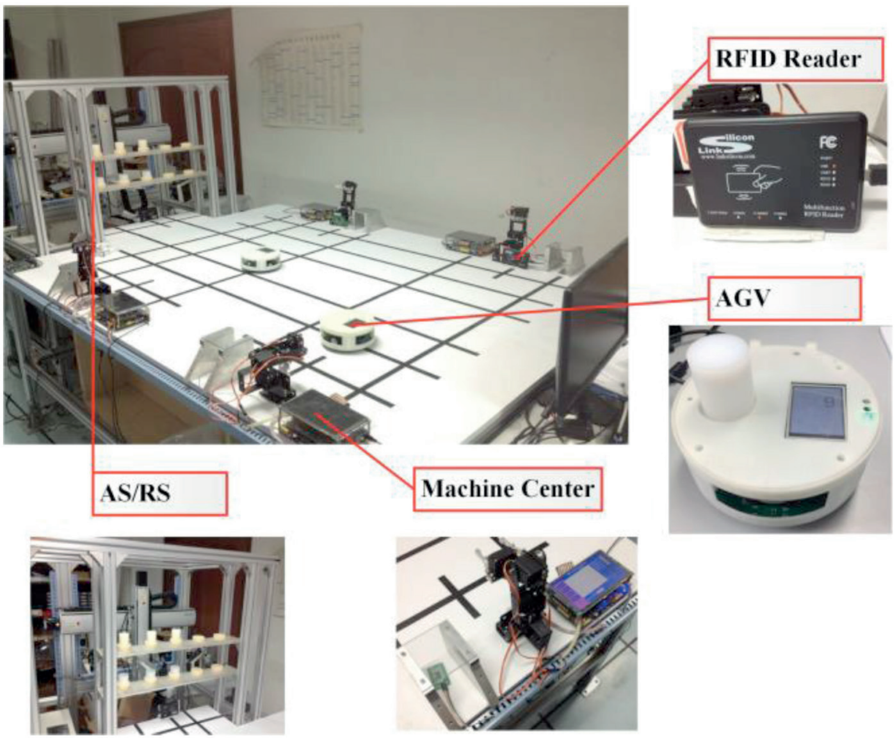

Fig. 16 Experimental simulation platform with the main parts [8]

time, the study points out that the system uses the shortest delivery time strategy first, so it will need to develop the optimalisation model for different manufacturing strategies.

These three practical examples also show that manufacturing systems have need and potential for development at the enterprise level as well as at the operational level. Effective interaction of each cell with the subsystems and with each other greatly affects delivery time and quality. As the study of Zhang et al. [8] has shown, a few percent improvement can be achieved with a not too complicated optimization process, which is a long – term interest for all enterprises.

6 Conclusions and outlooks

Due to the development of the global market, the need for agility, flexibility and adaptability is increasing among companies. This puts increased demands on enterprise process management systems such as MES or ERP. In this article serie, subsystems (like AS/RS), tools (like HAR) and methods (like lean principles) for supporting MES have been presented, with particular reference to the latest industry solutions, like HRCC.

This review article describes the practical operation and architecture of the MES on the corporate applicability side. A special version of MES, HMES, has also been described. In addition, there are several examples of collaborative systems and solutions that can help improve the efficiency of MES, and finally, the production solutions that help MES and ERP in companies improve their operational level. In order to make the topic easier to understand, the author summarized the most important subsystems, tools and methods in the first article in Table 3.

By analyzing these aspects, the Author hopes to contribute to the understanding of the structure, operation and task of MES in the 21st century from a theoretical and practical point of view. For the next generation of MES, it is essential to have a thorough understanding of the planning, manufacturing and execution problems of enterprises in different industries, in addition to exploring the theoretical model, capabilities, advantages and limitations of the MES.

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Table 3 Subsystems, tools and methods for supporting MES

1	AGV	Automated Guided Vehicle	23	IMS	Intelligent Manufacturing System
2	ARM	Advanced RISC Machine (Controller)	24	MBPP	Model – Based Planning Process
3	AS/RS	Automated Storage/Retrieval System	25	MBSE	Model – Based System Engineering
4	BDI	Belief Desire Intention	26	MIB	Manufacturing Information Bus
5	CAx	Computer Aided Technologies	27	MSP	Manufacturing System Planning
6	CDI	Cut Detection Interface	28	NCS	Networked Control System
7	CFPP	Collision Free Path Planning	29	PCS	Production Control System
8	CoCo	Collision Control (Simulation Environment)	30	PD	Product Development
9	CP	Constraint Programming	31	PROSA	Product, Resource, Order and Staff holon Architecture
10	CPMS	Cyber Physical Manufacturing System	32	RFID	Radio Frequency Identification
11	CVS	Computer Vison System	33	ROS	Robot Operating System
12	DES	Discrete Event System	34	SAT	Smart Agent Technology
13	DFA	Deterministic Finite Automaton	35	SCADA	Supervisory Control And Data Acquisition
14	DIKW	Data – Information – Knowledge Wisdom (hierarchy)	36	SCT	Supervisory Control Theory
15	D – MAS	Delegate Multi-Agent System	37	SE	Skillnet Execution
16	GPMG	Grip – Planning and Metainfo Generation	38	SM	Smart Manufacturing
17	HAL	Hardware Abstraction Layer	39	SOEC	Safety Oriented Execution Controller
18	HAPBA	Holonic Adaptive Plan-Based Architecture	40	SS	Sheduling System
19	HAR	Human Activity Recognition	41	SysML	System Modeling Language
20	HMES	Holonic Manufacturing Execution System	22	TPI	Total Performance Index
21	HRCC	Human – Robot Collaborative Cell	43	VMES	Viable Manufacturing Execution System
22	HRC-FE	HRC Fusion Engine	44	VSM	Viable System Model

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