POLITECNICO DI TORINO

Doctoral School
Production Systems and Industrial Design

Ph.D. Thesis

Manufacturing Execution Systems for lean, adaptive production processes

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April 2016

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Abstract

In order to deal with global competition, industries have undertaken many efforts directed to improve manufacturing efficiency. From a broad perspective, the adopted approaches could be classified in two categories:

1. the simplification of manufacturing processes and relative control systems, leading to lean manufacturing methododologies and techniques;
2. the massive deployment of information tools and computational algorithms, aiming to plan and control all the activities in detail, in spite of system complexity.

For several years, these two approaches have been assumed to be mutually exclusive; nevertheless, information collection and analysis are mandatory to define improvement strategies and assess their impact; therefore, the deployment of lean manufacturing methodologies cannot exclude the integration of Information Technology (IT) tools.

The aim of this work is to investigate on methodologies and techniques adoptable to improve the efficacy of Manufacturing Execution Systems (MES), a class of software that allows data exchange between the shop-floor and the organizational levels, enabling the implementation of the lean manufacturing approach.

Today, the feedback information in the available MES mainly consists in key performance indicators, such as cycle time, work in process and resources utilization. Beside this, MES requires the integration of functionalities for process monitoring and control, aiming at the reduction of wastes and supporting continuous improvement. Hence, mathematical techniques able to analyze data in real-time and provide useful information to adaptively control the process are studied in this work. To provide the evidence of the feasibility and effectiveness of the approach, as well as the independence from any specific manufacturing technology, different case studies, both in the fields of subtractive and additive manufacturing, have been developed. In the former, a technique for the automatic alignment of a spur gear has been studied: geometrical measurements are acquired and analyzed in real-time to provide the values for two feasible part rotations resulting in the

gear configuration with minimum positioning error. Such gears are manufactured for applications in aeronautics, and the deployment of this automation system is particularly significant because of the tight tolerances to be satisfied. The latter case study deals with a Fused Deposition Modeling process: an algorithm able to monitor part surface accuracy and identify defects has been developed. This methodology allows to evaluate in real-time whether the quality of the part is satisfactory or not; in case of negative response, the process can be stopped avoiding material loss. The implemented techniques enable product quality improvement, as well as the reduction of wasted material and time. Nevertheless, the deployment of such information only for process control purposes is restrictive; a framework to use this knowledge for supporting the design and the continuous improvement of a product or a process is presented.

Furthermore, two case studies have been dealt to extend the application of MES tools from manufacturing operations to ancillary services. The first one is in the field of automated warehouses: a combined approach made of mathematical models and simulations has been developed. Analytical tools have been defined to evaluate the average performance of a system in simple, pre-determined situations; conversely, the simulation tool aims at a higher detail level of assessment, since in the real shop-floor deployment, different, composite storage and retrieval activities can take place. In the second case-study, mathematical models and simulation are used to support the re-design of a manufacturing process; the focus is on the transport of items through the line, performed by automated vehicles. The mathematical model has been developed to identify the optimal layout of the workstations; simulations are used to evaluate the tasks to be performed by the automated vehicles and the resulting performance. In both the applications, the deployment of simulation tools allows to evaluate complex or even unexpected scenarios by predicting the behavior of a system, preventing criticalities, and evaluating the impact of a change in the process. The management criteria can be adapted according to the features of the real situation to be faced; this leads to better exploit the available resources, to improve productivity and identify waste sources, consistently with the lean paradigm.

Chapter 1
Introduction

Abstract Today manufacturing companies experience several challenges, such as the growing complexity of their processes and supply networks, cost pressures, increasing customer expectations for quality, lead time, and customization. In order to perform profitable production processes and improve competitiveness, different actions can be undertaken. Among them, one approach is the implementation of lean manufacturing practices, to identify and eliminate non-value added operations and sources of waste. Another strategy is the deployment of information tools, to better manage and control the production process. For long time, these two paradigms have been considered mutually exclusive; conversely, this research work aims at developing a framework for their integration. In this introductory Chapter, an overall review of the two approaches is provided. Further, the key directions enabling factories to remain competitive in future, are presented: they are all driven by the development of innovative IT tools.

1.1 The need for information

Today enterprises are driven by a market demand characterized by fierce competition, rapid pace of business and continually compressed time schedules. On the one hand, manufacturing is characterized by shortened production cycles and reduced batch sizes; on the other hand, the variety of product types and their customization is increasing, as well as customer demands rapidly change. Hence, to maintain and improve their competitive advantage, leading organizations in different industrial sectors need to improve process optimization and efficiency.

One of the initiatives that a company may undertake to improve its competitiveness is the implementation of lean manufacturing practices. The term *Lean manufacturing* has been first introduced by Womack et al. (1990) to describe the working philosophy deployed in Japanese companies, with particular concern for Toyota. The essence of this methodology is the elimination of waste and non-productive process, in order to focus on value added operations and produce high-quality products, at the customers demand pace, with little waste.

Another approach is the deployment of automation and IT tools, which allow to improve process planning and control, as well as to enhance the performance of each step of the manufacturing process. The landscape of the existing software classes and their purposes has been changing over the years, and is still evolving at a high pace. Today, the focus is on the integration and the communication between different information tools and among systems deployed by different companies (for example, among firms belonging to the same supply chain).

For several years, lean manufacturing has been considered as opposed to the deployment of IT tools and their integration within and between firms (Ward and Zhou, 2006). On one side, the philosophy of lean is "less is better": to improve the performance of a company, inventory, variability, material handling, options and choices must be reduced as much as possible. Conversely, the philosophy of IT is "more is better": IT tools allow to better manage more information, increased flexibility, functions and features.

According to Ward and Zhou, the two classes of instruments are complementary both in the concept and in the application: IT tools were considered a kind of higher-level planning system, while lean practices were related to shop-floor control and execution activities. Nevertheless, in order to define improvement strategies and assess their impact, the collection and analysis of information is mandatory: the deployment of methodologies for lean manufacturing cannot exclude the integration of IT tools. Hence, in the last years, IT instruments have been widely adapted, upgraded and expanded to deal with process monitoring and control activities.

The remainder of this Chapter is organized as follows: in Section 1.2 an introduction about lean manufacturing is provided. In Section 1.3 the information tools mostly deployed in manufacturing are reviewed. Section 1.4 is devoted to the analysis of the requirements that factories have to satisfy in future to remain competitive. Finally, in Section 1.5 the aims of this work are presented.

1.2 Lean manufacturing

Muda is a Japanese word meaning "waste": it is referred to any human activity that needs dedicated resources, but does not create value. Taiichi Ohno, a Toyota executive, introduced the concept of *muda* in manufacturing, to label all the activities that require resources to take place, but do not add value to the process or to the product (Ohno, 1988). In particular, he defined seven classes of waste that typically affect a manufacturing process. Namely:

1. *Overproduction*: the production of unordered items, or manufacturing of goods before the customers demand. It is often considered as the worst of all the seven wastes: overproduced items have to be stored, leading to possible criticalities in handling materials or in movement through the plant. Further, storage is costly and items stored for long time risk to become obsolescent.
2. *Waiting*: the time that items spend idle while they are not processed or transported, in the form of raw material, work in progress, or finished product. This waste is mainly due to slow, not synchronized flow of material.
3. *Transport*: it is given by the unnecessary movement of materials and items (both semi-finished and finished) that does not add value to the product. Avoidable transport is a cost, due to items that spend time into a useless condition and to the resources performing the transport. Further, it is a source of risks, such as deterioration, damages or product loss.
4. *Extra processing*: it is given by the manufacturing operations performed to achieve a quality level not requested by the customer.
5. *Inventory*: it is the counterpart of waiting. Inventory is the quantity of components necessary to manufacture an item present in the process, in the form of raw material, work in progress, or finished product. Excess of materials in the process are money not producing income.
6. *Motion*: it is the counterpart of *Transport* concerning resources, rather than items. This waste is due to unnecessary movement of resources through the shop-floor without an increase of product value. These movements occur due to poor work planning or to a non optimal shop-floor layout. Beside the money cost, motion can result in ergonomic criticalities for personnel, leading to safety and health issues.
7. *Defects*: they are the most noticeable among all the wastes. Mismatching between the expected and the real quality of the produced parts require reworking operations leading, in turn, to additional cost and utilization of

resources. In case defects are found after product sale, image issues may arise and further costs are necessary to replace all the defective parts.

These wastes do not add value to the product, hence customers are not willing to pay for them. Manufacturers have to become less wasteful in order to be more profitable and improve their competitiveness. A systemic method to eliminate *muda* is *lean manufacturing* (Womack and Jones, 1996). It is an approach inspired by Japanese management methods, in particular by the Toyota Production System. The effectiveness of this approach led to interest among European and American companies. The first attempts in exporting Japanese production methods have been made in the 1970s. At that time, the experience was not successful; according to the prevalent opinion, this was due to cultural differences and to the unique social context of Japan. Nonetheless, in the early 1990s, deeper empirical and theoretical research has been performed and the basis for the first definition of lean manufacturing has been provided (Houy, 2005; Womack et al., 1990). This approach is structured in the following 5 principles.

1. *Specify value*. Value is created by the producer; nonetheless, it is defined by the ultimate customer, and refers to a specific product, a specific price, a specific time, a specific area. Hence, lean thinking must start through a dialogue with the target customers to define what is the value: providing the wrong product or service is a *muda*.
2. *Identify the Value Stream*. The value stream is the set of all the actions required to lead a product through the critical management tasks of a business: (i) problem-solving, i.e. the transformation of a concept into a physical product through detailed design; (ii) information management, i.e. transform orders into deliveries through detailed scheduling; (iii) physical transformation, i.e. the processes that transform raw materials into finished products. A careful analysis of the value stream is necessary to identify all the actions currently performed in the process that do not add value for the customer or lead to provide items that do not meet the customers request.
3. *Flow*. After the elimination of wasteful operations, the remaining value-added steps have to be re-engineered to flow. The work flow has to be rethought and enabled to provide positive contribution to value creation; this step often involves a switch from departments and batches towards product teams and flows.
4. *Pull*. The change brought by *Flow* leads to a dramatic reduction in the time necessary to design and produce an item. This, in turn, enables inventory reduction and a shortened return of investment. Nonetheless, this is not sufficient to achieve lean manufacturing. A precise scheduling must be performed to produce items at the right time, i.e. when the customer pulls them. This approach is opposite to the push system, in which items are put into the market and may be unwanted, leading to *muda*.

5. *Perfection*. The four steps presented above enable a company to perform a *kaikaku*, i.e. a radical improvement, due to the realignment of the value stream. Nonetheless, the four steps are not independent: they interact with each other and can be iterated in a virtuous circle: this is the *kaizen* approach, which is the philosophy of continual, incremental improvements aiming to achieve perfection.

Given these 5 principles, plenty of tools and techniques have been developed to improve parts of a process and achieve *lean manufacturing*. Among them, the most common are:

1. Single Minute Exchange of Dies (SMED): defined by Dillon and Shingo (1985), it consists in undertaking actions to minimize the setup times, which do not add value to the production. The quick changeover allows to profitably produce smaller size lots and, in turn, to reduce *waiting* and *inventory*.
2. Six Sigma: defined by Motorola in 1985, it consists in a strong reduction of process variability; the target of this methodology is to decrease the standard deviation of a given measure to a value lower than 1/12 of the specification limit. Six Sigma supports *defects* reduction: a process operating in these conditions produces, at most, 3.4 parts per million not matching the expected quality.
3. Kanban: it is a system of order cards grouped in two categories (Sugimori et al., 1977). A conveyance kanban is removed from a container when its content begins to be used, and is then attached to another container, upstream, containing another part. Similarly, a production kanban is used for containers with a part to be processed. In case no card is available, further parts cannot enter the line. Thus, the implementation of a kanban system supports the elimination of *Overproduction* and *Inventory*.
4. Value Stream Mapping (VSM): defined by Rother and Shook (2003), it is a tool to support the description of product path, from the supplier to the customer, through a careful representation of each step, in order to identify possible improvements and draw a map to describe how value should flow in future. It is particularly helpful in highlighting wastes in *transport* and *motion*.
5. Five-S (Osada, 1991) is a practice consisting in creating and maintaining well organized, clean, high effective and high quality workplaces. Namely, the five “S” are Japanese words that can be translated as Sort, Set in order, Shine, Standardize and Sustain. The result is a more effective organization, elimination of losses connected with failures and breaks, improvement of the quality and safety of work.

1.3 Information tools in manufacturing

Beside paradigms for waste reduction or elimination, the capacity of companies to competitively produce high quality products also depends on their ability to exploit IT solutions. Among the several information tools deployed within companies, two key classes of software are the Enterprise Resource Planning (ERP) and the Product Lifecycle Management (PLM). Each of them addresses different business needs for manufacturers and provides added value to the company. An introductory description is provided below. Each of these systems can be used independently; nonetheless, when integrated with each other, ERP and PLM result in a collaborative environment with increased impact on successful product development performance and the ability to maintain a competitive advantage (Omnify Software, 2007). A further tool is the Manufacturing Execution System (MES), which is the core of this research: it promotes information exchange between the ERP and the shop-floor.

1.3.1 Enterprise Resource Planning

In the 1960s, companies were used to keep lots of just-in-case inventory, in order to be able to satisfy customers demand and remain competitive. Some customized software packages were developed to handle the inventory, based on traditional concepts. In the 1970s, firms could not afford any more large inventory quantities; hence, a new kind of software was introduced: the Material Requirements Planning (MRP). This package supported the inventory management to calculate the requirements of resources, based on the bill of materials, and the quantity of materials already available or booked.

Later, scheduling techniques were integrated in these systems, in order to deal with capacity planning and to better schedule both factory activities and suppliers deliveries. Furthermore, functionalities for the financial accounting and management systems were integrated into the MRP, leading to the development of Manufacturing Resources Planning (MRP II). This kind of systems allowed to have a more complete overview of the business system.

The MRP II has been then enriched, in the 1990s, to incorporate all resource planning of the entire enterprise, related, for example, to sales, marketing, manufacturing, logistics, accounting and staffing, product design, warehousing, human resources, and project management. These various departments are supported by delivering improved processes, e.g. through automated methods for order fulfillment or methods for information standardization.

The term Enterprise Resource Planning has been used to identify this complete IT tool (Omnify Software, 2007; Riezebos et al., 2009; Umble et al., 2003). The definition for ERP provided in the Eleventh Edition of the APICS dictionary is "a framework for organizing, defining and standardizing the business processes necessary to effectively plan and control and organization so that the organization can use its internal knowledge to seek competitive advantage". A synthesis of the modules and the corresponding functionalities that can be integrated into an ERP is shown in Figure 1.1 (Shehab et al., 2004).

The main advantage of an ERP is the integration of information. Before the introduction of ERP, a company would have a marketing information system, a production information system, and so on, each with its own hardware, software, and methods of processing data and information. Such unintegrated systems might work well within each individual functional area, but to be competitive, a company must share data among all the functional areas. When a company information systems are not integrated, costly inefficiencies can result, as well as the possibility of data errors, inconsistency or redundancy (Monk and Wagner, 2012). ERP systems have been widely adopted by large companies; nevertheless, the effort for their integration and maintenance into an organization is not trivial. This is the main reason for which ERP did not have a wide deployment in small and medium sized companies. The recent development of web 2.0 tools (i.e. platforms in which applications are no longer static, but are continuously modified by users, in a collaborative environment) and their integration in ERP software, made ERP suitable also for Small and Medium Enterprises (SMEs). Thus, beside big vendors such as SAP, Oracle, Microsoft and Sage, there also exist several open source ERP options: among them, Odoo, iDempiere, webERP, Openbravo.

1.3.2 Product Lifecycle Management

CIMdata (2002) defines PLM as "a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination and use of product definition information across the extended enterprise from concept to end of life integrating people, processes, business systems, and information".

The origins of PLM systems rely in the Product Data Management (PDM) practices. PDM was a first step to satisfy the needs of information traceability by including more information about the product than just the geometric data. PLM extends PDM out of engineering and manufacturing into other areas like marketing, finance and after sale service and at the same time, addresses all the stakeholders of product throughout its lifecycle (Gunpinar and Han, 2008). PDM evolved during the 1990s to become PLM, providing

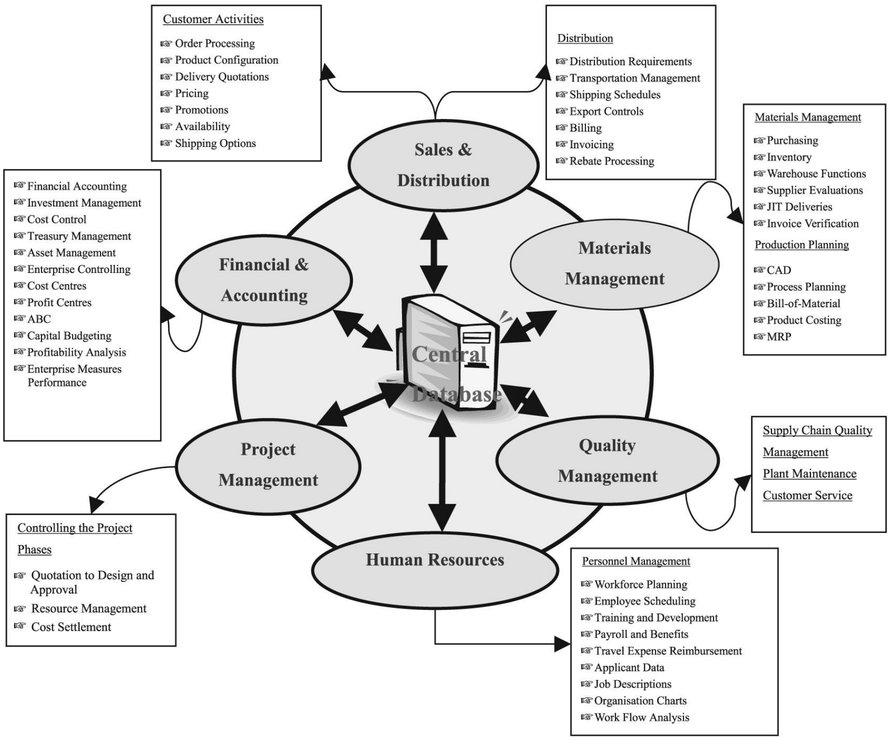

Fig. 1.1 A synthesis of the functionalities integrated into an ERP. Picture taken from (Shehab et al., 2004).

decision support at an enterprise level as well as continuing to handle traditional PDM functions (Abramovici, 2007; ATOS, 2010). The PLM concept integrates all the information produced throughout all the phases of a product life cycle to everyone within an organization, at every managerial and technical level, as well as with key suppliers and customers (Sudarsan et al., 2005).

Collaboration in PLM is made through the exchange of information related to the product; this exchange may regard different kinds of data such as design specifications, drawings, parameters, documentation, customers feedback, maintenance instructions, etc. (Garetti et al., 2007). From a production point of view, PLM is mainly about structuring product information in an orderly fashion, so that it is always available and can be accounted for on all levels in the manufacturing process and throughout the whole life cycle of each product. A PLM system works like a nervous system that communicates with all participants in a product manufacturing process, where the whole entirety leads to a developed product that can be verified in each step of the design and manufacturing process. A server holds the brain function and the communication is responsibility of the core services of the PLM system. PLM tracks and manages component data, bill of materials, documents, information for vendors and suppliers, and compliance data.

A key feature of PLM systems is the automated Change Management facility, that allows users to electronically propose changes to the information stored in the system. These proposals are then automatically routed to the appropriate resources for approval; finally, the PLM system automatically updates the information of the involved products with the suggested changes. If the PLM is integrated with an ERP, such information update is also communicated to the ERP. This electronic, integrated information update leads to a significant improvement in the performance of the engineering change: all the involved resources can simultaneously share information, reducing the cycle times for design and request of new parts; furthermore, the quality of transmitted data is increased, since issues due to hand-entering data are eliminated (Omnify Software, 2007).

PLM was first deployed in the automotive and aerospace industries: two sectors with complex, manufactured products (Abramovici, 2007). Despite its origins, PLM has now expanded to other industrial sectors (electronics, pharmaceutical, ships and buildings construction, etc.) and with a high diversity of products. Until recently, PLM solutions were designed exclusively for large, distributed manufacturing enterprises that had the extensive resources required to deploy and maintain them (CIMdata, 2011). However, SMEs are strongly motivated and they are attempting to integrate PLM into their business practice: they are a massive part of the world economy but a tiny part of the PLM marketplace. In the USA they contribute up to 30% of industrial output, while in countries such as Italy they form up to 95% of the industrial sector (PLM Interest Group, 2011).

Despite the promises made by some of the largest PLM software vendors, they have not yet delivered any PLM product to the market of small manufacturing companies. Nonetheless, there are open source solutions aimed for SMEs, such as Aras Innovator (CIMdata, 2011): companies can download, install, customize and use the software without any financial obligation to Aras.

1.3.3 Manufacturing Execution Systems

The very first precursors of the MES are the data collection systems developed in the early 1980s: each area of a company (e.g. production planning, staff, quality monitoring, . . .) had a dedicated acquisition system, which was independent from the others. The interdependencies of these areas began to arise with the emergence of the Computer Integrated Manufacturing (CIM) concept: production, personnel and quality were no longer seen as completely independent, and data crossovers were permitted from one task to another.

In the early and mid-1990s, these specialized data collection systems began to be upgraded and new features were added to integrate different fields (e.g. staff work time logging with PDA, PDA together with Machine Data Acquisition – MDA). Even with a small number of combination systems, a data collection (and sometimes a data evaluation) system able to take into account many functional areas of a manufacturing company could be defined. Nevertheless, the system components were already independent with each other and their synchronization required major work on interfacing. Over the course of time, combination systems performing several tasks arose from the independent data collection systems; their functionalities describe the functional scope of MES today:

- Production: from PDA, MDA, Distributed Numerical Control, control station;
- Resources: from staff work time logging, access control, short-term manpower planning;
- Quality assurance: from Computer Aided Quality Assurance, measured data acquisition.

However, these three task areas cannot be separated from each other: production accordingly needs suitable personnel to the quality it is producing. If mutually independent systems exchange their data or if data exchange is performed through the corporate level, too much time is lost and this can compromise the effectiveness of the reaction. Therefore the demand of more connected, or even horizontally integrated systems, arose (Kletti, 2007; Meyer et al., 2009).

Networked data acquisition and evaluation systems were developed to allow homogenized data exchange with the ERP system or with the automation level. Here data was exchanged with external systems via standardized interface mechanisms. Hence, data collection systems became closer to the MES concept. Systems of this kind support manufacturing operations by complying with the 6 R's rule which states: *A product will not be created in the most economically efficient manner unless the Right resources are available in the Right quantity at the Right place at the Right time with the Right quality and with the Right costs throughout the entire business process.*

If the networked data collection systems are integrated with elements of quality assurance, document management, document preparation and also performance analysis, the whole can already be regarded as a powerful MES system (Kletti, 2007). Several advantages can result from the MES deployment; among them, for example, improved product traceability, reduction of wastes and scraps, reduction of downtime, reduced production costs (Freedom Technologies, 2012).

Today, several commercial MES packages are available on the market, and the demand of such systems is increasing. A more detailed description about MES functionalities and the state of the art is provided in Chapter 2.

1.4 New requirements for future factories

Today manufacturing companies experience several challenges, such as the growing complexity of their processes and supply networks, cost pressures, increasing customer expectations for quality, lead time, and customization. In order to perform profitable production processes and improve competitiveness, different actions can be undertaken.

According to the European Commission (2014), the capacity of European companies to remain competitive while keeping the production phases in Europe strongly depends on their capacity in integrating state-of-the-art ICT solutions in their manufacturing plants. Among them, Smart Process Applications are a new class of software that combines the benefits of process applications and advanced analytics to help businesses and factories manage their resources, processes and systems more efficiently. They collect, process and analyze data by devices spread across production lines, logistic systems and plant sites, to provide meaningful information to decision makers.

Smart Process Applications are able to access and collect production data in real-time and to tag them to historical statistics, to obtain and analyze information collected directly on the shop-floor, to capture plant management information on production status, performance monitoring, and quality assurance. Furthermore, they are able to perform advanced computations to support the model creation and to test several scenarios and operating conditions in little time.

The market for Smart Process Applications was estimated to reach EUR 20.2 billion by 2015, and to grow at a CAGR[1] of roughly 18% towards 2018. Hence, one of the European research priorities focuses on factory design, data collection and management, operation and planning, from real-time to long-term optimization approaches. EFFRA (2013), the European Agency for the Factory of the Future, has identified the following key directions for the deployment of ICT tools in manufacturing:

1. **Solutions for factory floor and physical world inclusion**. Real-world resources such as machines, robots, lines, items and operators are an integral part of the information structure of production processes. All of them need to be connected with each other and to back-end systems and, at the same time, to be self-aware of the surrounding environment.
2. **Solutions for data storage and information mining**. A huge amount of data from the shop-floor and the supply chain needs to be stored in a fault-tolerant way. Information embedded within these data has to be extracted and made available. New IT solutions should allow complex queries on distributed and heterogeneous data sources to be run (almost) in real-time to facilitate online decision-making across all the levels of the enterprise.

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[1] Compound Annual Growth Rate

3. **Solutions for modeling and simulation tools**. Complex environments need to be consistently described by semantic models in order to correlate information, describe the dynamics, and forecast their behavior. Knowledge from different sources must be made available and fully exploited by dedicated modeling and simulation tools.
4. **Collaborative and decentralized application architectures and development tools**. In extended enterprises and globalized markets, applications (e.g. life cycle management, supply chain management, monitoring and control, and customer relationship management) must no longer operate in closed monolithic structures. Stakeholders and customers must be able to cooperate on a common application platform implemented with the cloud approach for rapid development and deployment.

1.5 Aim of this work

In the previous Sections, two approaches to improve the performance of a process have been introduced: the deployment of lean manufacturing techniques and the integration of information tools. For several years, they have been considered mutually exclusive; nonetheless, recently the importance of the cooperation between the two techniques has been understood: IT tools can collect and analyze data useful to extract information significant for undertaking continuous improvement practices.

As introduced in Section 1.3.3 (and further detailed in Chapter 2), MES is in charge of collecting data, perform analyses and dispatch the resulting information. Nonetheless, the MES currently available on the market mainly focus on the top-down data flow (i.e. from the business level to the shop floor) through detailed jobs scheduling and dispatching. The opposite flow is mainly dealt through performance indicators. However, heterogeneous, rich data can be collected at the shop floor.

Further, current MES are static and are not able to adapt adequately to the evolvable production environments. The high dynamicity of future manufacturing systems requires a constant optimization of quality and resources usage, and the amount of knowledge extracted from the shop-floor should be fully exploited by MES (European Commission Business Innovation Observatory, 2014).

Hence, the aim of this research work is the development of mathematical techniques able to analyze the data collected by sensors systems and provide hints to reduce the sources of waste, thus improving the performance of the process and the quality of the product. These techniques are designed to be integrated into a MES and to cooperate with other tools, such as design tools. The findings of this work can support the development of a new MES generation capable to deal with highly dynamic environments and support a more sustainable manufacturing.

The present work aims to address the following research questions:

1. In which manufacturing fields MES can be able to support lean practices?
2. Is it possible to identify a common approach for different areas or a specific path must be developed for each application?
3. Is the path for MES implementation dependent on the specific mathematical techniques to be used?
4. Is it possible to integrate MES with further information tools? Which benefits could result from such integration?

The first step of this work is the definition of a rigorous methodology. It consists in three steps, as shown in Chapter 3: (i) identify the sources of waste; (ii) deeply understand the process; (iii) develop the solution to deal with the target issue.

The methodology has been applied to different technologies: machining through traditional, subtractive manufacturing (Chapter 4) and additive manufacturing processes (Chapter 5). In both the cases, techniques to solve geometrical issues on the surface of the part have been developed. Further, two applications to ancillary services (with respect to the manufacturing process) have been studied: the tools presented in Chapter 6 allow to manage and evaluate the performance of automated warehouses, as well as to prevent possible issues. Conversely, the tools discussed in Chapter 7 aim at enhancing the transport of items along the shop-floor through automated vehicles.

The tools introduced in the following Chapters can be used with two deployment scale. The first one is the identification of actions enabling process improvement at short, medium and long term scales. The second one is the extraction of experience-driven knowledge that has to be formalized and integrated into design tools: in this way, it can be made available for further developments and shared by all the potential users.

Chapter 2

Manufacturing Execution Systems

Abstract This Chapter is devoted to a deep review of Manufacturing Execution Systems, a class of software born in the early 1990s to support communication and data exchange between the business level of a company and the shop-floor. An exhaustive definition of such systems and their functionalities has been provided into the standard ISA 95 (2000). Here, the tasks in charge to a MES are reviewed, and the state of the art in the field is depicted from three points of view: (i) MES market is analyzed from the business perspective; (ii) the trend in intellectual property rights is shown to identify the top innovators; (iii) the most important research themes are synthesized to present the key directions identified by the scientific community.

2.1 Definition of MES

The first organization which defined the tasks to be dealt by a MES was the Manufacturing Enterprise Solutions Association (MESA), a US "global community of manufacturers, producers, industry leaders, and solution providers who are focused on driving business results from manufacturing information". MESA provided the following list of 11 functionalities (MESA International, 1997); combined with each other, they can form a MES solution.

1. **Resource allocation and status**. Manage and monitor resources, including staff, machines, tools and make available the documents necessary to start the working operations. Further, set up the equipment, and reserve resources and dispatch orders in order to meet the target objectives.
2. **Operations/Detail Scheduling**. Identify the optimal sequence planning based on priorities and resources availability, in order to minimize setups and downtime.
3. **Dispatching Production Units**. Manage the flow of production units (jobs, batches, lots, . . .), and adjust it in real-time as events (e.g. reworking operations) occur on the shop-floor.
4. **Document control**. Manage and control the information significant for the production process (work instructions, drawings, specifications, environmental compliance requirements, safety instructions, etc.) as well as the "as planned" and the "as is" information. Historical data are saved; the information must be accessible to the staff at the right time and right place.
5. **Data collection/acquisition**. Data related to the production can be collected both automatically or manually, and used to track deviations.
6. **Labor management**. Provide the updated status of the personnel, store the staff working hours, the criteria to manage absences, holidays, etc, as well as the ability to perform tasks. This package can be used to evaluate the cost of activities, and may interact with the ERP to optimize resources allocation.
7. **Quality management**. Measure production data and analyze them in real-time, aiming at ensuring product quality and identify in advance issues and criticalities. Actions to correct the issue can be included, as well as tools for process control (such as Statistical Process Control - SPC - or Statistical Quality Control - SQC) and for the management of inspections and offline analyses.
8. **Process management**. Monitor the production process; alarm management functions can be included and automatic corrections or decision-support tools can be integrated to correct and improve process activities.
9. **Maintenance management**. Track the use of operating material to plan periodic and preventive maintenance tasks, ensuring their availability according to the scheduled activities. The system also stores the chronology

of past interventions to support problem diagnosis and the execution of maintenance actions.

10. **Product tracking and genealogy**. Record all the production data across the entire manufacturing chain, to ensure that the position of each item can be identified in real-time as well as its manufacturing history (e.g. components suppliers, lot and serial number, operators working on it, alarms, . . .).
11. **Performance analysis**. Produce user-friendly, complete reports containing process and product information (e.g. resources availability and utilization, cycle times, noncompliances, . . .) and a comparison with the past history and the expected performance, to support the assessment of production efficiency and the detection of issues.

Later, in the 2000s, the standard ISA 95 has been issued by the International Society of Automation. In this standard, a functional hierarchy model consisting in five levels is defined:

- **Level 4**: Business planning and logistics.
- **Level 3**: Manufacturing operations and control.
- **Levels 2, 1, 0**: Batch, Continuous, Discrete control.

Level 0 indicates the manufacturing process; Level 1 indicates manual sensing, sensors and actuators used to monitor the process; Level 2 indicates the control activities that keep the process stable or under control. These tasks are not addressed in the ISA 95 standard: this document is mainly concerned with the activities for Levels 3 and 4, and with their interface for data exchange. Level 4 activities include tasks for business management, which are usually performed by an ERP. Conversely, Level 3 is related to production management; the functionalities of this level correspond to the list of 11 tasks shown above, defined by MESA International (1997). The standard ISA 95 has been adopted and extended by the International Electrotechnical Commission, named "IEC62264: Enterprise-control system integration". Currently, this standard consists in 5 parts:

- **Part 1: Models and terminology**. It describes the Level 3 activities, and the interfaces within Level 3 and between Levels 3 and 4. The last edition has been issued in 2013.
- **Part 2: Objects and attributes for enterprise-control system integration**. It specifies generic interface content exchanged between manufacturing control functions and other enterprise functions. The last edition has been issued in 2013.
- **Part 3: Activity models of manufacturing operations management**. It defines activity models of manufacturing operations management that enable enterprise system to control system integration. The last edition has been issued in 2007.
- **Part 4: Objects models attributes for manufacturing operations management integration**. It defines object models and attributes exchanged

between the manufacturing operations management taking place in Level 3 and defined in the previous Part. The last edition has been issued in 2015.

- **Part 5: Business to manufacturing transactions**. It defines business to manufacturing transactions and manufacturing to business transactions. The last edition has been issued in 2011.

In Figure 2.1 a schematic of the hierarchy model levels, the associated company levels, and the corresponding supporting IT tool is provided. Further, a graphical indication about the time-scales and the detail of the transmitted information is given. The time scale for the planning provided by the ERP is in the order of weeks-months; the more detailed schedule elaborated by the MES involves events in the order of hours-days; the phenomena occurring at the shop-floor have lower time-scales, in the order of minutes or hours. Conversely, on the shop-floor a huge quantity of data can be acquired. Such data must be analyzed and transformed into a smaller amount of information to be transmitted to the business level, in order to have a complete and exhaustive picture and take proper tactical decisions.

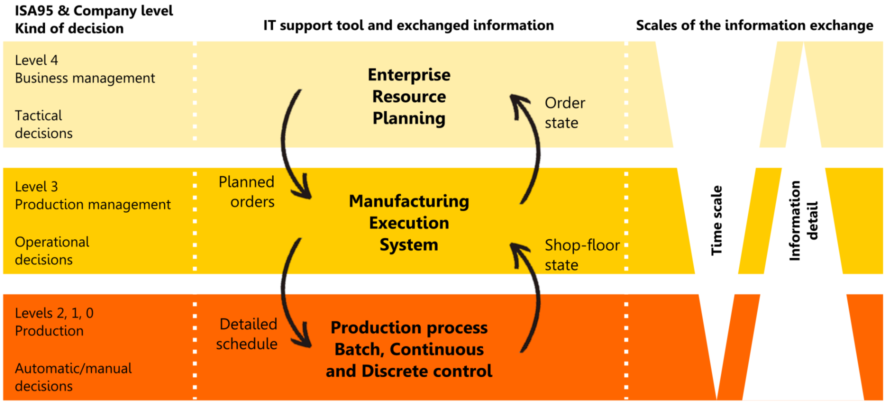

Fig. 2.1 The functional levels defined in the standard ISA 95 and the supporting IT tools.

2.2 State of the art

In this Section, the state of the art concerning MES is depicted. The content is divided into three subsections, to analyze different perspectives: (i) the business point of view, by a synthetic market analysis and the identification of megatrends supporting the spread of MES; (ii) the industrial point of view, through a patent landscaping, to identify which are the trends in intellectual property rights and who are the innovation leaders; (iii) the academic point of view, through an analysis of the most recent scientific papers.

2.2.1 *MES market*

According to the last report of Markets and Markets (2015), the MES turnover is expected to reach USD 12.6 Billion by 2020 at a CAGR of 10.85% between 2015 and 2020. For a long period, Europe has been the main market for MES; nevertheless, in recent times the Asia Pacific region has superseded Europe as the biggest regional market. North and Latin America are, respectively, the 3rd and the 4th market (DKSH, 2014).

The major players in the MES market include ABB Ltd. (Switzerland), Andea Solutions (Poland), Dassault Systemes SA (France), Emerson Electric Co. (US), General Electric Co. (US), Honeywell International Inc. (US), Rockwell Automation, Inc. (US), SAP AG (Germany), Schneider Electric SE (France), Siemens AG (Germany), and Werum IT Solutions GmbH (Germany).

The market for MES is growing at a high pace, driven by the increasing demand of the following technologies: (i) The internet of things; (ii) Big Data; (iii) Cloud computing; (iv) Analytics. The combination of these technologies within a production management system makes feasible a representation of the production environment that goes beyond the boundaries of the plant, and is able to pervade the entire supply chain from the raw material to the final customer. Furthermore, the availability of real-time information concerning both the basic components and the finished products allows production processes to transform themselves constantly, adapting to the market conditions to optimize production times, reduce waste, maximize inventory turns, improve efficiency and, ultimately, ensure the satisfaction of the customer. The information generated by MES has a high value for companies: the ability to include information collected directly from the finished product in real time adds a whole new dimension to the analysis.

Nevertheless, the implementation of a MES requires a reorganization of production processes – due to technological investments – as well as a cultural change: each link in the production chain cannot independently determine its own strategy, but has to align its strategy with those of the other elements and must behave as one component in the full transformation of the entire system (De Bernardini, 2015).

2.2.2 *MES intellectual property rights*

In order to depict the inventive landscape in the field of MES, a patent search has been performed. A systematic analysis using the Orbit database has been made: the string “Manufacturing Execution System” has been searched into titles, abstracts and claims of patents deposited starting from 1990. The research, updated in January 2016, resulted in 660 patents.

The first interesting result is the time trend for the first priority date[1], plotted in Figure 2.2: the increasing pace of deposited patents shows that the interest in MES is increasing, as well as the necessity to provide innovative features. It must be highlighted that, due to the 18 months nondisclosure period, the data corresponding to 2014 and 2015 are not complete. The list of the top ten assignees is shown in Table 2.1: Siemens and Taiwan Semiconductor Manufacturing are the companies that most invested in intellectual property rights. Since the landscaping covers a wide time span, a narrower research, focused on the period 2009-2014, has also been performed. The last two columns in Table 2.1 show who have been the top innovators in MES in the last years. The list is made of companies involved in software and factory automation (Siemens, Rockwell Automation, IBM), as well as companies focused on specific manufacturing fields (materials and semiconductors). Nevertheless, the list of top vendors provided in the previous Section does not totally fit with this one: there exist some MES suppliers who do not own patents, as shown in Table 2.2. US and China are the countries which have invested more in the field of MES; the leader country in Europe is Germany.

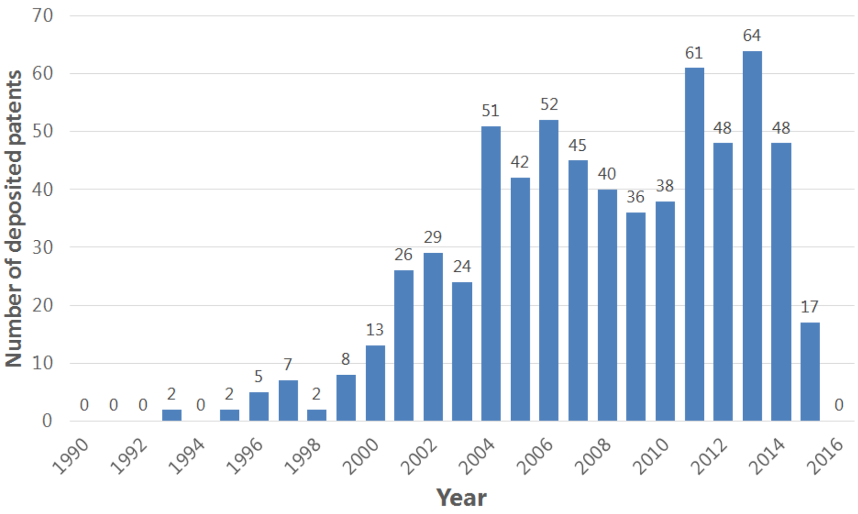

Fig. 2.2 Time trend of the deposited patents in the field of MES.

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[1] The first application date for a given invention

Table 2.1 List of the top patents assignees in the field of MES.

Rank	Assignee	Nr. of patents 1990-2014	Nr. of patents 2009-2014	Ratio
1	Siemens	78	45	58%
2	Taiwan Semiconductor Manufacturing	73	8	11%
3	Rockwell Automation	28	12	43%
4	Shangai Huali Microelectronics	27	27	100%
5	Applied Materials	22	0	0%
6	IBM	20	4	20%
7	Advanced Micro Devices	16	0	0%
8	Semiconductor Manufacturing International	15	10	67%
9	Powerchip Semiconductor	15	0	0%
10	Global Foundries	13	6	46%

Table 2.2 Patents portfolio of the top MES vendors.

Vendor	Nr. of patents
ABB	9
Andea Solutions	0
Dassault Systemes	0
Emerson Electric Co.	0
GE	8
Honeywell	2
Rockwell Automation	28
SAP	3
Schneider Electric	0
Siemens	78
Werum IT solutions	0

2.2.3 *MES scientific literature*

The third step performed to depict the state-of-the-art in the field of MES is an academic literature review. The content of this Section is grouped through keywords, to point out the directions identified by the scientific community.

Traceability. For a long time, bar codes have been used for product traceability; nevertheless, some issues arose as the adoption of this technology increased. Among them: (i) the low effectiveness, as only one bar code can be acquired through a scanning action; (ii) the low reliability, since bar codes can be easily damaged; (iii) the abundance of manual operations, for example to scan the codes. As the RFID technology became mature, it replaced the deployment of bar codes; several research works published in the last years present successful integration of RFID devices (tags, readers, and data transfer tools) along the manufacturing process, to support real-time data flow and analysis. Chen et al. (2009) introduced a system to integrate production management, labor management and warehouse operations (inventory tracking and visibility) for a mix-model assembly line. RFID devices are deployed to turn warehouses, conveyors, workstations, critical components and operators into traceable smart entities, and to facilitate intelligent operational functionalities of the system. Wang et al. (2012) presented a case study (a mold and die company) for a RFID-enabled MES to realize real-time, accurate control of a one-of-a-kind production processes Dai et al. (2012) introduced RFID devices to collect real-time data on the shop floors in a cost-effective way, to transform it into meaningful information to enable both convenient operations for the operators (e.g. work-in-progress visibility and traceability) and efficient decision making for shop-floor supervisors (e.g. work-shop scheduling). Further, the authors aim to facilitate and rationalize shop-floor management. The case study was provided by an engine valve manufacturer. Fu and Jiang (2012) used RFID networks to collect quality data including static and dynamic parameters, based on the result of real-time status tracking for manufacturing. Zhong et al. (2013) deployed RFID tags to improve real-time data collection, planning and scheduling as well as to efficiently trace items.

Support to lean manufacturing. As stated in Section 1.2, for a long time the deployment of IT tools and the lean practices have been considered mutually exclusive. However, recently, the importance of deploying MES to support continuous improvement techniques has been shown. Cottyn et al. (2011a; 2011b) presented a method to align MES with lean objectives: the information provided by the MES and its standardized way of working can trigger and validate the lean decision-making process. The importance of MES-lean integration is explored through the case studies of a furniture firm and a food and beverage company.

MES design. The decision-making process of a MES can be hierarchical or distributed. In the former structure, the control is centralized; this kind of structure leads to efficient and robust results for stable and predictable manufacturing environments. However, a centralized MES is not efficient in dealing with unplanned disruptive events leading to reschedule tasks. Hence, the adoption of a distributed approach can be more convenient: in this case, shop-floor control is not carried out by a central unit, but is the consequence of the actions and interactions of local controllers in the system. An approach for a distributed architecture is the deployment of holonic MES: holons are autonomous and cooperative blocks of a manufacturing system, consisting in an information processing part and a physical processing part. A solution is proposed in (Simao et al., 2006). Valckenaers (2007) and Verstraete (2008) presented an holonic MES that uses a given schedule as a guideline to select among task execution alternatives but is also able to find solutions when the schedule is infeasible or unplanned events occur. This design, following the PROSA architecture (Van Brussel et al., 1998), is made of three agent-types: (i) resources (managing the resources on the shop-floor); (ii) products (that know how a product can be manufactured by the resources); (iii) orders (which consult the product agent to identify the necessary resources and looks for their availability). This approach is also used by Blanc (2008) to design a MES for the manufacturing of laminated bullet-proof security glasses, ready-to-assemble on vehicles. In (Rolón and Martínez, 2012), the autonomic MES is based on two classes of intelligent, open, self-managing units for simultaneous scheduling and control of an object: orders and resources, which interact according to a monitor-analyze-plan-execution loop.

Collaborative environments. The term *collaborative* can be used on two different scales. The first one is related to collaboration **within** the company. In 2004, the term C-MES (Collaborative MES) was coined, and a further role for MES was provided: it was considered not only as the communication layer between the business level and the shop-floor, but it was also seen as a real information hub. In this view, MES is a hub able to integrate information and dispatch it throughout the company; other functionalities (e.g. business, technical or logistical) are just users entering the MES platform to access data (MESA International, 2004). A schematic of C-MES approach is provided in Figure 2.3. On the other side, to approach agile manufacturing, collaboration is also required **among** the suppliers and the partners of a company. Thus, the information tools should reach high levels of integration. One way to approach this result is the use of cloud computing, to improve the effectiveness of information exchange among companies. One approach has been proposed by Helo et al. (2014).

Modeling and simulation. In order to make production planning dynamically adaptive to changing requirements, Rao et al. (2008) integrated simulation tools into the MES. To implement a real-time process control based on real data, an on-line simulation tool was deployed for decision making and evaluation. MES provides real-time data as input to the simulator which, in turn, provides the MES with the optimal production plan. Hence, simulation is no longer used as a long-term optimization tool, but is deployed to deal, over short-term time scales, with variability and unplanned events.

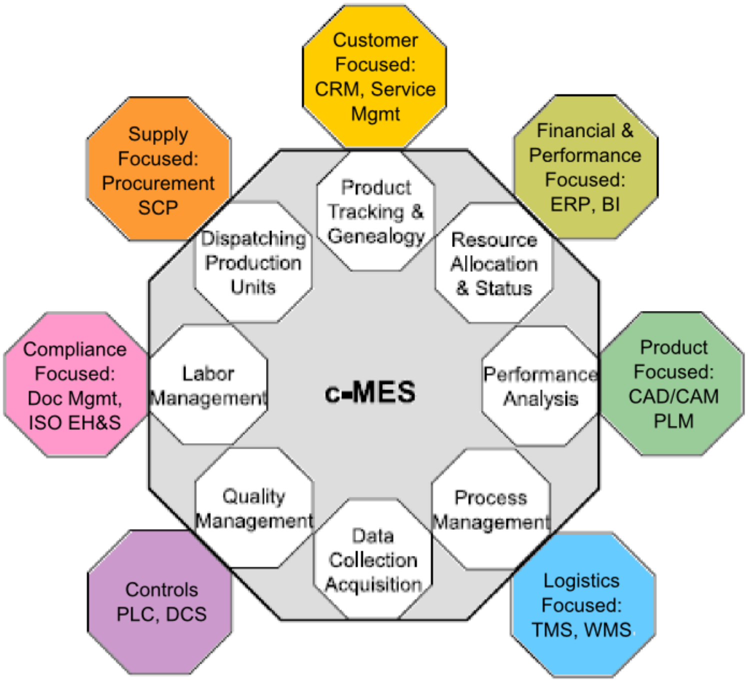


Fig. 2.3 The structure for C-MES model proposed by (MESA International, 2004).

Chapter 3
Research methodology

Abstract In this Chapter, a three-steps methodology is defined: in order to accomplish the research aims of this work, the definition of a work methodology is mandatory. The first step is the identification of the process wastes, according to the classification of *muda*, that affect the process at stake and need to be eliminated. The second one is an exhaustive description of the process: this allows to identify the sources of the target wastes that must be kept in control. Finally, the strategy to acquire significant data and transform them into information useful to eliminate wastes is identified. Beside the description of the three steps, a schematic tool is also presented, to support the application of the methodology to the case studies dealt in the following Chapters.

3.1 Introduction

In the previous Chapter, a thorough introduction about MES has been provided: synthetically, these systems are in charge of taking data as input, analyze them through appropriate techniques and dispatch the results. This approach holds both for the top-down data flow (i.e. orders and targets provided by the business level to be transformed into manufacturing planning) and for the bottom-up data flow (the feedback information from the shop-floor).

In this work, new mathematical techniques to be integrated into a MES are presented, with the ultimate aim of achieving lean manufacturing. However, in order to best address the development work, the definition of a rigorous research methodology is necessary. The methodology deployed in this work consists of three steps:

1. Identification of waste classes to be faced: the kinds of waste that (can) affect the performance of the process are identified and classified according to the 7 *muda* defined in Section 1.2.
2. Description of the process: in order to identify the sources of waste and identify possible interventions to improve the performance, a well-structure, exhaustive description of the process is necessary.
3. Data-analysis: it is the core of this research. In order to develop mathematical techniques, the source of input data, the target output information and the technique to transform data into information must be defined.

The first step is performed by the manufacturer; it can be made both onto an already existing process (thus, identifying wastes already affecting the process), or during the design phase, to evaluate possible process wastes and reduce them before the physical realization of the system. The two subsequent steps are further detailed in the following Sections. A graphical representation to synthesize the three steps is defined in Figure 3.1: this schematic is also used in the following Chapters to provide an exhaustive, easy to read description of each case study.

3.2 General description of a manufacturing process

In Figure 2.1 a layered model to describe a company has been provided. This structure can be adopted to describe a manufacturing process from the firm point of view, i.e. focusing on the business necessities, on the operations requirements or the shop-floor control. Each of these levels needs different information, which must be provided with different details depth and at different time-scales.

An alternative approach consists in describing the process from the process perspective itself. The family of standards ISO 15531 (2004) has been published to define, in detail, the data structures to be exchanged within and between firms, to correctly perform a manufacturing process. In these standards, a distinction between resources and flows is given: the former class contains *any device, tool and means, except raw material and final product components, at the disposal of the enterprise to produce goods or services*; the latter consists in the *motion of a set of physical or informational objects in space and time*.

Nevertheless, in this work a structure detailed like the one provided in the standard is not necessary. The description used in this work is shown in this Section. It is a layered representation in which two classes of items cooperate to perform the manufacturing process: resources and components. Both the categories are made of physical objects and information, and can be provided as input for the process or obtained as output.

Components

The term *Components* denotes all the items transformed by the manufacturing process to obtain a (semi-)finished object: they can be grouped into *Input components* and *Output components*, as shown in the following. Each of these categories consists of both information and physical objects, and can be split into further categories.

Input components

This category includes all the components given as input to the manufacturing process. To better address the categorization, this group can be split into the following three subgroups:

1. **Suppliers**. The suppliers of a manufacturing process provide raw materials or semi-finished parts to be further processed. They can be external partners as well as upstream manufacturing processes within the same company. Together with the physical objects, a set of information must be provided. For example, the properties of the supplied parts (e.g. the composition of material, chemical, mechanical, electrical properties, ...) as well as their manufacturing history (when each part has been produced, where, which were the suppliers, ...). Furthermore, the constraints of the supplier must be known (e.g. supply capacity, cost, reactivity to new orders, ...). This information must be managed and dispatched by the ERP.
2. **Planning**. This input class only consists in information necessary to plan the production and, thus, to control the shop-floor. In a push production system, the interarrival time and variability for the input compo-

nents must be evaluated, as well as the size of the batch to be produced. Conversely, in a pull system, information about customers demand (average desired quantity per time unit and variability) must be provided. The MES is responsible for this information, since it is in charge of optimizing the production planning and flow.

3. **Design**. The third class of input is related to the instructions necessary to produce the parts: which are the materials necessary, which are the machines, the part-programs, the parameters required to produce the desired part. Furthermore, the positioning of the material into the machine, the tolerances to be satisfied and the final dimensions of the item must be known. This information is stored into the PLM.

Output components

This category includes all the components resulting as output from the production process. Two subgroups can be identified:

1. **Performance**. The process provides, of course, the (semi-)finished products, along with a set of performance indicators to characterize the line: among them, the cycle time, the work in process, the throughput, the queues, the average utilization of the machines, their availability, the incidence of failures. These data can be stored and further analyzed (e.g. through time-series analyses) to synthesize the behavior of the line over the time-scales of interest.
2. **Quality**. Information about product quality is getting to be mandatory for manufacturers. It may result from a simple "pass or non-pass" test to quickly verify whether the tolerances are satisfied or not, or from a more complex monitoring system based on the deployment of sensors. Furthermore, quality information can be obtained both from on-line test and off-line verifications, through inspections performed in dedicated areas after the production process (e.g. metrological measurements performed in a controlled environment). Information concerning the incidence of reworking and scraps can be necessary.

Both the two classes of information are managed by the MES: this system must collect performance and quality information, analyze and merge it through proper mathematical techniques, and provide an exhaustive and synthetic report to the business level, in order to verify whether the process is working in a correct and profitable way, or if an intervention for performance improvement must be taken.

Resources

The definition for *Resources* is adopted from the standard ISO 15531. Even in this case, a distinction between input and output resources can be performed; a further distinction can be made to distinguish *Reusable* and *Disposable resources*.

Input resources

This category comprises all the resources necessary to run the manufacturing process. The following two groups can be defined:

1. **Reusable**. This group includes all the resources that can be re-used in the manufacturing process after the production of a part. Among such resources, there are the operators, the transportation means, and the machine; eventually, a setup operation may be necessary to restore the initial state of the resource (e.g. a break for the operator; battery-charge for a forklift; tool change for a machine, . . .). The information concerning the state of the resources at the beginning of the manufacturing process must be stored.
2. **Disposable**. This group collects the resources which are used for the purposes of the production process and cannot be reused or restored: for example, the energy and the fluids (compressed air, lubro-refrigerants) used by the machine, or the tool, which must be changed after a finite number of manufacturing operations.

Output resources

This group can be divided into the following categories too:

1. **Reusable**. The physical output quantities are the same that were provided in input (the number of operators, the machine, the transportation means). Nevertheless, the manufacturing operation changed their state: hence, information about their state after the process must be collected.
2. **Disposable**. Given the nature of these components, nothing can be collected at the end of the process, except scraps. Information about the consumption of the process must be collected.

The data acquired before and after the process must be compared to evaluate its real impact and cost. The tool in charge of this task is the MES: it collects information on the shop-floor, analyzes it and provides a report to the business level, in order to check whether the process is operating in an economically sustainable condition or not.

3.3 Methodology for data analysis

One of the aims of this thesis is the development of smart mathematical techniques to be integrated into a MES, able to transform data into valuable information. In literature, several definitions for data and information are provided. Authors agree in stating that data are discrete observations which are unorganized and unprocessed, and hence without any specific meaning (Bocij et al., 2008; Groff and Jones, 2011; Valacich and Schneider, 2011). Conversely, information is given by formatted data that can be defined as a representation of reality (Valacich and Schneider, 2011); according to Bocij et al. (2008), information is: (i) data that have been processed so that they are meaningful; (ii) data that have been processed for a purpose; (iii) data that have been interpreted and understood by the recipient. Bocij et al. (2008) and Curtis and Cobham (2008) provide a list of the processes that allow to convert data into information. It consists in: (i) classification; (ii) rearranging/sorting; (iii) aggregating; (iv) performing calculations; (v) selection.

The most popular paradigm for the transformation of data into information is provided by the DIKW (Data – Information – Knowledge – Wisdom) hierarchy (Ackoff, 1989): it is often represented as a pyramid with the data at its base and the wisdom at the apex; each level of this hierarchy is the essential precursor for the above one. However, while the distinction between data and information is clear, there is less agreement about the processes that convert the former into the latter. Since information is obtained by organizing and structuring data, any scheme that has meaning and relevance for an individual, community or task, provides meaning to the data (Rowley, 2007). Hence, the rigorous definition of a technique to analyze and organize collected data plays a strategical role.

The methodology for data analysis introduced in this Chapter consists of the five key steps described in the following. It is an adaptation of the strategy defined by Abellan-Nebot and Romero Subirón (2010): their working area is in the field of intelligent monitoring systems; here, the methodology is extended and generalized in order to deal with monitoring and control systems integrated into manufacturing machines as well as with the analysis of any kind of data collected on the shop floor.

Data source

The first step of the methodology is the identification of the data necessary to perform the analysis and the definition of the data collection devices.

On the shop-floor several kind of devices can be deployed to collect data. First, the PLC of the machine involved in the process can provide helpful data concerning, for example, axes position and errors, axes and spindle movement, the deployed tool and the content of the warehouse, the applied power and torque, and some key performance indicator (e.g. cycle times, throughput, the incidence of failures). Furthermore, different kind of sensors can be integrated into the machine to collect data related to the quality process and the state of the tool. Measurements performed by sensors can be classified into direct and indirect: the former are more accurate but usually expensive and difficult to implement in a machining environment; the latter are more economical and consist in inferring variables to have knowledge about the state of the process. In machining processes, the most deployed sensors are dynamometers, accelerometers, thermometers, acoustic emission and current sensors (Abellan-Nebot and Romero Subirón, 2010; Teti et al., 2010). Sensors can be used both online – while the process is occurring – or offline, for example to evaluate the quality of a finished part (e.g. geometrical dimensions, mechanical strength, electrical properties, . . .); further, sensors collecting different kind of data can be used and their information can be integrated to have a more exhaustive picture.

Nevertheless, the shop-floor is not the only data source for MES. These systems also receive information from the design department, such as the bill of process, the bill of materials, the properties of the machines, the layout of the plant. The management level of the company provides the MES with data concerning the target to be reached (e.g. the bill of orders), or target levels to be respected (e.g. performance indicators). Such data must be considered to best plan and manage the production flow taking into account all the constraints. Furthermore, a part of the data used by the MES is generated by the MES itself, as the result of previous analyses: for example, time trends for productivity and performance indices, or the identification of statistical distributions to describe phenomena occurring at the shop-floor.

Data processing and Feature generation

The second step of the methodology consists in choosing the mathematical technique to analyze the collected data. The aim of the data processing technique is to transform data, regardless of the source, into such information, through the generation of a finite set of features. Thus, the choice and the implementation of an appropriate processing technique is mandatory for a correct data interpretation and for a successful decision-making strategy. According to the specific case study, an approach already existing in literature of a technique developed ex-novo can be used.

Mainly, two classes of data processing techniques can be used. The first one consists in mathematical models, based on deterministic or statistic approaches. This technique is convenient when the analyzed system is not too complex and its behavior is fully known. In particular, the statistical approach is effective in dealing with a huge amount of data and is widely used, for example, with data acquired by a sensors set. Different indicators and graphical representations can be extracted to have information about the central tendency, the dispersion and the shape of the data. Deeper analyses can be performed through regression tools or interpolation techniques, or through analysis of variance, to identify which are the factors and their interactions which most impact the process. A data-fusion approach (Boström et al., 2007) can be used when heterogeneous data sources are used, in order to reciprocally integrate the collected data and investigate the relationships among variables, aiming at obtaining a more exhaustive and reliable description of the process.

The second class of data processing techniques consists of simulation tools: they are preferable when the analytical description of the system is too complex. Data provided in input to the simulation can provide from several sources: theoretical (or expected) data can be used to evaluate the behavior of the system in standard situations; real data, collected at the shop-floor are helpful to be aware of the reaction of the system in the current situation.

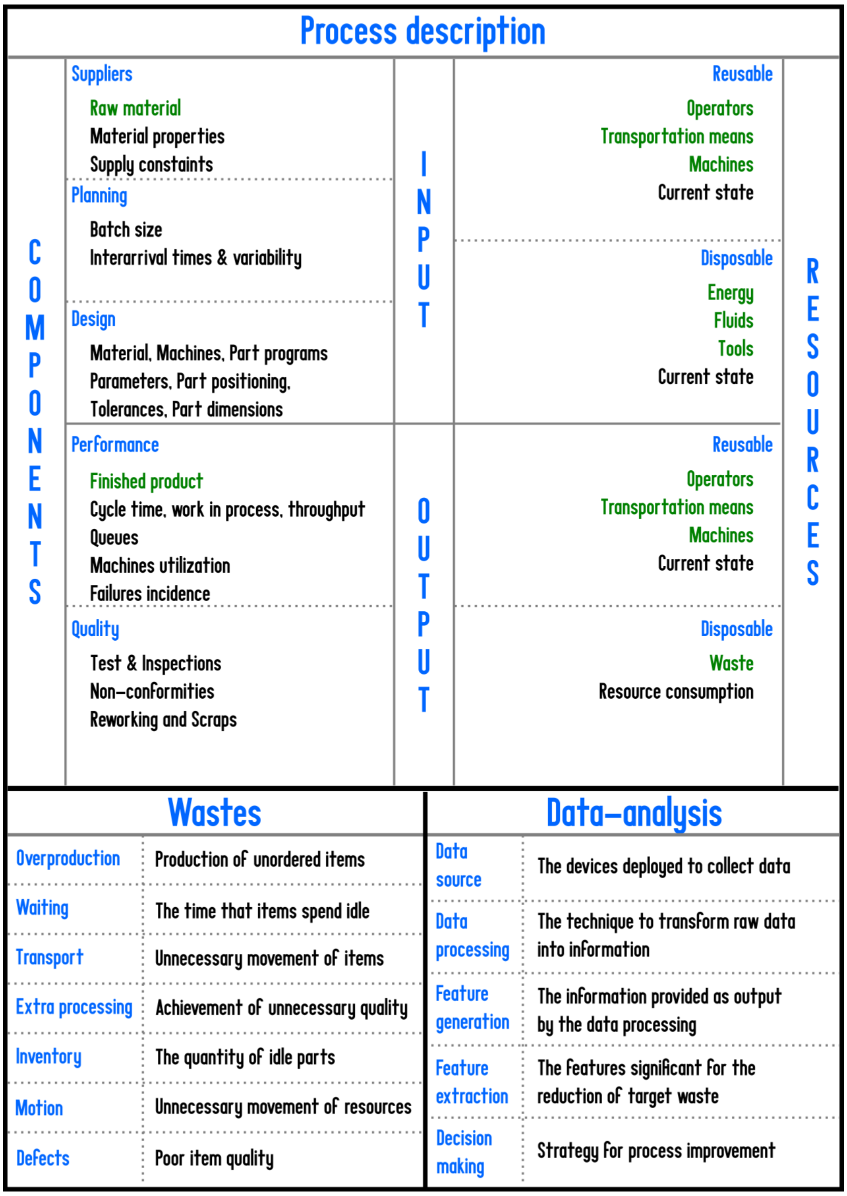
Feature extraction and Decision making

The role of the data processing technique is to synthesize the collected data into a smaller set of information features; nevertheless, some of them may be not significant or reliable to take decisions and, thus, should be discarded. Furthermore, new significant features can be extracted by combining some parameters: overall indices can be obtained by averaging features, by generating response surfaces or by comparing the expected state with the real condition of a process or a product.

Finally, a strategy for decision making must be defined, based on the results of the feature extraction. The decision can be automatically taken by an algorithm able to choose the values of a set of parameters in order to optimize a given metric. Alternatively, the algorithm may provide hints to an operator and leave him free to act on the process. Furthermore, the decision making algorithm should also provide an estimation of the state of the process after such intervention, to evaluate the impact on the performance of the process.

3.4 A schematic tool for the methodology

The three steps described in the previous Sections have been synthesized into a unique schematic, shown in Figure 3.1, with a twofold aim. First, it can be used to point out ideas when dealing with a case study. The schematic must be filled in a clockwise direction: first, the sources of waste must be identified and highlighted; second, the process must be thoroughly described; third, the technique for data analysis must be designed. The second purpose of this schematic is to provide the reader with a synthetic, exhaustive overview of the case study. In the Figure, black color represents information; green color is used for physical quantities.



Process description

COMPONENTS

INPUT

Suppliers
Raw material
Material properties
Supply constaints

Planning
Batch size
Interarrival times & variability

Design
Material, Machines, Part programs
Parameters, Part positioning,
Tolerances, Part dimensions

RESOURCES

Reusable
Operators
Transportation means
Machines
Current state

Disposable
Energy
Fluids
Tools
Current state

OUTPUT

Performance
Finished product
Cycle time, work in process, throughput
Queues
Machines utilization
Failures incidence

Quality
Test & Inspections
Non-conformities
Reworking and Scraps

Reusable
Operators
Transportation means
Machines
Current state

Disposable
Waste
Resource consumption

Wastes	
Overproduction	Production of unordered items
Waiting	The time that items spend idle
Transport	Unnecessary movement of items
Extra processing	Achievement of unnecessary quality
Inventory	The quantity of idle parts
Motion	Unnecessary movement of resources
Defects	Poor item quality

Data-analysis	
Data source	The devices deployed to collect data
Data processing	The technique to transform raw data into information
Feature generation	The information provided as output by the data processing
Feature extraction	The features significant for the reduction of target waste
Decision making	Strategy for process improvement

Fig. 3.1 The schematic of the methodology used to develop this work. Black color represents information; green color is used for physical quantities.

Chapter 4

MES for monitoring and control of a finishing operation

Abstract Gears manufactured for aeronautical applications must meet very high quality, due to the tight tolerances required and the possible consequences of a failure. Further, the grinding process for such gears is a costly operation to be executed in the best conditions; the positioning of the gears into the machine is performed using two reference surfaces previously finished. Hence, great accuracy must be ensured in the finishing operation. A manual alignment of the gear in the finishing machine is not satisfactory any more; hence, an automation system has been developed. It is based on a monitoring and control system equipped with sensors for surface measurement; a mathematical technique has been studied to identify the current gear position in the finishing machine and provide the orientation parameters that minimize the residual errors. Beside online control, the integration of such monitoring and control system with a MES supports process stability as well as the evaluation of longer term analytics. Further, the information generated by the MES can be used as a feedback to redesign or revise manufacturing operations, in order to enhance the quality of the product and the performance of the production process. This experience-driven knowledge must be integrated in the PLM, to be available for future production, and shared in different places or among cooperating companies.

4.1 Introduction

The work shown in this Chapter deals with the development of a real-time monitoring and control system to be deployed in the manufacturing of aeronautical spur gears: such workpieces exhibit a high unitary production cost, and the accuracy of the final product must be high. During the manufacturing process, heat-treatment is performed, leading to high geometrical distortions. Hence, the general attitude of the gear must be recovered to guarantee the required form accuracy. The recovery process usually starts from a well-defined workpiece alignment with the grinding machine axis. For this purpose, a prototype machine has been developed to generate the gear axis by finishing the countersinks of the gear. According to the experience of the manufacturer, there exists a specific point located on the gear axis which is not affected by heat treatment distortion, and it can be deployed as a pivot for workpiece alignment, in agreement with the currently deployed manual centering operation.

The aim of this work is the development of a mathematical technique able to lead to the best workpiece alignment within the prototype machine. The technique described in this Chapter is based on measuring a set of surface points of the spur gear: to perform the measurement, the part is mounted on the machine rotary table and a suitable set of sensors acquires data by performing one workpiece revolution. Such data are used to calculate the values for two angular rotations of the gear axis about the pivot, leading to the best alignment of the workpiece with the machine axis. The rotary table and a set of actuators allow to perform the alignment; thereafter, the countersinks of the gear are finished, to define the workpiece axis for the subsequent grinding of the gear teeth.

The content of this Chapter is organized as follows. In Section 4.2 an exhaustive description of the existing scientific and technical literature is provided. In Section 4.3 the case study at stake is introduced. Both the hardware part of the monitoring system and the developed mathematical algorithm are described in Section 4.4. Numerical results are provided in Section 4.5: the technique is validated using simulated datasets and comparing the results obtained on data acquired through the monitoring system and a Coordinate Measuring Machine (CMM). An alternative alignment strategy is provided in Section 4.6, to emulate the results of the current manual procedure. The role of the MES is described in Section 4.7: its deployment on different time scales as well as its integration with the monitoring and control system and with a PLM are discussed. The contribution of MES to lean manufacturing is shown in Section 4.8. Finally, in Section 4.9 some conclusions and hints for future work are provided.

4.2 State of the art

A wide literature concerning the issue of workpiece localization and positioning is available: research works have been developed in several manufacturing fields to deal with this topic. The approaches can be grouped in two categories. The first is the definition of an error function, given by the sum, over all the sampled points, of the distances among the measured coordinates of the workpiece points and the corresponding nominal ones; through the least squares principle, transformations (translations and/or rotations) are evaluated such that the workpiece approaches the desired position as much as possible; this approach has been used, for example, by Anotaipaiboon et al. (2006); Li et al. (1998); Sun et al. (2009); Yau and Menq (1996). Another largely deployed algorithm, still belonging to this class of techniques, is the Iterative Closest Point, introduced by Besl and McKay (1992). The second kind of approaches consists in a minimax technique: the transformations are evaluated to minimize only the maximum value among the distances between the measured points and their expected positions (Chatelain and Fortin, 2001; ElMaraghy et al., 2004).

The industrial significance of this problem is confirmed by the number of patents concerning methods to identify the optimal positioning for axi-symmetric workpieces that have been deposited. A first approach consists in employing mathematical means (eventually weighted). The technique proposed by Nagata et al. (1980) consists in measuring a set of internal and external points to identify the center of mass of a hollow cylinder. In (Kunugi and Sasaki, 1990), the coordinates of two points on the external surface of a workpiece are measured; the line joining these two points is supposed to be parallel to the symmetry axis. Similarly, in (Niewmierzycki, 1995), the circular sections orthogonal to the symmetry axis are approximated by the circle lying on the three measured points. In other applications, the Least-Squares (LS) principle is used. In (Noda et al., 2009), the diameters of several cross-sections are measured, and a proper error function is minimized to reach the best workpiece positioning. In (Akerley et al., 1992), the line representing workpiece axis is obtained through a LS interpolation of the coordinates of cross-section centers. Finally, in (Sagues et al., 2001), the points measured on the external workpiece surface are interpolated through a LS circle representing the cross-section.

However, the solutions currently present in literature are not fully applicable to this case study because of the complexity of the measurement system. Hence, an algorithm based on the error function approach, integrated with non-linear least-squares interpolations, has been developed.

4.3 Description of the process

Gears used in the aeronautic field must be manufactured with great accuracy. Such requirement is obtained through a multi-step manufacturing process, in which the principal operations are machining, heat treatment and grinding processes.

Heat treatment is performed to achieve the necessary surface hardness and through-toughness of the gear. During this process, some form distortions are introduced; thus, in order to produce a gear with the necessary accuracy, the finishing tool must be able to remove all the distortions. Grinding is a mandatory technological process for the finishing operations, since it allows to achieve smooth surfaces and tight tolerances: this operation consists in removing the material in the form of small chips, through the mechanical action of a grinding wheel. However, since grinding is a costly operation (with respect to other machining processes), it should be utilized under optimal conditions (Alagumurthi et al., 2007). The definition of a new reference system is necessary before the grinding operation. This operation must be performed accurately: even a small misalignment could dramatically affect the result of the grinding process, leading to *defective* workpieces or even to low quality items to be rejected. This results in increased resources utilization, since a further effort must be performed to balance the defects of the process and produce the right number of items with the right quality level. In turn, excessive *waiting* and *inventory* may accumulate due to poor quality of the produced parts. Hence, the centering of the workpiece into the grinding machine plays a key role for process performance.

To improve the performance of the grinding operation, a pre-processing task is made to identify the workpiece axis that minimizes the geometrical distortions. This task is performed by finishing the two countersinks of the gear, which are used to position the part into the grinding machine. At present, in the considered process, the centering operation for the countersinks finishing is a manual, time-consuming task based on the experience of the operator. Given the importance of this task, an innovative, automatic machine has been developed to perform the centering operation. It has been equipped with a monitoring and control system consisting in measurement sensors, a control unit, and devices to automatically correct the position of the gear.

In this case study, two kinds of geometrical tolerances are addressed for the spur gears: total axial run-out and concentricity (ISO 1101, 2012). The former is prescribed for the side surfaces of the gear, and consists in the distance among two parallel planes, orthogonal to workpiece reference axis, which contain one of the gear side surfaces. Concentricity tolerance is prescribed for the bearing seats (BS) and the gear: it consists of a cylinder centered on the workpiece reference axis, that contains the mean points of all the couples of opposite surface points; in the following, eccentricity tolerance will be used, which is equal to one half of concentricity (because it is referred to a radius rather than a diameter). The prescribed tolerances rely on the definition of an ideal reference axis, which is simulated by the machine axis. To define the simulated datum axis, an innovative locking system is employed: it consists in a double row of spheres inserted in the internal groove of the wheel hub to define the simulated datum axis.

The case study is synthesized in Figure 4.1 in agreement with the methodology defined in Chapter 3: the classes of wastes affecting this process are highlighted. The process is schematically described and a synthesis of the mathematical technique is presented.

4.4 Monitoring and control system

In the monitoring phase, the measurements performed by the machine allow to determine the actual form of the workpiece. The choice of the features to be measured is strictly tied to the tolerances prescribed by the manufacturer. A representation of the measurement system is shown in Figure 4.2; it is composed of four displacement transducers with touching probes: three of them are able to move along the radial direction, to measure the distances from the machine axis to the bearing seats surfaces and to the pitch circle of the gear. The forth transducer moves along a direction parallel to the machine axis (identified with z) to measure the run-out of the side surface of the gear. The resolution of the sensors is equal to 0.1 µm; the repeatability error of the measurement system is 10 µm, the reproducibility error is 30 µm: these data have been provided by the sensors supplier. All the measured quantities are referred to arbitrary zeros. The sensors measuring the bearing seats and the side surface acquire $N_p = 4096$ points at a fixed angular step, while the gear sensor measures one point per each tooth gap. An example of measured points is shown in Figure 4.3: the acquired measurements were transformed into a common Cartesian reference system.

In the control phase, a mathematical algorithm determines the transformations that must be applied to the workpiece to correct its position and minimize the residual errors. This procedure allows to optimize the utilization of the raw material in the heat treated part, in order to assure the respect of the geometrical product specification through the next grinding operations.

4.4.1 *The mathematical technique*

Since the measures collected from the different sensors are referred to arbitrary zeros, the first step of the algorithm is the transformation of mea-

Process description

	COMPONENTS		RESOURCES
INPUT	**Suppliers** Gears leaving the heat treatment Gears ID & part type		**Reusable** Operators Centering machine Current state
	Planning Batch size: 1 Interarrival times & variability		**Disposable** Energy LubroreFrigerants & compressed air Countersinks Finishing tool Current state
	Design Part dimensions Tolerance types & values Working parameters		
OUTPUT	**PerFormance** Finished gears Cycle time, work in process, throughput Failures incidence		**Reusable** Operators Centering machine Current state
	Quality Residual geometrical error ConFormity to tolerances Incidence oF non–conFormities		**Disposable** Worn out tool Resource consumption

Wastes

Overproduction	
Waiting	✓
Transport	
Extra processing	
Inventory	✓
Motion	
DeFects	✓

Data–analysis

Data source	Four displacement transducers
Data processing	Least–squares interpolation
Feature generation	Coordinates oF the centers oF the sections
Feature extraction	Eccentricity and runout errors
Decision making	Part rotation to minimize the sum oF residual errors

Fig. 4.1 The application of the methodology introduced in Chapter 3 to this case study. Green colors represent physical quantities; black colors is used to denote data.

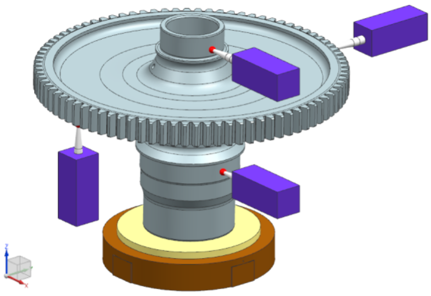


Fig. 4.2 A representation of the measurement system integrated into centering the machine.

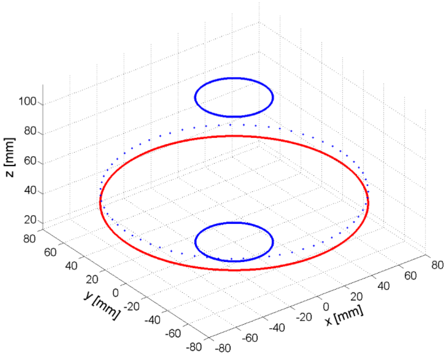


Fig. 4.3 An example of measurements collected by the monitoring system, transformed into a common Cartesian reference system.

sured data into a common Cartesian reference system, taking into account the positions of the four touching probes. Then, the three radially measured sections are considered. To be as general as possible, the intersection of a cylinder with a plane not orthogonal with the cylinder axis is considered: hence, the measured sections should be represented through ellipses. Thus, a non-linear least squares (Myers, 1990) interpolation is made; the extracted features are the coordinates of the centers of each section, denoted with $\hat{O}_i = (\hat{x}_i, \hat{y}_i, \hat{z}_i)^T, i = 1,2,3$, since they contain an information exhaustive to evaluate the eccentricity error. In the following, only the points $\hat{O}_i$ will be used. The deployment of this feature allows to discard the whole set of measured points, reducing the computational cost of the algorithm and the influence of outliers and data imperfections. Two rotation matrices, corresponding to the corrective transformations, are applied to the points $\hat{O}_i$. In the machine, the clockwise rotation about the z axis (denoted with α) first occurs; it is described by the matrix R_z:

$$R_z = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4.1}$$

Hence, the coordinates $\tilde{O}_i = (\tilde{x}_i, \tilde{y}_i, \tilde{z}_i)^T$ of the points after the rotation α are given by:

$$\tilde{O}_i = R_z \hat{O}_i = \begin{bmatrix} \hat{x}_i \cos\alpha + \hat{y}_i \sin\alpha \\ -\hat{x}_i \sin\alpha + \hat{y}_i \cos\alpha \\ \hat{z}_i \end{bmatrix} \tag{4.2}$$

Then, the counterclockwise rotation about the y axis (denoted with γ) is applied; it is described by the matrix R_y:

$$R_y = \begin{bmatrix} \cos\gamma & 0 & -\sin\gamma \\ 0 & 1 & 0 \\ \sin\gamma & 0 & \cos\gamma \end{bmatrix} \tag{4.3}$$

The coordinates

$$O_i = (x_i, y_i, z_i)^T$$

of the centers after the two transformations are given by:

$$O_i = R_y \tilde{O}_i = \begin{bmatrix} \tilde{x}_i \cos\gamma - \tilde{z}_i \sin\gamma \\ \tilde{y}_i \\ \tilde{x}_i \sin\gamma + \tilde{z}_i \cos\gamma \end{bmatrix} = \begin{bmatrix} (\hat{x}_i \cos\alpha + \hat{y}_i \sin\alpha)\cos\gamma - \hat{z}_i \sin\gamma \\ -x_i \sin\alpha + y_i \cos\alpha \\ (\hat{x}_i \cos\alpha + \hat{y}_i \sin\alpha)\sin\gamma + \hat{z}_i \cos\gamma \end{bmatrix} \tag{4.4}$$

Thus, for each section, the residual eccentricity is given by the following expression, as a function of the two admissible transformations α and γ:

$$\begin{aligned} e_i(\alpha, \gamma) &= \sqrt{x_i^2 + y_i^2} \qquad (4.5) \\ &= \sqrt{((\hat{x}_i \cos\alpha + \hat{y}_i \sin\alpha)\cos\gamma - \hat{z}_i \sin\gamma)^2 + (-\hat{x}_i \sin\alpha + \hat{y}_i \cos\alpha)^2} \end{aligned}$$

The points on the side surface of the gear also undergo both the rotations α and γ, according to Equations 4.2 and 4.4. Since the prescribed tolerance is an oscillation along the z axis, only the z coordinates of the points after the rotations are evaluated:

$$z_k = (\hat{x}_k \cos\alpha + \hat{y}_k \sin\alpha)\sin\gamma + \hat{z}_k \cos\gamma, \quad k = 1, \ldots, N_p \tag{4.6}$$

The residual eccentricities and the oscillation of the points on the side surface of the gears are collected into an objective function, which is given by the sum of the four residual errors divided by the corresponding prescribed tolerances $w_i, i = 1, 2, 3$ for the three radially measured sections and w for the axially measured feature:

$$F(\alpha, \gamma) = \sum_{i=1}^{3} \frac{e_i}{w_i} + \frac{(\max_k z_k - \min_k z_k)}{w} \tag{4.7}$$

In Figure 4.4, a schematic representation of the transformations applied to the points is shown. The developed approach is similar to the Iterative Closest Point (ICP) method; however, this technique is not fully applica-

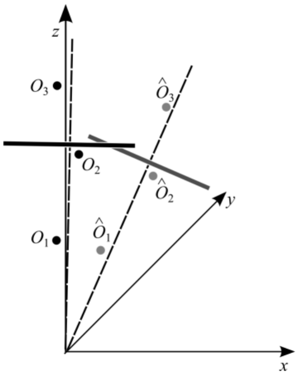


Fig. 4.4 A schematic representation of the transformations applied to the points. Picture is not in scale.

ble in this case study, because reference points are not given for the side surface: the manufacturer is only interested in minimizing the oscillation. Further, only two corrective transformations are allowed while the ICP acts on six degrees of freedom. Thus, the objective function proposed in the ICP method has been adjusted to take into account these constraints.

The algorithm has been implemented in a Matlab code; the values for α and γ that minimize F are evaluated through the `fminunc` function, which uses a quasi-Newton method.

For the application in this machine, the rotation γ is transformed into a displacement Δ exerted by a translator with a given z coordinate H; the value for Δ is evaluated through the following equation:

$$\Delta = H \sin\gamma \tag{4.8}$$

Finally, the two transformations are mathematically applied to the centers of the ellipses and to the points on the side surface to check whether the final workpiece configuration is in compliance with the maximum admissible tolerances or not. The algorithm can be synthesized as follows:

1. Transform data into a common reference system
2. Interpolate the 3 measured sections through LS ellipses
    a. Evaluate the coordinates of the centers
    b. Evaluate the eccentricities as a function of α, γ
3. Evaluate the residual oscillation of the side surface as a function of α, γ
4. Build the objective function F
5. Evaluate α, γ that minimize F
6. Transform the rotation γ into a displacement Δ
7. Evaluate whether the final positioning complies with the prescribed tolerances or not

4.5 Results

In order to test the presented technique, the algorithm has been first applied by simulating the data acquired in the measurement process: 30 simulations have been run, in which a spur gear – equal to the ones produced by the manufacturer – without geometrical errors is measured. The only source of error affecting these data is a Gaussian measurement noise with zero mean and standard deviation equal to 10 μm. For each simulation, a different initial workpiece position, randomly determined, was assumed. The residual positioning errors after the centering process are synthesized in Table 4.1. The oscillation of the side surface exhibits high values, compared to the eccentricities, because no interpolations are made on this feature; the largest part of the oscillation is due to the Gaussian noise: the 99.7% of the simulated points lies into an interval whose width is equal to 6 times the standard deviation of the noise, i.e. 60 μm. The small values for the standard deviations of the residual errors lead to state that the developed algorithm exhibits a good reproducibility of the final configuration.

After assessing the performance of the algorithm on simulated data, real data have been deployed as input. A sample gear has been measured both through a CMM and the sensors system installed on the monitoring and control system of the manufacturing machine. The deployed CMM is a Dea Global Advantage; the diameter of the touching probe is 2 mm. To have more reliable results, the measurement on the manufacturing machine has been repeated 5 times: at the end of each session, the gear was removed from the machine and placed again on it.

First, to evaluate the quality of the measurement system installed on the manufacturing machine, the data acquired by the two systems have been compared. To do this, the measured data have been preprocessed in order to have equivalent workpiece configurations: for each dataset, the centers of the two bearing seats sections have been identified and moved onto the z axis through a set of translations and rotations; the same transformations have been applied to the whole set of measured points. Since the positions of the workpiece into the manufacturing machine and into the CMM are now equivalent, the differences in the data may only be attributed to the measurement system. The amplitudes of the oscillations measured on the two bearing seats (i.e. a roundness error), the residual eccentricities of the pitch circles and the amplitudes of the oscillations of the side surfaces have been compared. A comparison among acquired data is reported in Table 4.2 and in Figure 4.5: the amplitudes of the oscillations measured on the bearing seats and on the side surface, and the pitch circle eccentricity are slightly larger on the data acquired through the manufacturing machine. However, the results obtained through the two measurement systems are comparable. The small values for the standard deviation of the oscillations

Table 4.1 Residual errors after the alignment of a simulated workpiece with 30 different initial positions.

Simulation	Corrections		Eccentricities [µm]			Side surface
	α [°]	Δ [mm]	Lower BS	Upper BS	Gear	oscillation [µm]
1	308.28	3.53	0.2	0.0	0.7	66.3
2	104.36	2.26	0.2	0.0	3.2	67.3
3	298.28	2.63	0.5	1.1	0.1	73.4
4	289.00	4.91	0.2	1.2	2.2	75.3
5	60.61	4.49	0.6	0.0	1.5	70.2
6	328.35	3.88	0.5	0.0	2.1	78.8
7	118.97	6.35	0.6	0.0	4.0	71.5
8	306.27	1.83	0.3	2.9	1.3	69.1
9	6.47	4.56	0.4	0.0	4.3	72.6
10	352.85	4.80	0.1	0.1	2.2	76.3
11	327.86	1.87	0.1	0.9	1.5	71.6
12	14.81	6.46	0.1	0.4	3.4	66.8
13	61.48	2.88	0.3	0.0	4.0	72.3
14	133.15	6.57	0.3	0.0	1.9	71.4
15	143.00	9.14	0.1	3.2	4.6	84.7
16	68.14	10.81	0.1	0.0	3.4	80.2
17	53.75	12.89	0.4	0.1	2.5	90.2
18	4.78	5.07	0.1	1.4	0.3	74.7
19	57.72	5.83	0.4	1.4	0.0	71.6
20	69.91	2.10	0.5	0.0	1.1	75.9
21	31.99	7.42	0.5	2.4	1.9	71.8
22	238.98	6.41	0.1	0.0	1.8	74.3
23	29.93	9.22	0.2	3.3	0.0	80.8
24	14.69	10.41	0.3	0.0	2.8	84.4
25	80.38	1.83	0.4	1.7	1.6	77.8
26	319.08	6.71	0.3	0.5	2.1	78.3
27	344.61	2.15	0.3	0.0	0.7	69.4
28	42.54	2.43	0.8	2.1	1.2	72.7
29	80.69	7.50	0.2	0.0	0.9	67.3
30	28.88	5.39	0.3	0.0	2.3	69.7
Mean			0.3	0.8	2.0	74.2
Std. deviation			0.2	1.1	1.3	5.7

measured on the manufacturing machine confirm the good reproducibility of the measurement system.

After having assessed the metrological quality of the measurement system, the alignment algorithm was applied to the datasets acquired both through the CMM and the manufacturing machine. To have comparable initial configurations, the reference system of the data measured on the CMM was transformed to simulate the locking system employed on the manufacturing machine. The values for the corrective transformations and the residual errors are shown in Table 4.3 and in Figure 4.6: in each plot, the curves of the data measured on the manufacturing machine exhibit similar behaviors and confirm a good reproducibility of the measurement system of the machine. However, systematic differences can be detected through the

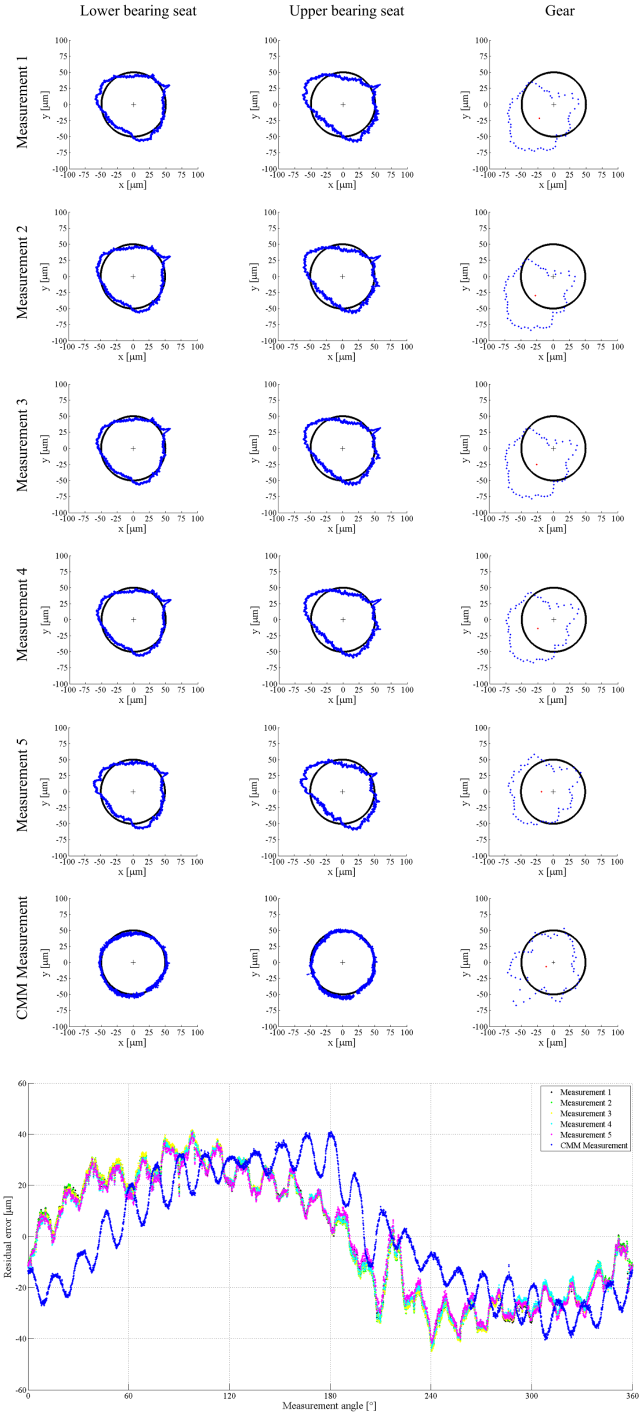


Fig. 4.5 Comparison between the measurements acquired through a CMM and the monitoring system: blue points represent the acquired data; black points correspond to the reference circles; red points are the centers of the gear.

Table 4.2 Comparison between the measurements acquired through a CMM and the monitoring system of the manufacturing machine.

Measurement	Bearing seats oscillation [µm]		Gear eccentricity [µm]	Side surface oscillation [µm]
	Lower BS	Upper BS		
CMM	16.1	16.8	15.0	82.8
1	23.0	31.4	31.2	85.0
2	23.1	29.4	40.7	85.9
3	22.6	28.1	36.5	86.7
4	23.6	30.5	28.3	84.8
5	22.3	33.5	18.2	82.4
Mean	22.9	30.6	31.0	85.0
Std. deviation	0.5	2.0	8.6	1.6

Table 4.3 Residual errors after the alignment of a workpiece measured both through a CMM and the monitoring system of the manufacturing machine.

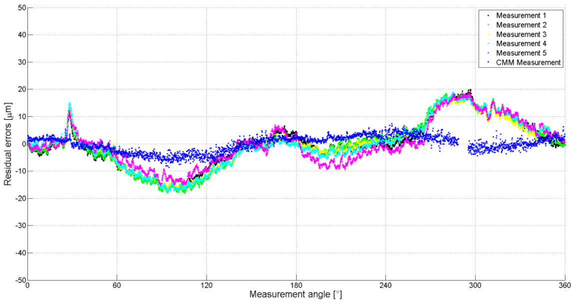
Measurement	Corrections		Eccentricities [µm]			Side surface oscillation [µm]
	α [°]	Δ µm	Lower BS	Upper BS	Gear	
Tolerances			50	50	50	120
CMM			2.6	8.4	12.2	75.4
1	232.01	76.8	9.6	2.3	36.3	75.8
2	225.86	88.6	10.9	2.8	45.3	74.7
3	226.16	81.8	9.8	3.8	40.9	74.4
4	239.34	77.9	10.4	2.6	36.3	73.1
5	252.93	65.7	8.4	0.7	26.8	73.1
Mean			9.8	2.4	37.1	74.2
Std. deviation			0.8	1.0	6.1	1.0

comparison among the results obtained from data acquired with the two measurement systems. Thus, in order to reduce the impact of such systematic differences, the measurement system should be further adjusted. Two additional gears have been measured on the manufacturing machine: even these results (shown in Table 4.4) confirm the good reproducibility of the measurement system, and its capability to provide an acceptable workpiece centering.

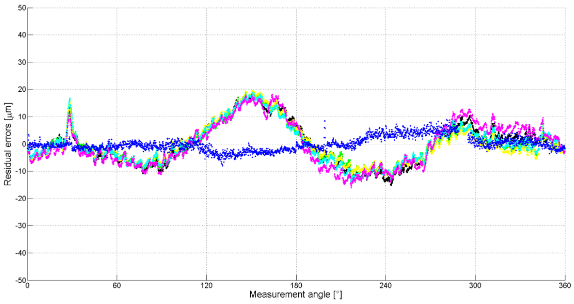
4.6 Alternative positioning technique

The introduction of the monitoring and control system presented in this Chapter allows the automation of a manual task, leading to improved accuracy and repeatability of the process. The developed mathematical technique is also able to predict whether, after the repositioning operation, the configuration of the workpiece satisfies the tolerances or not.

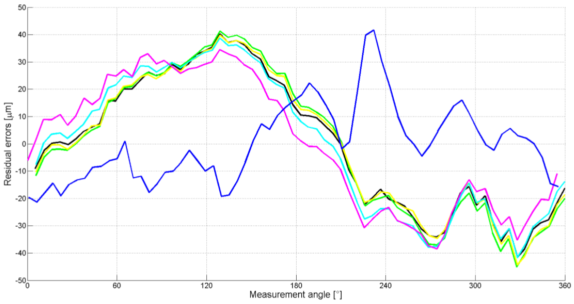
However, the locking system of the machine results in a gear positioning constraint which is not present in the manual task: when the centering is performed, the row of spheres is locked; since it is very close to the lower



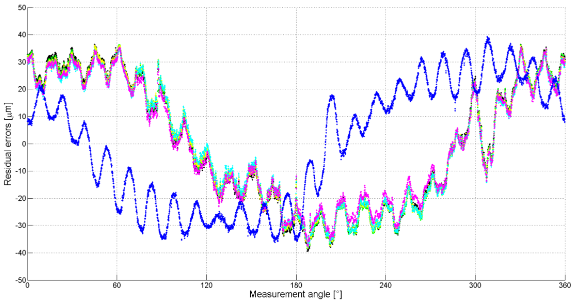
(a) Lower bearing seat



(b) Upper bearing seat



(c) Gear



(d) Side surface

Fig. 4.6 Residual errors after the alignment of the workpiece measured both through a CMM and the monitoring system.

Table 4.4 Residual errors after the alignment of two workpieces measured through the monitoring system of the manufacturing machine.

Measurement	Corrections		Eccentricities μm			Side surface
	α [°]	Δ [μm]	Lower BS	Upper BS	Gear	oscillation [μm]
Tolerances			50	50	50	120
Workpiece 1						
1	270.97	11.0	0.5	13.9	5.4	38.8
2	299.55	14.8	4.0	14.3	0.5	42.3
3	268.91	11.1	2.5	12.1	5.1	40.0
4	278.28	12.3	3.0	14.6	3.5	35.3
5	291.30	13.9	7.5	34.4	0.7	36.7
Mean			3.5	17.9	3.0	38.6
Std. deviation			2.3	8.3	2.1	2.5
Workpiece 2						
1	64.01	45.7	8.3	0.0	5.4	58.6
2	81.36	43.5	11.1	14.6	1.5	98.3
3	61.50	41.4	7.8	0.0	4.5	51.2
4	59.24	53.5	16.8	25.0	4.8	92.9
5	44.16	40.0	11.7	27.4	11.5	51.6
Mean			11.1	13.4	5.5	70.5
Std. deviation			3.2	11.8	3.3	20.7

bearing seat, the movement of this feature is very limited. Conversely, in the manual alignment, the operator has a higher number of degrees of freedom and is free to move this feature; thus, he can increase the positioning error on the lower bearing seat in order to compensate errors on other features. Hence, due to such constraint, it is possible that the algorithm for automatic positioning does not identify a repositioning within the prescribed tolerances, even if there would be at least one acceptable positioning reachable by increasing the error for the lower bearing seat. Thus, to avoid the rejection of acceptable parts, in case the automatic positioning does not lead to acceptable configurations, a second algorithm, based on the ICP algorithm (Besl and McKay, 1992), is run to simulate the manual operation. In case the result of the ICP technique is acceptable, the gear is manually placed into another machine for countersinks finishing, and centered through dial indicators.

Conversely, in case even the second algorithm does not find a solution able to satisfy the prescribed tolerances, form error may be arisen in previous manufacturing operations. To solve this issue, the value for the planarity error of the side surface is evaluated. If the value for this form error is high, a reworking operation is performed: the side surface is finished again to reduce the form error, and then the gear centering process is restarted. Otherwise, if the value of the planarity error is low, the issue can be due to a misalignment between the bearing seats, or to a non-orthogonality condition between the side surface and the axis of the gear.

An overall flow chart of the operations performed by the monitoring and control system is shown in Figure 4.7. In Table 4.5 the results concerning 12 sample pieces are synthesized: the automatic centering algorithm is able to provide a result that satisfies the prescribed tolerances for 5 parts; acceptable results are obtained for three further parts through the manual positioning. Finally, the positioning of four gears is not acceptable neither with the automatic operation nor with the manual one. One of them is affected by a high value for the planarity error of the side surface; thus this feature must be finished again, to reduce the form error before countersinks grinding. The three remaining workpieces exhibit low values for the planarity error, and the non-acceptable centering can be due to form error of the bearing seats or a deformation of workpiece axis: because of this, these three part are rejected.

4.7 The role of MES

The whole strategy shown in Figure 4.7 can be synthesized into a unique software to be installed into the PLC of the manufacturing machine or into an external computer connected to the machine; this stand-alone solution could be used by the operator in charge of loading the part to be finished and running the operation. The output consists in a flag (“the alignment is acceptable” or “the alignment is not satisfactory”), and in the evaluation of the residual errors. The deployment of an automation system allows to improve the quality of the output: the automatic alignment results in the configuration with the minimum residual errors; conversely, the manual technique leads to a configuration with higher residual errors, although the tolerances are satisfied. The higher positioning reproducibility provided by the monitoring and control system also enables a reduction of variability in the quality of the finished parts.

The replacement of a manual task with an automatic machine also allows to reduce the variability of centering time. Furthermore, the flexibility of the process is enhanced: in case a new kind of gear is to be centered, no training for the operators is required; only an adjustment to the software is necessary, to enable the objective function in Equation 4.7 to take into account the proper features, and to set the correct values for the tolerances.

Nevertheless, this monitoring and control system is also able to provide data which can be transformed into information useful for further purposes. The integration of this technique with a MES allows to collect information concerning both the results of the centering process and the performance of the process (e.g. cycle time, work in process, downtimes).

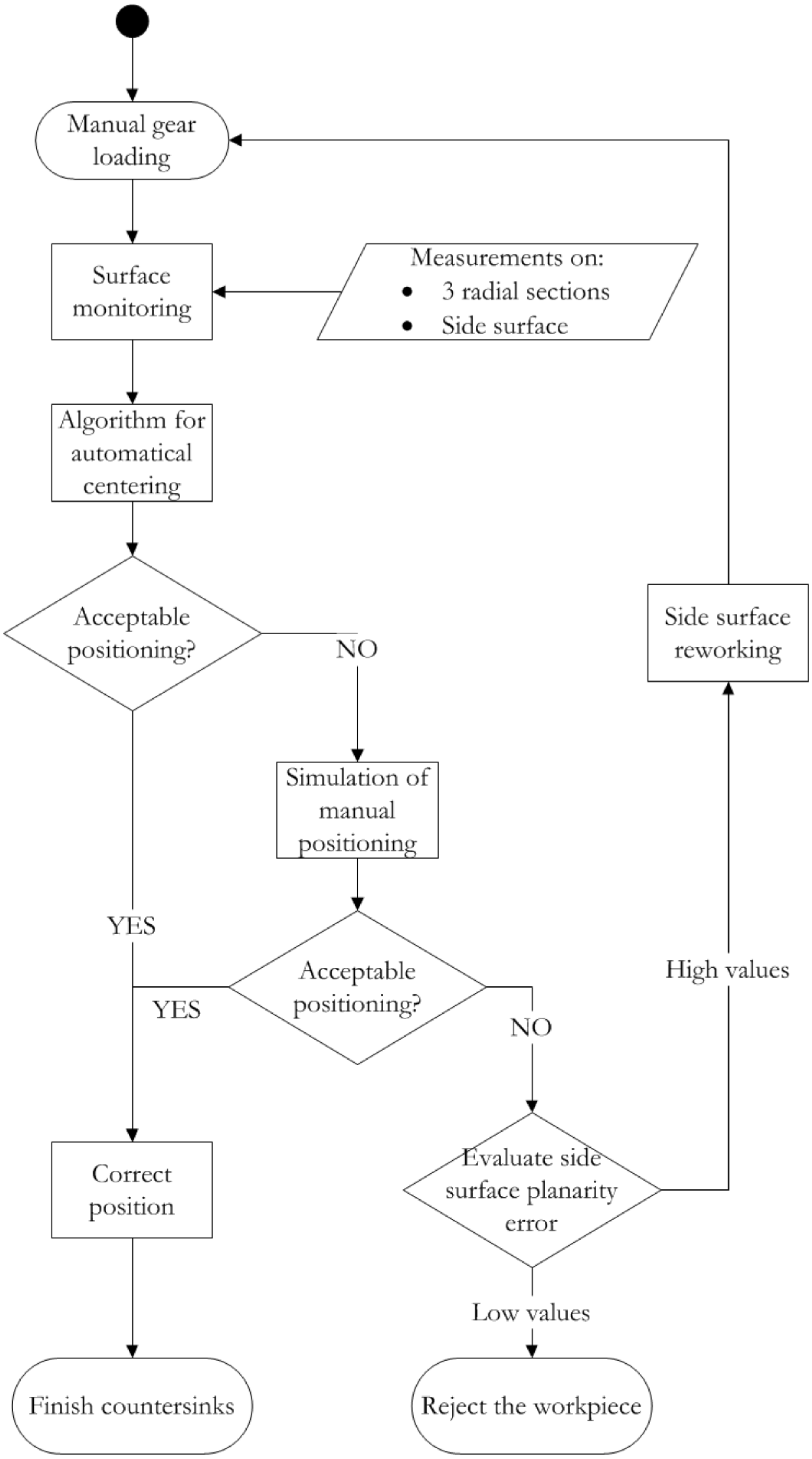


Fig. 4.7 Synthesis of the operations performed by the monitoring and control system.

Table 4.5 Results of the alignment strategy on 12 workpieces.

	Automatic alignment					**Manual alignment**				
	Eccentricities [µm]			Side surface oscillation [µm]	Acceptable?	Eccentricities [µm]			Side surface oscillation [µm]	Acceptable?
Workpiece	Lower BS	Upper BS	Gear			Lower BS	Upper BS	Gear		
Tolerances	50	50	50	120						
1	9.7	70.8	17.7	43.8	✗	13.3	31.1	57.6	46.4	✗
2	21.8	35.2	34.2	76.8	✓					
3	24.6	51.3	34.3	30.2	✗	16.6	28.5	50.0	49.1	✓
4	22.7	140.6	0.0	167.7	✗	13.8	29.5	128.4	125.5	✗
5	38.6	40.2	20.4	46.2	✓					
6	7.9	87.9	2.5	121.2	✗	13.7	40.5	63.2	110.1	✗
7	16.4	22.0	0.0	174.9	✗	4.8	20.3	22.9	128.2	✗
8	4.7	30.0	20.4	44.0	✓					
9	5.7	22.4	26.2	62.6	✓					
10	9.0	42.9	0.0	119.4	✓					
11	3.8	22.8	109.3	104.4	✗	1.2	21.4	25.5	120.0	✓
12	14.9	18.2	57.8	160.9	✗	2.9	24.0	30.6	117.0	✓

4.7.1 *Integration between the monitoring and control system and a MES*

As stated in Chapter 2, one of the roles of MES is to collect data from the shop-floor, analyze it and dispatch the resulting information to the departments that can benefit from this feedback.

Several commercial solutions are available to deal with information concerning the performance of the process; thus, here the attention is focused on product and process quality data. The integration of the shown monitoring and control system with a MES enables to analyze and use the collected data at different time-scales with different purposes.

On the short-medium term, MES allows to check whether the process is stable or not. Further, when instability symptoms appear, MES can predict when the process is going to be out of control and produce parts not matching the expected quality. Thus, setup or maintenance interventions can be planned in a preventive approach, also taking into account further constraints, such as the availability of operators or already planned downtime. This kind of prediction is helpful to avoid producing parts that will be rejected, thus reducing waste.

On the long term, the information collected into the MES can be further analyzed to extract historical trends, to synthesize criticalities and identify the sources of issues and wastes. The integration of a traceability system strongly supports this functionality: in this case study, each workpiece is identified by a unique ID. Information concerning each gear, such as the time at which the centering operation occurs and the expected results of the alignment, can be collected and stored into a database. This information can be useful to monitor the results of the centering process over time, and identify the reasons for possible decays or drifts; however, a careful analysis of these data is necessary, since issues identified on the centering machine can be due to inefficiencies in the upstream workstations. The results of this analysis can be shared with different departments of the company. For example, the business unit can benefit from this information to define new strategies, or to correct the previously defined ones; the design department can use this experience-driven knowledge to improve the design of a product or process. The feedback information provided by the MES supports the test and validation of new process or product releases. This, in turn, enables the implementation of kaizen practices for continuous improvement, such as the PDCA cycle.

4.7.2 *Integration between MES and PLM*

In the previous Chapters, the functionalities of PLM and MES and the benefits that result from their deployment have been introduced. The two information systems have different purposes: PLM contains information concerning the to-be product and the production process; conversely, as-built data are stored in the MES. The integration among these two systems allows to create a feedback information mechanism that can enhance the performance of the production process and the quality of the manufactured parts.

When a new product or production process is released, the PLM contains all the information that, according to the project, allows to meet the required specifications. Then the ramp-up phase is run, and a tight monitoring is necessary to detect any difference between the real products and the expected output. A careful analysis of the data collected in this phase is necessary: they can be rich of useful indications to optimize process and product design, allowing to improve the performance of the production process and the quality of the manufactured parts. The deployment of a MES is also useful after the ramp-up phase, when the steady state is reached: a continuous analysis of shop-floor data allows to monitor the behavior of the process and detect systematic trends, criticalities or deviations. For example, the MES can trace process variability: as machines get aged, the quality of the products can be lower and machined parts may result out of tolerances. The results of such analysis have to be used to identify strategies or practices for performance and quality improvement. These actions lead to redesign or revise some operations: such changes must be integrated into the PLM system, in order to store this experience-driven acquired knowledge, and make it available for the future production. A system for product traceability, based, for example, on RFID tags, would enhance this task: correlations between the state of the process and the quality of the products can be extracted, and the causes that led to a specific kind of issue can be detected. Furthermore, the knowledge collected by the PLM can be shared even among several different plants or with different suppliers; thus, the expertise acquired in one place can be standardized and made available elsewhere.

4.8 The support to lean manufacturing

Beside improving the efficacy of the information collected at the shop-floor and enabling to deploy it with several purposes and at different time-scales, the MES also enhances the implementation of lean manufacturing techniques to improve the performance of the process.

According to the scheme in Figure 4.1, the first source of waste to be reduced is *defects*. The monitoring and control system allows to improve the precision of the gear positioning into the machine and its reproducibility, resulting in better quality for the finished parts and in the prevention of issues that can affect workpiece quality and lead to their rejection. This, in turn, allows to reduce the activities necessary to improve the quality of the output, such as reworking operations resulting in time waste. The automation of a manual process and the resulting quality improvement also allow to face with *inventory* and *waiting* reduction. The reduced process variability enables to substantially decrease the lead time and the work in process: the measurement cycle and the repositioning of the gear take less than 90 seconds, and the algorithm computes the results in real-time; the previous manual procedure takes a much larger amount of time. With the deployment of this new technology, the lead time and the Work In Process (WIP) are expected to be reduced by 40%; the improved precision of the performed operations should lead to a 50% reduction of parts to be rejected or reworked.

The reduction of these waste sources also allows to improve the sustainability of the process. From the economical point of view, the cost of the processes to be executed after the heat-treatment should decrease by, approximately, 60%. From the environmental perspective, the first consequence of the presented system is a reduction in the amount of material necessary to have good-quality finished products; nonetheless, the reduction of extra processing also allows to reduce the energy demand of the process: this is not a negligible task for manufacturers, given the increasing cost of energy and the tighter constraints to be reached in energy and pollution footprint.

4.9 Conclusions

In this Chapter, an algorithm integrated into a manufacturing machine for the automatic centering of a spur gear after the heat treatment has been introduced. The technique is fully described in Section 4.4.1. The approaches currently available in literature are not fully satisfactory to deal with our case study, since they do not allow to optimize the position of a points cloud in real-time. Conversely, patented solutions, including algorithms for optimal workpiece alignment, are not sufficiently accurate to satisfy the tight tolerances usually prescribed in the field of aeronautics. A correct alignment is mandatory, since grinding is a costly operation and even a small misalignment may heavily affect the result of this operation.

In the considered case study, before the introduction of this innovative machine, the positioning of the workpiece was a manual task based on the experience of the operator. The replacement of this procedure with an automatic monitoring and control system allows to improve the precision and the reproducibility of the positioning of the gear into the machine: the enhanced workpiece positioning results in higher quality of the ground gears, with lower scraps and reduced reworking operations. Further, the reduction of variability sources allows to decrease wasted, leading to improved process performance.

The importance of integrating the monitoring and control system into a MES has been shown, as well as the necessity to share the results of MES analysis with the PLM.

In this work, the attention was focused on geometrical issues affecting the gears; in future research, new functions can be integrated into the monitoring and control system. First, the analysis of the measured data can be extended to the verification of form tolerances, such as the flatness (defined in the norm ISO 12781:2011) of the side surface, the roundness (ISO 12181:2011) of the bearing seats and the cilindricity (ISO 12180:2011) of the whole spur gear. Further, the cooperation between MES and PLM can enhance a comparison between the as-is and the to-be states of the part, to identify focused issues.

Beside the functionality concerning the workpiece centering, additional tasks can be implemented to enrich the information provided by the MES. Sensors to monitor the countersinks finishing can be integrated into the machine; for example, the temperature of the tool, the current requested by the machine or the vibration produced by the tool can be monitored: these variables have been identified as significant to predict the quality of the finished part and to evaluate the remaining life of the tool itself (Abellan-Nebot and Romero Subirón, 2010).

Note This work has been supported by Regione Piemonte under the research project MANUM5, "Study, design, development and realization of a reconfigurable production system for aeronautical gears, holistic of methods, fixtures, tools, coolant, measurement and human interaction". The results of this research have been published in:

- G. Barbato, P. Chiabert, G. D'Antonio, M. De Maddis, F. Lombardi, S. Ruffa. *Method for automatic alignment recovery of a spur gear*, International Journal of Production Research (2015). doi:10.1080/00207543.2015.1064180
- G. D'Antonio, J. Sauza Bedolla, P. Chiabert and F. Lombardi. *PLM-MES integration to support collaborative design*. In: Proceedings of The 20th International Conference on Engineering Design (ICED15) **10**: Design information and knowledge management, pp. 81–92. Milano, Italy, July 27–30, 2015

Furthermore, the following patent application has been deposited:

- F. Lombardi, G. Barbato, P. Chiabert, M. De Maddis, F. Ricci, S. Ruffa, G. D'Antonio, S. Milletari and R. Siccardi. *Metodo di recupero automatico dell'allineamento di un pezzo in lavorazione, in particolare una ruota dentata, e relativa macchina di lavorazione automatica*, application number TO2014A000066.

Chapter 5

MES for monitoring of product geometry failure

Abstract The deployment of Additive Manufacturing (AM) processes had a rapid and broad increase in the last years, and the same trend is expected to hold in the near future. To better exploit the advantages of such technology, the use of appropriate information tools is mandatory. However, today there is a lack of software applications devoted to this innovative manufacturing process. In particular, at the state of the art, there is no application of MES in this technological fields. To overcome this issue, a laboratory case study has been developed to show the importance of MES deployment even in additive manufacturing. Furthermore, the importance of supporting design with shop-floor data is discussed: hence, a framework is presented for the integration between MES and Design for Additive Manufacturing (DFAM), a set of methods and tools helpful to design a product and its manufacturing process taking into account AM specificities from the early design stages. The case study is developed in the form of a proof of concept, in order to understand the advantages of such cooperation: the obtained results are promising, hence an online implementation is recommended.

5.1 Introduction

In the ASTM standard, Additive Manufacturing (AM) is defined as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining”. Several synonyms are also defined for AM: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layered manufacturing, rapid manufacturing and freeform fabrication. To perform an additive fabrication process, the model data of the object to be produced is decomposed into a number of 2D cross sections and a file is created: common standards for such file are STL, VRML or the recently introduced 3MF. Then, the file is sent to the AM machine, which adds material layer by layer to produce the physical object.

To fully exploit, support and promote this technology and its advantages, appropriate information tools are necessary. However, currently there is a lack of software applications devoted to this innovative manufacturing process. In particular, few work has been done in the deployment of real-time monitoring systems to improve the quality of the product and the stability of the process. However, the topic of machine monitoring has industrial relevance. EOS has deposited a patent (Perret and Philippi, 2014) for the automatic calibration of a machine through a scanner; the MIT deposited a patent (Perez et al., 2015) for an AM process control methodology including a camera to acquire images of the object being manufactured.

In traditional manufacturing processes, monitoring and control systems are integrated with Manufacturing Execution Systems (MES). However, in literature no applications of MES exist in the field of AM. Thus, the aim of this paper is to extend the state of the art providing a framework for the deployment of new information tools for AM; a case study for the monitoring of surfaces created by 3D printers is introduced to validate the framework. Beside quality monitoring, the information collected by such monitoring system can be deployed during the design phases for product or process adjustments; hence, the integration between MES and Design For Additive Manufacturing (DFAM) is also discussed. DFAM is a set of methods and tools helpful to design a product and its manufacturing process taking into account AM specificities from the early design stages (Laverne et al., 2015). The scientific contribution of this paper is to propose and validate, through a use-case, a framework for the integration of MES and DFAM.

The remainder of the paper is organized as follows: in Section 5.2 the state of the art on AM technologies and methodologies is provided. In Section 5.3 the developed case study is introduced; the monitoring and control system used to deal with the problem is described in Section 5.4. The results of the application are described in Section 5.5. The role of MES and a framework for its integration with DFAM are discussed in Section 5.6; their support to lean manufacturing is described in Section 5.7. Finally, some conclusive remarks and hints for future work are provided.

5.2 State of the art

5.2.1 AM processes

Several AM processes are currently available: 7 process categories are defined in the ASTM standard; previously, a classification of the production technique had been given by Kruth (1991). The choice of the fabrication process is strictly tied to the deployed material: polymers, metals, ceramics and organic materials are among the main ones (Doubrovski et al., 2011). Material extrusion is one of the most deployed methodologies: a thermoplastic material is heated over its glass transition temperature and extruded through a nozzle in a controlled manner. The extruded material is used to print 2D sections successively, one on-top of another, until the object is complete. ABS and PLA are the most common thermoplastic polymers in material extrusion, because of their relatively low glass transition temperatures (Mellor et al., 2014; Rao et al., 2015). Recently, an innovative technique, named CLIP, has been developed and patented: a continuous liquid interface is used to build 3D objects; it is much faster than “traditional” additive techniques (Tumbleston et al., 2015). Metal AM techniques are mainly based on powder; the mostly used materials are steels, pure titanium and titanium alloys, aluminum casting alloys, and this list of alloys is continuously growing as new processes are developed (NIST, National Institute of Standards and Technology, 2013). Nevertheless, currently no process is able to create net shape parts, and a post-processing operation is necessary (for example, to remove supports or to finish the surface). This kind of operations can lead to some deformations and, sometimes, to destruction of the AM part. Consequently, post-processing operations can be a source of functional problems for the part: dimensional, shape, roughness errors, etc. Thus, a stand-alone AM implementation is not yet feasible, and the integration among production processes is necessary (Mellor et al., 2014).

AM processes allow an extraordinary design freedom: this advantage makes feasible shape complexity and geometry customization levels that are not reachable with traditional manufacturing technologies (Vayre et al., 2012). Furthermore, material waste is reduced, since structural parts without functionalities for the user can be unnecessary (NIST, National Institute of Standards and Technology, 2013). Time-to-market is shortened with respect to traditional processes, both because the design can be quicker and because additive fabrication totally occurs in a single place (while traditional processes can take place in different locations). This makes feasible

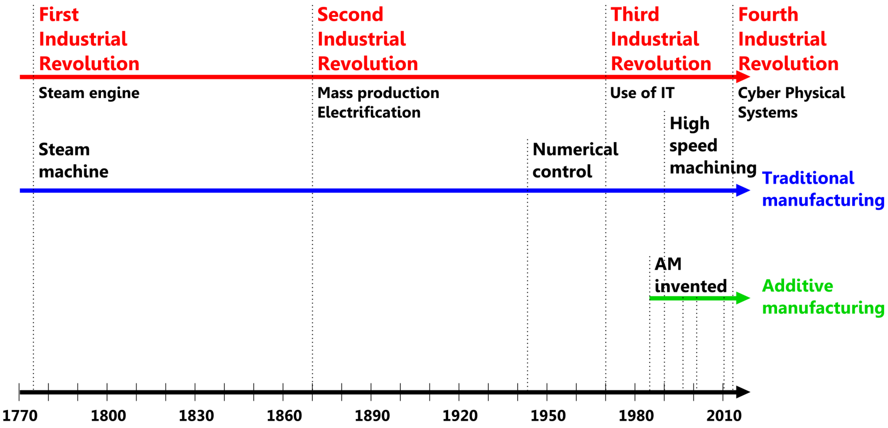


Fig. 5.1 Comparison among the timelines for industrial revolutions, traditional manufacturing and additive manufacturing technologies.

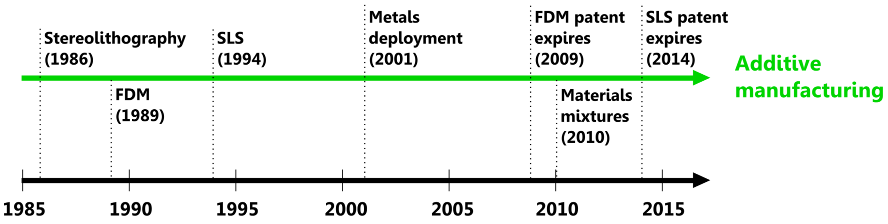


Fig. 5.2 Focus on the timeline for AM development.

a just-in-time production approach, as well as a reduction in transportation problems, cost and energy consumption (Vayre et al., 2012).

AM processes are quite new, compared to traditional manufacturing processes: in Figure 5.1, a comparison between the timelines for industrial revolutions and the development of traditional and additive manufacturing techniques is shown; however, AM development has been very quick and rich of milestones (see Figure 5.2). This class of process is still rapidly changing, and new applications arise as new materials become available. This rapid growth is also due to the support of the technological tools that led to the third and the fourth industrial revolutions. Currently, AM technology is mainly deployed in aerospace, automotive and biomedical devices manufacturing. The high customization level allows to profitably use freeform fabrication in personalized products and in the production of small lots (Atzeni and Salmi, 2012; Mellor et al., 2014). Beyond end-user products, an indirect usage of AM is also feasible, for example to develop and produce tools for conventional machines as well as for reverse engineering of components which are out of production or under maintenance (Vayre et al., 2012).

The AM market is significantly growing in every manufacturing sector: according to the last report by Wohlers Associates (2014), the global addi-

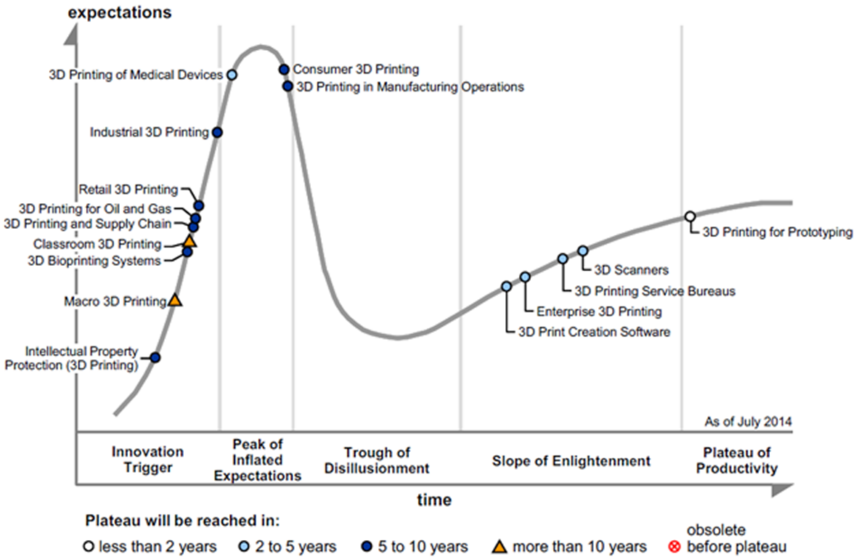


Fig. 5.3 Hype Cycle for AM technology Basiliere and Shanler (2014).

tive manufacturing market in 2013 was $3.07 billion (corresponding to 2.8 billion, given a change rate equal to 1 dollar = 1.11 euro); the yearly increase, with respect to the 2013, is 35%.

5.2.2 *AM methodologies*

The hype cycle presented in Figure 5.3 (Basiliere and Shanler, 2014), envisages that in the next 5-10 years AM will be deployed in several different production fields such as bioprinting systems, oil and gas, and medical devices. Currently, research in AM is mainly focused on the development of new materials and fabrication techniques; conversely, little investigation is performed on the methods for designers. Yet, the design has a remarkable impact on the downstream phases, e.g. production, distribution, utilization and disposal. The DFAM methodologies are now a major issue to exploit in an appropriate way the potential of AM technologies for product development (Laverne et al., 2015). Furthermore, digital fabrication and on-demand production dramatically changed the manufacturing paradigms: a customer can look for a product in a digital catalogue, customize it and send the resulting file to a small firm to fabricate it (Doubrovski et al., 2011). AM allows to produce huge quantities as well as small volumes of a product, with little or no stock; however, this technology is not yet used for the production of large products lots, because of economic reasons (Atzeni and Salmi, 2012).

To manufacture high-quality products, the properties of the material must be well-known; these properties can strongly vary according to the production parameters, such as the orientation of the part in the 3D printer, the build speed and the tool path. Thus, the deployment of a consistent and structured design approach is mandatory. In traditional processes, Design for Manufacturing (DFM) practice is deployed to eliminate production issues, and minimize manufacturing, assembly and logistics costs (Gibson et al., 2010). However, additive processes have different constraints and DFM cannot be used as it is; it must be re-thought to take into account the unique capabilities of AM, in order to fully exploit the advantages of such technology and consider its limits from the early design stage (Ponche et al., 2012) in particular, new design tools are necessary to define and explore product shape and properties, new materials, new efficient manufacturing processes, and to assess lifecycle costs (Huang et al., 2015).

DFAM is a set of methods and tools helpful to design a product and its manufacturing process taking into account AM specificities from the early design stages: DFAM allows to determine an optimized process planning from the functional specifications (Ponche et al., 2014). Mançanares et al. (2015) developed a method to select the best manufacturing process for a part, in order to best satisfy the target. Rosen (2007) defines DFAM as the synthesis of shapes, sizes, geometric mesostructures, material compositions and microstructures to best utilize manufacturing process capabilities to achieve desired performance and other life-cycle objectives. He also defines the DFAM structure shown in Figure 5.4. Design is represented by the right-left flow: functional requirements are transformed into properties and an appropriate and realistic geometry; a process planning is performed to formulate a potential manufacturing process. On the left-right flow, the designed product and its fabrication are simulated to determine how well the original requirements are satisfied. Another structure for DFAM is formulated by Ponche et al. (2014) (Figure 5.5): their methodology is organized in three steps: determination of part orientation into the machine; topological optimization of the part; optimization of the manufacturing paths. This methodology allows to take into account the characteristics and constraints of the chosen AM process from the early stage of design.

Thus, different definitions for DFAM are given in literature. Nonetheless, this work is mainly focused on information systems to collect and analyze data from the additive machine: the spread of MES in the field of additive technology is discussed in the following Section.

5.2.3 *MES for Additive Manufacturing*

At the state of the art, there is no application of MES in the field of additive manufacturing. In literature some predictive models based on the values of machine parameters have been developed. Vijayaraghavan et al. (2014) formulated a model to predict the wear strength of a part, based on layer

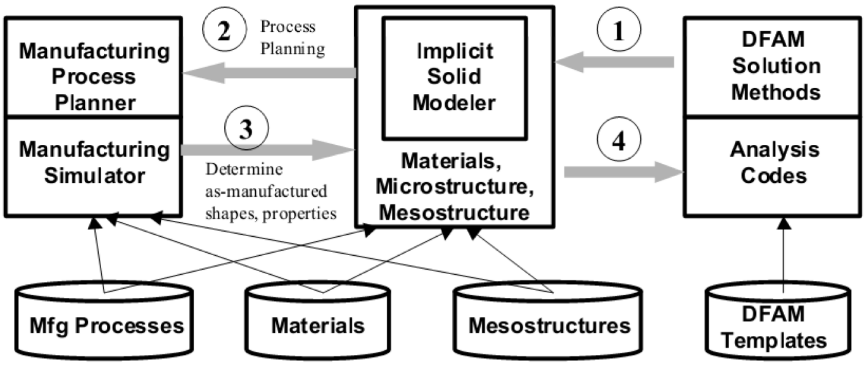


Fig. 5.4 Design for DFAM methodology extracted from (Rosen, 2007).

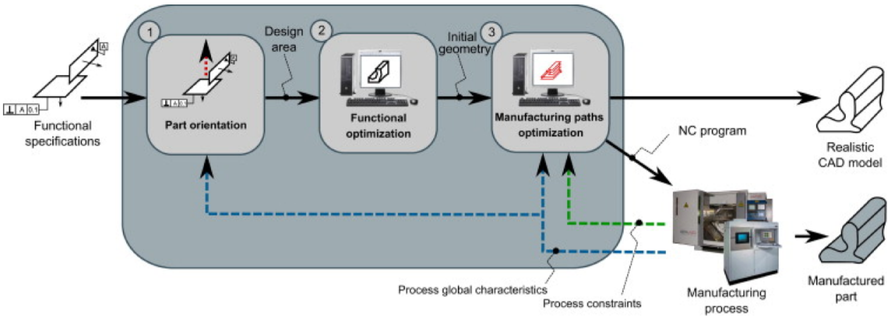


Fig. 5.5 Design for DFAM methodology extracted from (Ponche et al., 2012).

thickness, orientation, air gap, raster angle and width. Byun and Lee (2006) developed a decision making strategy for part orientation based on surface quality, building time and part cost. Sood et al. (2012a,b) used air gap, raster angle and raster width to predict the wear rate and the compressive resistance of a part. Boschetto and Bottini (2014) developed a model to predict dimensional deviations of fabricated parts as a function of the process parameters. However, machine parameters are not sufficient to predict possible anomalies and failures; hence, the use of sensor-based monitoring systems is necessary. Rao et al. (2015) measured vibrations and temperatures to optimize process conditions, in order to obtain the best surface roughness and to real-time detect possible drifts. Bukkapatnam (2006) used a set of accelerometers to trace in real-time variations in process dynamics and to early detect possible anomalies. Dimensional and geometrical measurement and control of the manufactured parts also plays a key role. Faes et al. (2014) deployed an optical sensor to measure layer width and height and to control the geometrical error in the *z* direction (perpendicular to slicing direction, traditionally vertical).

Two kinds of technologies can be used to evaluate the quality of the produced geometry. Contact measurements through a probe are not currently feasible in AM, since the part is fixed in the manufacturing environment, and the room for a moving probe is very scarce; this technology can be used for offline measurements, after removing the part from the machine. For example, the object can be measured onto a CMM; this process leads to high quality measurements, but requires a huge amount of time, both for the measurement and for the creation of the measuring path. An alternative technology is given by non-contact measurements. Several different tools can be used to measure an object in a few seconds, according to the available room, the dimension of the object to be measured and the desired accuracy of the output. For example, optical measurements can be performed and different technologies can be chosen (such as time of flight or stereoscopic vision).

At the state of the art, the deployment of real-time monitoring systems in AM is restricted because of the lack of proper smart sensors. This is mainly due to two factors. The first one is the reduced access to the build chamber: in high-performance additive machines the printing environment is closed to keep constant the temperature, and cannot be opened. On the other side, the temperatures are too high for a common measuring device. The second factor is the need for intensive computing power: due to the very small time scale at which additive phenomena occur, fast and reliable in-situ measurements and analyses must be performed.

Given the importance of MES role in AM combined with a monitoring system, in the next Sections the core part of this research work is introduced: a theoretical framework is presented for the integration between MES and DFAM, and describe a case study for optical measurement of an additive manufactured part.

5.3 Description of the process

The test sample used in this study consists in a set of toys representing hollow ducks fabricated through a BFB 3D Touch machine, an additive machine based on the fused deposition modeling technique. Although a toy, the surface geometry of this part is not trivial at all, from the building process perspective. The dimensions of the ducks (as designed) are 80.6 mm (length), 45.6 mm (width) and 51.5 mm (height). The objects have been produced both in PLA and ABS. After the production of some parts, a non-detected issue in axes calibration arose, leading to surface *defects* of the final products. In particular, the part shown in Figure 5.6 exhibits a hole which width is 1.5 mm. The presence of defects is a source of waste by itself; nonetheless, it also implies increased utilization of the resources, since a higher number of operations must be performed to have the target number of parts matching the desired quality.

Fig. 5.6 The toy duck used as a case study, which exhibits a fabrication defect.

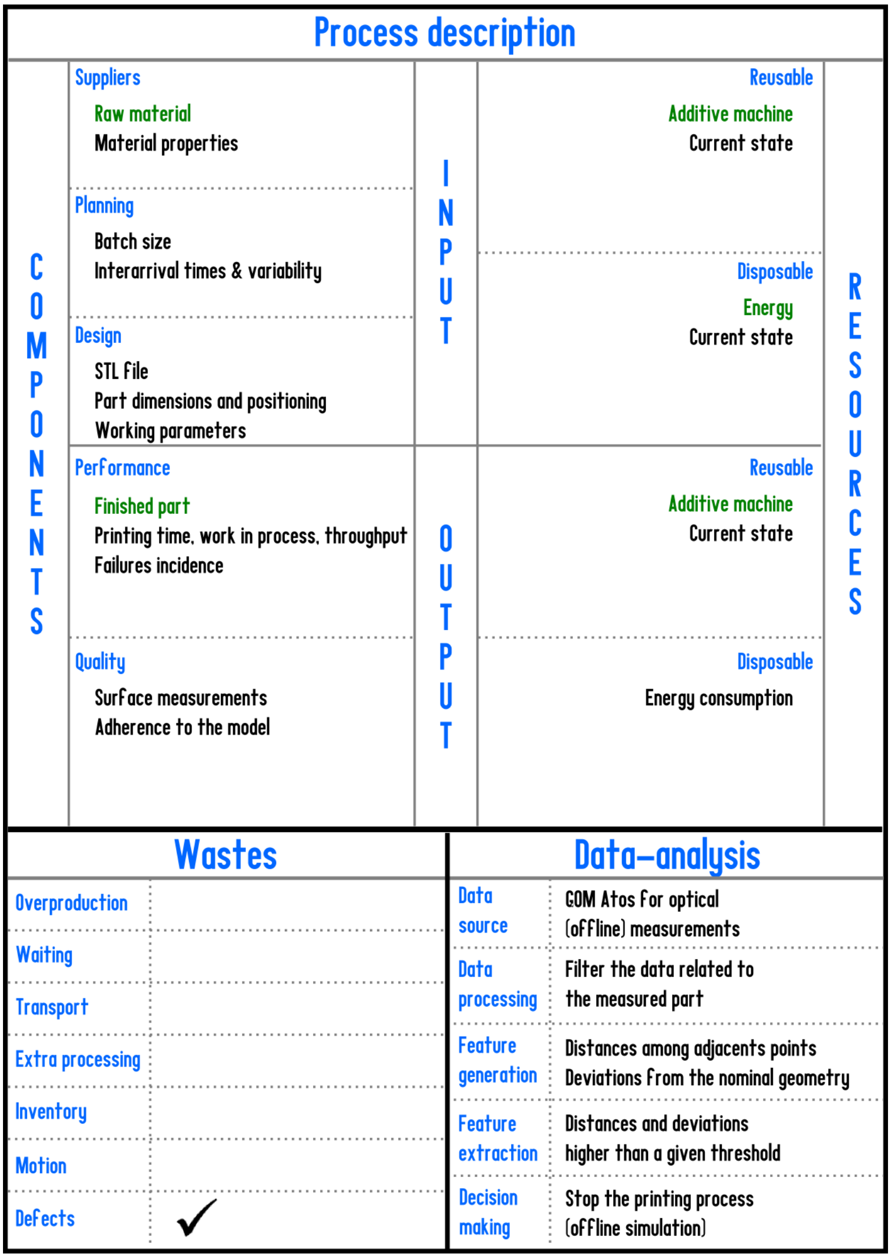
The case study is synthesized in Figure 4.1, according to the methodology defined in Chapter 3: the classes of wastes affecting this process are highlighted. The process is schematically described and a synthesis of the mathematical technique is presented.

5.4 Monitoring and control system

Due to the lack of sensors discussed in the previous Section, in this study offline laboratory measurements have been performed: the whole profile of the defective part has been measured after the fabrication. The surface has been scanned through a GOM Atos machine; the distance between adjacent measured points is 0.6 mm. The technique for measurement analysis has been implemented in Matlab, and consists in two parts: in the first one, the presence of possible discontinuities in the surface of the part is detected. In the second part, the scanned points grid is compared with the nominal cloud of points to evaluate the adherence to the expected output. In the following, a pseudo-code of the two algorithms is provided (also see Figure 5.8):

1. Test for part integrity
    a. Identify the points without close neighbors: for each scanned point, evaluate whether other surface points were detected in a square centered in the point with edge size equal to 2 mm.
    b. Identify the boundary points: for each scanned point, evaluate whether there exist some points that can be considered boundaries or not. For each direction, a 0.5×20 mm rectangle is considered: if no points are detected into this area, the point is tagged as boundary point.
    c. Identify the points without close neighbors which are not boundary points, i.e. the points found in step 1a which do not respect the criteria in item 1b.

    The points identified at step 1c are tagged as risky points: the lack of close neighbors and the presence of other, far, points with a similar x or z coordinate could be due to a discontinuity in the surface of the object.
2. Alignment to the nominal geometry



Process description

COMPONENTS

INPUT

Suppliers
Raw material
Material properties

Planning
Batch size
Interarrival times & variability

Design
STL file
Part dimensions and positioning
Working parameters

RESOURCES

Reusable
Additive machine
Current state

Disposable
Energy
Current state

OUTPUT

Performance
Finished part
Printing time, work in process, throughput
Failures incidence

Quality
Surface measurements
Adherence to the model

Reusable
Additive machine
Current state

Disposable
Energy consumption

Wastes

Overproduction	
Waiting	
Transport	
Extra processing	
Inventory	
Motion	
Defects	✓

Data-analysis

Data source	GOM Atos for optical (offline) measurements
Data processing	Filter the data related to the measured part
Feature generation	Distances among adjacents points Deviations from the nominal geometry
Feature extraction	Distances and deviations higher than a given threshold
Decision making	Stop the printing process (offline simulation)

Fig. 5.7 The application of the methodology defined in Chapter 3 to this case study.

a. The CAD file for the nominal geometry is transformed into a cloud of points.
b. The scanned points are roughly aligned to the nominal geometry: 3 translations are performed to align the two centers of mass, as well as rotations to align the axes directions.
c. The ICP algorithm (Besl and McKay, 1992) is used to best align the measured points cloud to the nominal model, by minimizing the distances between the two surfaces. The repositioning performed at item 2b is used as initial condition for the ICP, and allows to reduce computational time.
d. For each scanned point the distances from the nominal surface are measured.

The position of the nozzle during printing is not available; in future developments, the tools introduced in this work should be integrated into a virtual manufacturing environment to validate the nozzle path and the post-processing operations.

5.5 Results

In Figure 5.9 some snapshots from the simulation for the integrity test algorithm are shown. Points on the surface of the duck are plotted in cyan; black points are the boundary points; red dots represent the risky points, i.e. the points which do not have near neighbors, but cannot be considered as boundary points (identified at step 1c). Thus, red points would not exist if the surface of the object does not exhibit discontinuities. In the example, 4612 points are scanned on the surface of the object; among them, 115 are considered risky.

In Figure 5.10 some results for the comparison between real and expected geometries are shown. Beside the hole, in some areas the distance between the fabricated surface and the expected one is greater than 2 mm. Even in this case, the algorithm is able to generate an alarm and the user can decide whether to interrupt the fabrication process or not.

The algorithm has been run on a common laptop with CPU frequency 1.7 GHz: the computational time necessary to analyze the whole dataset (approximately, 4600 points) with the two algorithms is lower than one minute; since the material deposition rate is much slower, the inspection algorithm can be used to real-time detect the presence of issues, given a suitable class of sensors.

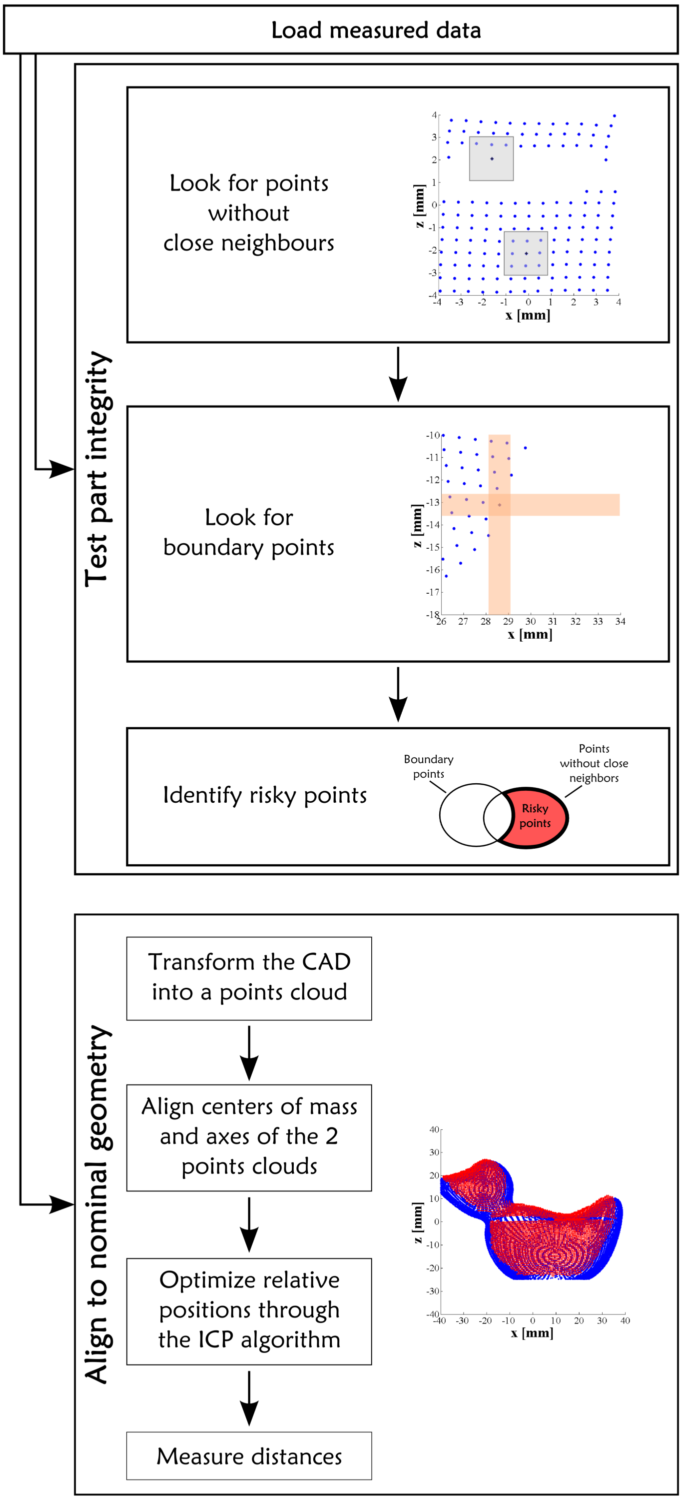


Fig. 5.8 Pseudo-code of the algorithms for measurements analysis.

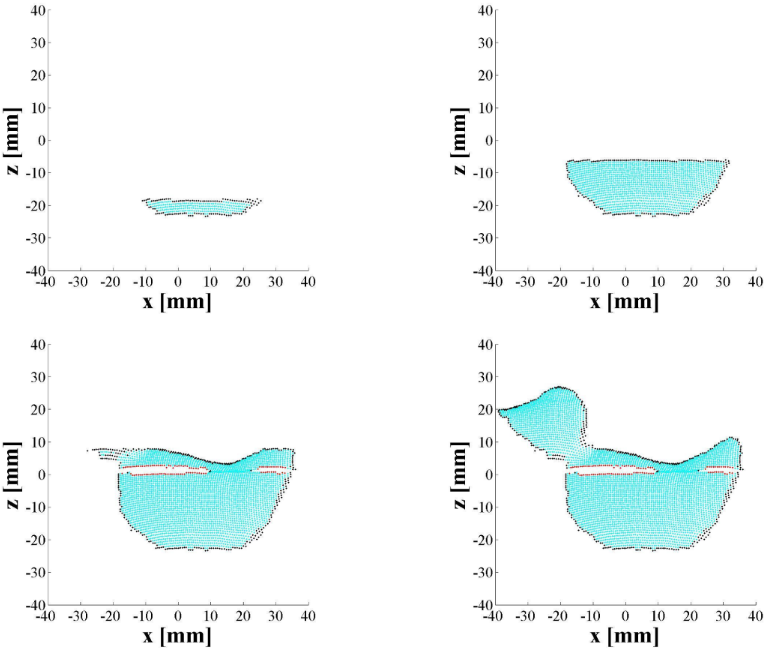


Fig. 5.9 Results of the simulation for the integrity test algorithm. Points on duck surface of the duck are plotted in cyan; black points are the boundary points; red dots represent the risky points.

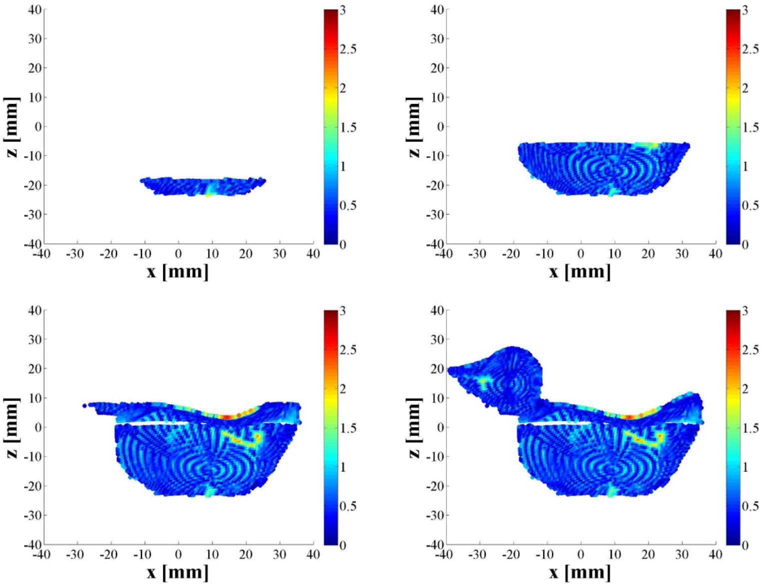


Fig. 5.10 Results of the simulation for the algorithm to compare the fabricated surface with the expected geometry.

5.6 The role of MES

The technique for surface monitoring can be used as a stand-alone application able to provide alarms in case an issue arises. However, beyond the monitoring and control of the fabrication process, the output of the algorithm can be used with further purposes.

If the monitoring and control system is used offline, like in this study, MES allows to compare the performance of the last production process with the previous ones and detect symptoms of possible criticalities. The information analyzed and stored by the MES represents an instrument to support automatic correction or compensation strategies, as well as to improve the awareness of operators decisions. The availability of data-sources able to perform online measurements would enhance this capability, allowing to adjust the process in real-time and improve the quality of the part undergoing the printing process.

Over longer time-scales, syntheses of the collected data can be performed to highlight the reasons for which criticalities occurred. This capability is very significant in the field of additive manufacturing: currently, the most important challenges for this technology are poor part accuracy and lack of process repeatability (Rao et al., 2015). These issues are due to the complex relationships among variables which are, in many cases, still unknown. Hence, the information provided by the MES allows acquire knowledge about the process and to improve its performance.

5.6.1 Integration between MES and DFAM

A broader deployment of MES results can be done if they are integrated with tools for design: DFAM has been introduced in Section 5.2.2.

MES can profitably be supported by the design: the cooperation between the two systems allows MES to continuously compare the “as-is” product and process states to the expected conditions and quickly detect mismatchings. In the presented case study, this task is performed by the algorithm that evaluates the adherence of the measured points cloud to the expected output.

MES can also profitably support design: the analyses performed over longer time-scales, based on real data, the information about criticalities and the in-field acquired knowledge allow to correct and improve the design of a product or its fabrication process (e.g.: change machine parameters, the positioning of the part on the machine tray, change material, choose a different machine, . . .). Given this reciprocal interaction, the framework in Figure 5.11 can be defined.

This framework allows to extend the DFAM model proposed by Ponche et al. (2014) shown in Figure 5.5: it consists in three tasks and is able to opti-

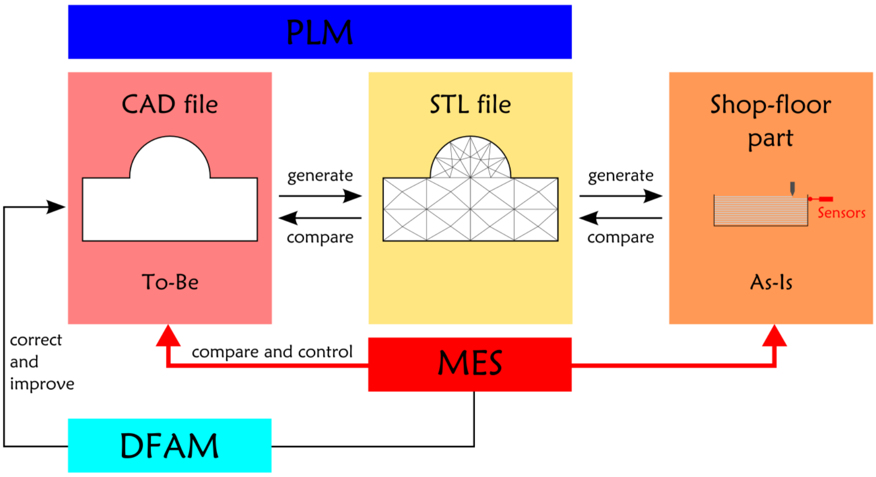


Fig. 5.11 Proposed framework for MES-DFAM integration.

mize the design of a product taking into account the capabilities and the constraints (such as the thermal distribution and the trajectories) of the process that will be used for its fabrication. MES support can be useful to improve the result of all the three tasks performed by the DFAM.

First, part orientation has a strong impact on the quality of the finished part. Decision support tools have been developed to identify the part orientation that results in the best roughness and accuracy of the produced object. However, such tools are based on predictions and simulations of process behavior. A feedback information from a set of sensors able to evaluate the quality of the physical part would be useful to validate the predictions and, in case of mismatching, to correct the orientation of the part into the machine. Also the simulation model can benefit from the feedback mechanism: it can be enriched or adjusted with the empirically acquired knowledge, resulting in a more accurate output; improved models can lead to better predictions and, in turn, to better support the DFAM. Second, the shop-floor information can also be used for further adjustments of the part geometry. In case the quality or the precision of specific features is not satisfactory, the shape of the object and the material distribution can be revised more quickly. The third task included in the DFAM methodology is the optimization of manufacturing paths and machine parameters. A feedback information from the shop-floor is useful because even minute uncontrolled variations can lead to strong differences in the quality of the fabricated part. Several variables can affect the production process, concerning the deposition and the material (melt pool geometry, temperature, deposition height); furthermore, the output quality is also correlated to the state of the deposition chamber, including temperature, humidity or oxygen concentration (Reutzel and Nassar, 2015). All these parameters interact with each other. It is not trivial to ensure the quality of a produced part by controlling only a few variables, but further adjustments to the machine parameters can be necessary according to the real operating conditions. Such adjustments can be taken according to the measurements performed by the sensors, and a MES-DFAM integration allows to quicker take decisions and actions to improve output quality.

This proposal for MES-DFAM integration also allows to extend the model proposed by Rosen (2007) in Figure 5.4: after planning a manufacturing process, simulations are performed to check whether the design process results in producing an object in compliance with the specifications. Such simulations can be supported by the MES feedback, that allows to continuously validate the process and its model and to better take into account process variability. In case an issue arises, alarms may be generated, or strategies for self-adaptation or self-compensation can be undertaken. Furthermore, functionalities to early detect possible decays of the process over a longer time scale can be implemented.

5.7 The support to lean manufacturing

The implementation of the techniques shown in this Chapter enables to reduce *Defects* sources of waste. The detection of issues performed in real-time would allow to stop the production of a part as soon as its quality is believed unsatisfactory: hence, the material waste due to finishing a part that will be rejected is avoided. Further, the deployment of a monitoring and control system supported by a MES allows to identify in advance criticalities, and to undertake corrections or compensations to avoid extra processing.

The deployment of a MES in the field of additive technology also allows to improve the economical sustainability of the process. Today, due to the unpredictability of the process, the unitary cost of a part produced through additive manufacturing is higher than producing it by the common technology. Nonetheless, AM is convenient to produce single parts or small lots, because it does not require the initial investments necessary to start the process in traditional manufacturing (e.g. specialized machines, moulds, ...). However, improved knowledge process results in improved predictability and output quality. This, in turn, could change the balance between traditional and additive manufacturing, and make AM economically convenient even for higher batch sizes.

5.8 Conclusions

In this Chapter, the importance of monitoring systems in an additive machine has been shown. The results obtained with offline tests are promising, and an online implementation would provide useful hints while the production process is still occurring. Nevertheless, the scanning system used in this work cannot be deployed in a production environment, since the ratio between costs and benefits would be excessively high. However, several different optical devices can be used to acquire a 3D cloud of points; there exist reliable, recently developed tools which cost is sufficiently low to allow the deployment of several devices to have a complete scan of the object undergoing fabrication (such as the Asus Xtion). Nonetheless, such devices cannot be integrated into the building chamber of an additive machine; a further miniaturization effort is necessary.

The advantages of a direct communication between MES and DFAM have also been shown: the efficacy of the knowledge extracted by the sensors system can be enhanced. The feedback mechanism allows to reduce the ramp-up phase of a new product, since machine parameters can be tuned in real-time. Similarly, information concerning process properties, instabilities or criticalities can be collected in a structured way. Hence, the acquired expertise can be used for further product developments, and improved quality of the output can be reached (e.g. lower surface roughness and stair-stepping effect, or improved stress resistance). This, in turn, allows to decrease material and energy waste for unsatisfactory productions, leading to cost reductions and improved sustainability of the process.

This study has been shown in the form of proof-of-concept. The approach is general enough to be deployed with any of the available additive technologies discussed in Section 5.2.1. In this work, the attention was restricted to a specific case study in the field of fused deposition modeling for a sample test; nevertheless, the deployment of a MES could be much more significant in high value-added productions, such as the production of aeronautical or biomechanical components, where the tolerances are very tight and expensive materials are deployed. MES-DFAM integration can also be helpful in testing new materials or alloys: the sensors-based system can collect information about the behavior of the process and the final quality of the product: the acquired data may validate the expected performance, or provide hints for further adjustments or improvements.

Note The results of this research have been published in:

- G. D'Antonio, F. Segonds, J. Sauza Bedolla, P. Chiabert, N. Anwer. *A proposal of Manufacturing Execution System integration in Design for Additive Manufacturing*. In: Proceedings of The IFIP 5.1 12th International Conference on Product Lifecycle Management (PLM15). Doha, Qatar, October 19-21, 2015
- G. D'Antonio, F. Segonds, F. Laverne, J. Sauza Bedolla, P. Chiabert. *A framework for Manufacturing Execution System integration in an advanced Ad-*

ditive Manufacturing process. Submitted to the Journal of Intelligent Manufacturing.

Chapter 6

MES for storing processes and warehouse management

Abstract The overall performance of a production system relies on the performance of the manufacturing operations as well as on the behavior of surrounding activities, such as logistics. To have a just-in-time production, both the raw materials and the finished products must be available at the right time and place, at the minimum possible cost. Several investments have been recently performed to improve warehouses efficiency, for example through the introduction of automation systems. Among the available technologies, systems based on the deployment of Autonomous Vehicle Storage and Retrieval System (AVS/RS) are very promising: they are based on the possibility to use lighter vehicles and to remove constraints among the movements along different axes. Despite the increasing diffusion of such systems, there is a lack in techniques for performance evaluation. Therefore, methods to evaluate and control the exploitation of an AVS/RS system have been studied. Due to the complexity of such systems, analytical techniques can be used for basic, predetermined cycles; a more complete overview can be obtained through the deployment of discrete events simulations, which enable to consider even complex scenarios with low efforts. The developed tools can be integrated into a MES to online evaluate and improve the performance of the system, and collect information for decision making; further, such tools can also support the design phase, to verify in advance the reaction of the system in front of multiple, composite scenarios.

6.1 Introduction

In the last decades, beside the performance improvement of manufacturing operations, great efforts have been done in enhancing the design and the management of warehouses. Similarly to manufacturing activities, one way to better deal with global competition is the deployment of automation solutions to successfully face with complex situations and quickly take decisions, as well as to replace repetitive, manual tasks. One innovation that increasingly spread in the last decades is the deployment of automated systems able to store and retrieve items in and from warehouses. The market of automated warehouse is increasing at a high pace, driven by the outstanding growth of e-commerce.

The most common Automated Storage and Retrieval Systems (AS/RS) consist in a set of stacker cranes moving along aisles. In order to move the items in the warehouse, the stacker cranes can perform three types of movements: longitudinal, on a rail along the aisle; vertical, up the column of the stacker crane; transverse, in order to store or retrieve a unit load (UL) into the rack. The cranes are able to move, at the same time, both on the longitudinal and the vertical directions, in order to minimize the traveled distance and the cycle time. Here, the term *cycle time* refers to the time necessary to store and/or retrieve unit loads starting and finishing at the same location, according to a round trip (Bozer and White, 1984). The main drawback of these systems is low flexibility: ULs are processed one by one, hence in case of high variability in the storage or retrieval activities, the reactivity of the system is limited.

Recently, different types of AS/RS able to uncouple the vertical and the longitudinal movements have been developed; in this work, the attention is focused on systems able to separate vertical, the longitudinal and the transverse movements. To perform these movements, the system adopts autonomous vehicles, hence it can be classified as an Autonomous Vehicle Storage and Retrieval System (AVS/RS), as defined by Malmborg (2002).

Two aspects are crucial to best exploit the capabilities of such systems: first, an accurate performance evaluation is necessary; second, appropriate tools must be used for operations management, execution and control. Nonetheless, up to date few work has been done for the evaluation of AVS/RS performance, as revised in Section 6.2. Furthermore, information tools to support warehouses are undergoing a reorganization: the arise of Warehouse Execution Systems is leading to a redefinition of the the tasks to be performed by each information tool and of the information to be exchanged.

Thus, the aim of this work is twofold. First, new analytical techniques are presented to estimate the cycle time of an AVS/RS. Second, a discrete-event simulation tool has been developed to test the impact of different management criteria and select the best one, according to the specific scenarios that can occur.

The remainder of the Chapter is organized as follows: in Section 6.2 the the state of the art for performance evaluation and information tools to support automated warehouses is reviewed. In Section 6.3 the case study at stake is presented. Then the performance evaluation tools are introduced. First, the analytical technique is shown in Section 6.4; an example of application is shown in Section 6.5. Second, the discrete event simulation tool is presented in Section 6.6 and applications to a case study are shown in Section 6.7. The role of the MES and the support to lean manufacturing are discussed in Sections 6.8 and 6.9. Final conclusions are presented in Section 6.10.

6.2 State of the art

6.2.1 Techniques for performance evaluation

AVS/RS have been introduced in the late 1990s in European facilities. The first scientific paper on this technology is dated 2002: Malmborg developed an analytical model to evaluate the utilization of the machines, the cycle time and the throughput of the system, based on the topology of the rack and the features of the vehicles. He focused on tier-to-tier configurations, i.e. racks in which vehicles are able to move through different levels using a lift, aiming at compare AS/RS and AVS/RS performances. He also developed (2003) analytical tools to estimate the proportion of dual command cycles (i.e. cycles in which both a storage and a retrieval task are performed) based on the demand of storage and retrieval tasks and the estimated cycle times for single and dual command cycles. Other approaches are based on queuing theory. Kuo et al. (2007) developed a model for estimating the cycle time and the utilization of machines in single command cycles. Zhang et al. (2009) presented a model to deal with non-Poissonian queues keeping analytical simplicity. Other queue approaches have been studied by Cai et al. (2014); Fukunari and Malmborg (2008); Roy et al. (2012). Ekren and Heragu (2009) developed a regression, simulation-based model to tie the average cycle time of the system to its features; in (Ekren et al., 2010), a design of experiment approach has been used to identify the factors affecting the warehouse performance: dwell point policy, scheduling rule, input/output locations and interleaving rule are significant factors.

These papers all consider single-depth rack. The only work that takes into account multi-depth racks is (Manzini et al., 2016): an analytical model is presented to evaluate the performance of a rack with arbitrary rack width.

All these works are based on the assumption that items are randomly stored into the rack, although the allocation criterion has been found to be significant in (Ekren et al., 2010). Furthermore, the developed techniques are mainly devoted for designers, in order to quickly identify the configuration of the rack that meets the end-user requests; no applications of models for performance monitoring during the deployment of the AVS/RS have been found in literature.

6.2.2 *Information tools for warehouses*

The main operations that a warehouse needs to plan and control are: (i) receiving items from a supplier; (ii) storing the items; (iii) receiving orders from customers; (iv) retrieving the requested items; (v) ship the orders to customers. These operations should be performed in the minimum time, at the minimum cost, with high reactivity and customer satisfaction.

To achieve these purposes, the support of information tools is essential. In the past years, two classes of tools have been developed. The first one is named **Warehouse Management System** (WMS): it provides the information necessary to manage warehouse resources and control the flow of products in a warehouse, from receiving to shipping (Forte Industries, 2014; Nynke et al., 2002). WMS are often integrated into ERP systems (Nynke et al., 2002). The second class of software is given by **Warehouse Control Systems** (WCS): they are in charge of the activities execution and the detailed equipment control on the warehouse floor (QC software, 2008).

Given these “traditional roles” for WMS and WCS, a gap exists between the long-term planning performed by the former system and the detailed, short-term control in charge of the latter. To fill this lack, a first approach has been the extension of the work areas of the two systems. Real-time systems for data acquisition have been integrated into WMS: they mainly consist in RFID traceability systems, enabling to facilitate data collection and storage, and to enhance the performance of the warehouse (Chow et al., 2006; Poon et al., 2009; Wang et al., 2010). On the other side, Amato et al. (2005) proposed an approach for short-term optimization, integrated with WCS, of handling sequences, in order to minimize the time to complete a little number of picking or storage missions, based on the current state of the system.

Nonetheless, the extension of tasks in charge for each system did not lead to the expected efficiency improvement. Therefore, in recent years, a further software layer has been developed: the **Warehouse Execution System** (WES). This system supports the communication between the planning and the control levels: it collects order data from software systems to provide a global view of the state of the equipment and optimize the movements of items based on what occurs in the various parts of the warehouse (Forte Industries, 2014). This enables more aware management decisions in terms of resources allocation and system layout to improve reactivity, for example, in front of seasonal peaks of activity: historical data can be analyzed to extract order profiles, customers preferences, profitable strategies to better deal with the demand. Functionalities for automated dynamic adjustments of the workflow can also be integrated (Intelligrated, 2013).

Hence, an analogy between the information tools devoted to manufacturing and to warehouses can be made. WMS matches ERP functionalities: it keeps a global view of the process and the stored inventory, and drops down the orders to a lower level. WES is in charge of the purposes typical of a MES: it provides performance metrics for operational and strategic planning; it also supports the validation of the current management strategy and provides hints for improvements based on the evaluated analytics. Finally, the detail level required for WCS is comparable to the one implemented in shop-floor systems.

6.3 Description of the process

As stated in the Introduction, AS/RS exhibit low flexibility and their performance is low in case of high variability for storage and retrieval requests. Conversely, in order to approach a just-in-time flow of items, the capability to deal with great variability keeping high system efficiency is mandatory: this is the strength of AVS/RS.

The case study chosen for this research is a system able to separate the movements along the vertical, the longitudinal and the transverse directions by using a set of autonomous vehicles. The rack is made of an arbitrary number of levels; each of them has a cross aisle that goes from one side to the other, to provide access to the channels. Three different kinds of machines are used:

- the lift is in charge of the vertical movement: one or more units are placed on the border of the rack;
- the shuttle performs the movement through the aisle;
- the satellite is the storage/retrieval machine: it moves through the channels, to deposit or pick an item at/from the target position.

Hence, the whole system consists of several vehicles (shuttles and satellites), autonomous and integrated with each other: the shuttle moves back and forth through the aisle transporting the satellite in front of the target channel. The satellite, in turn, transports the UL: it leaves the shuttle and enters the channel, to perform the storage or retrieval task. The shuttles change the operating level through the lift. Furthermore, there exist one or more bays, which are the interfaces of the system with the external world: the bays are the places where the satellites pick the parts to be deposited in the rack and leave the retrieved items. In this study, the bays are supposed to be on the same side of the rack. A graphical representation of the rack and the AVS/RS system is provided in Figure 6.1.

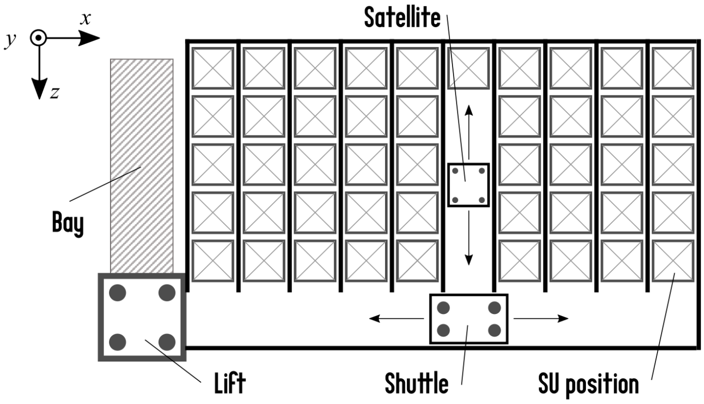


Fig. 6.1 A representation of the rack and the AVS/RS system.

The sequence of the operations to store a UL is the following:

1. The UL is carried in the input bay;
2. The UL is loaded by a satellite; the satellite joins the shuttle, and they get on the lift;
3. The lift moves to the target level, and the shuttle leaves the lift;
4. The shuttle moves through the aisle and stops in front of the target channel;
5. The satellite leaves the shuttle and enters the channel;
6. The satellite moves along the channel towards the last pallet stored;
7. The satellite unloads the pallet at the last empty location, according to a LIFO (Last In First Out) policy;
8. The satellite moves back through the channel and joins the shuttle.

The retrieval task is performed symmetrically. The capability of separating movements enables to perform, at the same time, different storage or retrieval tasks. For example, after operation 3 the lift is free to serve another shuttle that needs to move along the vertical direction. The system is able to reconfigure itself to face complex, variable scenarios.

However, the traditional methodologies to evaluate AS/RS performance do not take into account AVS/RS peculiarities, and the techniques shown in Section 6.2 mainly take into account single-depth systems. Conversely, in this case study, the length of the channel can be arbitrary. Further, criteria for items allocation are not taken into account into the analyses. Nonetheless, they are strategic factors for warehouse performance. Inappropriate management of the system can lead to avoidable motion of items and of resources. This, in turn, can reduce the reactivity of the warehouse, since requests for parts to enter or leave the warehouse need extended time to be satisfied, leading to *waiting* and *inventory*. For these reasons, in the following Sections a new analytical tool for performance evaluation is presented. A set of relationships to evaluate cycle times will be presented.

Since the term *cycle* implies that the initial and the final configuration of the system must be the same, in case of storage tasks, after operation 8 the above list is also performed backwards to carry each machine at the initial position. In literature, evaluations are mainly performed for *single-command* and *dual-command* cycles: these two expressions refer to the number of items transported during the cycle. In the former case, one storage or one retrieval task are performed; in the latter, both the tasks are executed. Nevertheless, in the system at stake the lift is able to transport up to two items at the same time. Hence, a broader combination of cycles is feasible: several levels can be visited during the same cycle, as well as more than two items can be involved in the movements on the same level. Hence, the model that will be introduced in the next Section concerns with general *multi-command* cycles; they will be classified as *homogeneous* (in case only one level is visited) or *heterogeneous* (in case more levels are visited).

The schematic in Figure 6.2 synthesizes how the methodology defined in Chapter 3 has been used to deal with this case study.

6.4 Analytical evaluation of warehouse performance

In this Section, an analytical technique, based on a probabilistic approach for the evaluation of cycle time is presented: it allows to calculate an average performance of the system and to compare it with some benchmarking situations. The evaluation is based on:

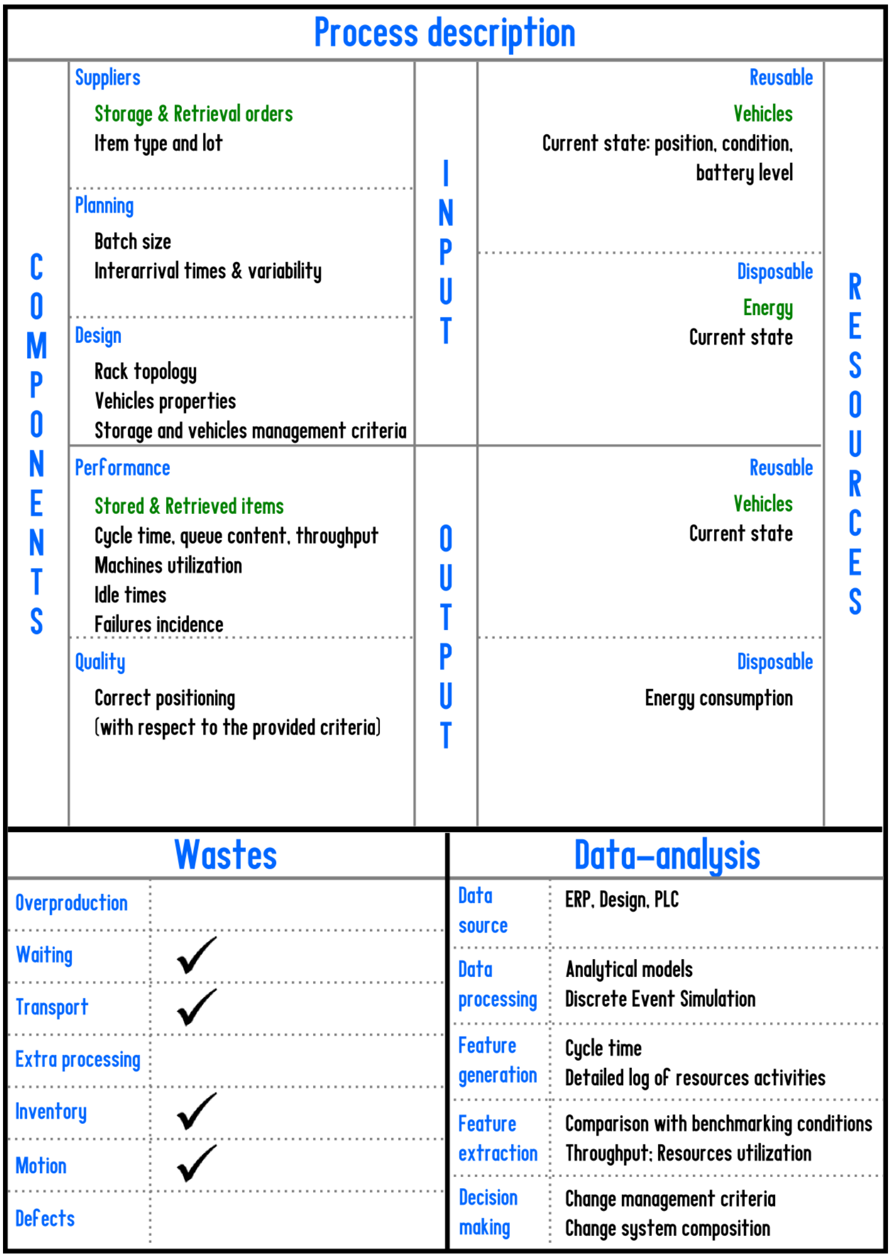
- the topology of the rack;
- the performances of the machines;
- the number of items involved and their task (storage or retrieval);
- the criteria for items allocation, in terms of statistical distributions.

Rack topology

The rack is supposed to be symmetric in each direction: all the aisles have the same number of channels, and each channel has the same number of storage positions. The (x,y,z) coordinates for each storage position in the rack must be known. For sake of simplicity, the lift is supposed to be in the position $(0,0,0)$; this assumption does not reduce the generality of the model. The following parameters are defined:

- N_x: the number of channels for each aisle
- N_y: the number of levels
- N_z: the number of storage positions for each channel.

The number of lifts, shuttles and satellites are provided, as well as the capability of the shuttles to travel without a satellite. These parameters are



Process description

COMPONENTS	INPUT / OUTPUT	RESOURCES
Suppliers Storage & Retrieval orders Item type and lot	INPUT	Reusable Vehicles Current state: position, condition, battery level
Planning Batch size Interarrival times & variability	INPUT	Disposable Energy Current state
Design Rack topology Vehicles properties Storage and vehicles management criteria	INPUT	
Performance Stored & Retrieved items Cycle time, queue content, throughput Machines utilization Idle times Failures incidence	OUTPUT	Reusable Vehicles Current state
Quality Correct positioning (with respect to the provided criteria)	OUTPUT	Disposable Energy consumption

Wastes

Overproduction	
Waiting	✓
Transport	✓
Extra processing	
Inventory	✓
Motion	✓
Defects	

Data–analysis

Data source	ERP, Design, PLC
Data processing	Analytical models Discrete Event Simulation
Feature generation	Cycle time Detailed log of resources activities
Feature extraction	Comparison with benchmarking conditions Throughput; Resources utilization
Decision making	Change management criteria Change system composition

Fig. 6.2 The schematic of the methodology used to develop this work.

necessary to determine which model, among the ones shown below, is to be deployed.

Machines performance

The acceleration and the steady-state speed of the machines are provided, both in the loaded and in the unloaded conditions. Given this class of input and the former one, the time necessary to reach each rack position from the bay can be evaluated:

- $t(x_i),\ i = 1,\dots,N_x$: the time necessary to move from the lift to the *i*-th channel
- $t(y_j),\ j = 1,\dots,N_y$: the time necessary to move from the bay to the *j*-th level
- $t(z_k),\ k = 1,\dots,N_z$: the time necessary to move from the channel entry to the *k*-th position in the channel

Number of items and tasks

. The cycle to be examined is described through the following parameters:

- I: the number of items involved in the cycle;
- T: the number of transitions from a storage to a retrieval task on the same level. It denotes the number of times in which the shuttle moves between two channels without passing through the lift;
- S: the number of times in which parallel activities of the satellite and the shuttle take place;
- P: the number of different levels visited in the cycle.

The value of S is tied to I and T through the following relationship:

$$S = I - (1 + T),$$

since for the first item and for transitions from storage to retrieval a shuttle-satellite uncoupling would not make sense.

Criteria for items allocation

For each level, channel, and position into the channel, the probability of interaction with the transport machines is evaluated through the following probability distributions:

- $\mathbf{a} = \{a_i\} = \{P\left(x = x_i\right)\},\ i = 1,\dots,N_x$ describes the movements along the x-axis;
- $\mathbf{b} = \{b_j\} = \{P\left(y = y_j\right)\},\ j = 1,\dots,N_y$ describes the movements along the y-axis;

- $\mathbf{c} = \{c_k\} = \{P(z = z_k)\}$, $k = 1, \ldots, N_z$ describes the movements along the z-axis.

Variables

Given the time necessary to reach each rack position and the probability distributions defined above, the following average times can be determined:

$$\begin{aligned} x_M &= E[t(x)] = \sum_{i=1}^{N_x} a_i t(x_i) \\ y_M &= E[t(y)] = \sum_{j=1}^{N_y} b_j t(y_j) \\ z_M &= E[t(z)] = \sum_{k=1}^{N_z} c_j t(z_k) \end{aligned} \tag{6.1}$$

Hence, x_M is the average time spent to move along the aisle from the lift; y_M is the average time spent moving in the vertical direction from the bay; z_M is average time necessary to move along the channel from its entrance.

Further, a shuttle may also move between two different channels on the same level (e.g. when it is switching from a storage to a retrieval operation): the duration of this travel is denoted by δx, and is evaluated through the probability distribution **a**. Similarly, the lift may need to move between different levels; the duration of this travel is denoted by δy.

$$\begin{aligned} \delta x &= E[t(\delta x)] = \sum_{i=1}^{N_x} a_i \left| t(x_i) - x_M \right| \\ \delta y &= E[t(\delta y)] = \sum_{j=1}^{N_y} b_j \left| t(y_j) - y_M \right| \end{aligned} \tag{6.2}$$

This quantity is not evaluated for the z direction, since there is no physical meaning for a satellite to interact with two positions in the same channel.

An additional variable must be evaluated to describe the case in which a shuttle can move even without a satellite: while the satellite is moving into the channel, the shuttle can go to the lift to pick the next UL to be stored and then move back to the channel to join the satellite. Alternatively, this situation can occur when two consecutive retrievals have to be performed: while the shuttle is leading the first UL to the lift, the satellite moves in the channel to pick the second item. Hence, the time that the two machines spend being uncoupled is given by the maximum duration among the two activities; it can be described through the following relation:

$$S_{xz} = \sum_{i=1}^{N_x} \sum_{k=1}^{N_z} a_i c_k \max\left\{x_i, z_k\right\} \tag{6.3}$$

Two classes of data sources are necessary to provide the input for data analysis. Design tools provide data concerning the topology of the rack and the performances of the machines. The data source for allocation criteria is the PLC of the system: it contains detailed data about the movements of the machines and the positions in the rack that have been deployed.

Given the variables defined above, the analytical models for the cycle time can be formulated. Different models, mutually exclusive, are formulated for systems consisting in one or more shuttles: this classification is necessary because in the former case the lift is idle while the shuttle is working along the aisle; conversely, in the latter case, the lift may serve one shuttle while another one is working along an aisle. The system chosen as case study can comprehend an arbitrary number of machines; nevertheless, the most common configuration consists in one lift and one or two shuttles. Thus, the models shown below are focused on these configurations. Furthermore, a distinction is made between homogeneous and heterogeneous cycles.

6.4.1 *Models for systems with one shuttle*

The models described in this Section can be used to evaluate the performance of systems consisting in one lift, one shuttle and one satellite.

First, models for **homogeneous cycles** are considered. In case the uncoupling of the satellite from the shuttle is not feasible (or it is supposed to be not convenient), the cycle time is given by:

$$\mathrm{CT} = 2y_m + \left[2Iz_m + (2I - 2T)\,x_m + T\delta x\right]. \tag{6.4}$$

The cycles that such a system is able to perform are: (i) 1 storage; (ii) 1 retrieval; (ii) 1 storage and 1 retrieval. In Appendix A, the full description of these cycles and a comparison with this analytical model is provided.

The cycle time for systems in which uncouplings of the satellite from the shuttle can occur is given by:

$$\mathrm{CT} = 2y_m + \left[2\,(I - S)\,z_m + 2x_m + (I - 1)\,\delta x + S \cdot S_{xz}\right]. \tag{6.5}$$

Two examples are provided in Appendix A to explain the model: (i) 2 storages (or 2 retrievals); (ii) 2 storages and 1 retrieval (or vice-versa). In case a lower number of items is involved, uncouplings do not take place and the model in Equation 6.4 can be used; the case in which 2 storages and 2 retrievals are performed is already described by the cycle in which

1 storage and 1 retrieval occur (except for the lift time). Cycles involving a higher number of items are not feasible, since the lift – usually – is not able to move more than 2 items at the same time.

In the models above, square brackets have been used to divide lift times from shuttle and satellite times. This distinction is helpful to introduce the models for **heterogeneous cycles**: they are a generalization of homogeneous cycles. The lift time is increased by the quantity δy multiplied by the number of times a switch between levels occurs. The subscript p is introduced to denote the events occurring at the level p (since different activities can take place at different levels). Thus, the heterogeneous model for systems without shuttle–satellite uncouplings is:

$$\mathrm{CT} = 2y_m + (P-1)\,\delta y + \sum_{p=1}^{P} \left[2I_p z_m + \left(2I_p - 2T_p\right) x_m + T_p \delta x\right]. \tag{6.6}$$

The heterogeneous model for systems in which shuttle–satellite uncouplings occur is:

$$\mathrm{CT} = 2y_m + (P-1)\,\delta y + \sum_{p=1}^{P} \left[2\left(I_p - S_p\right) z_m + 2x_m + \left(I_p - 1\right)\delta x + S_p \cdot S_{xz}\right] \tag{6.7}$$

6.4.2 Models for systems with two shuttles

The developed approach can be extended to systems consisting in more than a single shuttle. To fully exploit the system, while one shuttle is working on one level, the lift is free to serve the other shuttle. Hence, parallel activities occur and the working pace of the system is determined by the bottleneck machine.

The underlying assumption of this model is that both the shuttles are supposed to perform the same kind of activity on the level. Nonetheless, the rack positions involved in the cycle are different. At the beginning and at the end of the cycle, the lift is supposed to be in the bay; the shuttles are supposed to be at different levels.

Before calculating the cycle time of the system, the bottleneck must be identified. Thus, the following quantities must be evaluated:

- T_{level}: the time spent by the shuttle and the satellite to perform their task on a level; it is given by the terms within square brackets in Equations 6.4 or 6.5;
- T_{lift}: it is the time needed by the lift to serve the other shuttle, i.e. picking it to the level, going together the bay and then back to the level, and finally reach the level of the first shuttle. It is given by $T_{lift} = 2y + 2\delta y$.

In case $T_{level} < T_{lift}$, the lift acts as a bottleneck; the cycle time is given by

$$\mathrm{CT} = 10y + 3\delta y \tag{6.8}$$

Conversely, in case $T_{level} > T_{lift}$, the shuttle is the bottleneck and the cycle time is:

$$\mathrm{CT} = T_{level} + 8y + \delta y \tag{6.9}$$

A graphical representation for these relationships is provided in Appendix A.

A synthetic chart to summarize the presented models and to drive the choice of the model that fits with the system to be evaluated is provided in Table 6.1.

Table 6.1 Synthesis of the models for analytical evaluation of automated warehouses performance.

Nr. of shuttles	Type of cycle	Uncontraints	Model
1	Homogeneous	No	Eq. 6.4
		Shuttle – Satellite	Eq. 6.5
	Heterogeneous	No	Eq. 6.6
		Shuttle – Satellite	Eq. 6.7
2	Lift is the bottleneck	Lift – Shuttle	Eq. 6.8
	Shuttle is the bottleneck	Lift – Shuttle	Eq. 6.9

6.5 Results of the analytical model

The analytical tool for performance evaluation provides an estimation of the cycle time for predetermined cycles based on the real allocation criteria. The purpose of these tools is to evaluate whether the potential of the system is correctly exploited or not: the estimated cycle time can be compared with a set of benchmarking conditions to evaluate whether the overall performance of the system can be enhanced by changing the allocation criteria. Namely, the benchmarking conditions are:

- Best case: the machines always interact with the channel closest to the bay. It represents the best case of resources management (from the perspective of the cycle time) and leads the minimum possible cycle time;
- Worst case: the machines always interact with the channel farthest from the bay. It is the case of worst resources management and leads the maximum possible cycle time;
- Practical worst case: it is an intermediate case between the two previous ones; it represents the case of maximum randomness, thus is evaluated by supposing a totally random allocation criteria (i.e. the probabilities are given by uniform distributions).

The definitions for the three cases are adapted from (Hopp and Spearman, 2011). The former two cases define the interval of all the possible values that can be obtained by the analytical models; however, the last value is the most interesting, since it allows to state whether the management criteria is better than a random choice or not. Values higher than the practical worst case are due to issues in the allocation criteria: items frequently exchanged are stored too far from the bay, leading to time waste; an intervention should be undertaken to change the allocation criteria and improve the overall performance of the system.

As example, a warehouse with $N_x = 15$, $N_y = 4$ and $N_z = 5$ can be considered; the distance between adjacent levels, channels and storage positions is equal to 2 m. The storage and retrieval system consists of one lift and two shuttles; the shuttles are not capable to uncouple their movement from the satellites. The performances of the machines are listed in Table 6.2: the acceleration varies according to the presence of a UL above the machine, while the steady-state speed does not change.

Table 6.2 Performances of the machines involved in the case study

	Speed [m/s]	Acceleration [m/s^2]	
		Loaded	Unloaded
Lift	2.00	0.50	0.60
Shuttle	0.23	0.30	0.40
Satellite	1.20	0.50	0.70

At the beginning of the observation, the fill rate of the warehouse is approximately the 50%. During the observation, 300 items are stored and 284 are retrieved. The empirical distributions of the rack positions for storage and retrieval activities during this period have been evaluated; they are synthesized in Table 6.3.

Such empirical distributions are first used to evaluate T_{level} and T_{lift}, and decide which is the model appropriate to describe the system. Since T_{level} = 54.1 s and T_{lift} = 34.2 s, the model in Equation 6.9 has to be used.

The prevalent class of cycles observed consists in one storage and one retrieval on the same level. According to the model, the average cycle time necessary to perform this kind of cycles is 152.4 s. This value has been compared with the three benchmarking values. The results are shown in Table 6.4: since the cycle time provided by the model is higher than the practical worst case, the capability of the rack is not well exploited because the system tends to frequently use rack positions far from the bay. For example, positions far from the bay are used along the x direction: the 11% of the interactions involve the farthest channel, while there are almost no interactions with channels in the middle of the aisle. This result is obtained because items frequently exchanged are put far from the lift, thus leading to time waste: this means that the allocation criteria should be reviewed.

Table 6.3 Statistical distributions for the interaction between satellites and rack positions, evaluated by observing 300 storages and 284 retrievals.

x direction		*y* direction		*z* direction	
Coordinate [m]	Weight	Coordinate [m]	Weight	Coordinate [m]	Weight
2.00	0.03	2.00	0.82	2.00	0.21
4.00	0.23	4.00	0.09	4.00	0.12
6.00	0.15	6.00	0.02	6.00	0.24
8.00	0.08	8.00	0.07	8.00	0.23
10.00	0.10			10.00	0.20
12.00	0.01				
14.00	0.01				
16.00	0.01				
18.00	0.20				
20.00	0.00				
22.00	0.02				
24.00	0.05				
26.00	0.00				
28.00	0.00				
30.00	0.11				

Table 6.4 Results of the performance benchmarking performed through the analytical model.

Case	CT Value [s]
Best Case	125.73
Practical Worst Case	141.81
Analytical evaluation	**152.41**
Worst Case	361.44

The analytical tool presented in this Section represents a significant progress with respect to the state of the art: the approaches in literature mainly focus on single or double deep racks; the only work dealing with deeper racks is (Manzini et al., 2016), but this evaluation is not based on the criteria for UL allocation. The tool can be easily implemented (even on a common spreadsheet) and used.

Nonetheless, the analytical model provides average indicators, without information about the punctual behavior of the system; furthermore, the analysis has been extended to the allocation criteria, but it does not take into account the criteria used to manage the machines. Hence, a more detailed representation can be necessary to have a complete picture of the system. It can be obtained through a virtual representation; for this reason, the simulation tool shown in the next Section has been developed.

6.6 Deployment of Discrete Event Simulation

As stated, the alternative approach to evaluate the performance of the system is the deployment of a numerical simulation. Due to the physical characteristics of the system, a Discrete Event Simulation (DES) approach was chosen. In the main commercial DES software (e.g. FlexSim, Tecnomatix Plant Simulation, Arena) a net classification of the objects in the model is performed to distinguish servers and items. However, in this case study, there exist objects that behave both like servers and items (e.g. the shuttle is transported by the lift to move along the y direction, and transports the satellite along the x direction).

Thus, in order to be as free as possible and to skip such implementation issues, the simulation was coded from the scratch in a Matlab environment. The key steps for a **storage task** are synthesized here:

- A source introduces ULs into the system, according to a probability distribution or to a delivery table. Each UL is given a unique `ID`, an `ItemType` and an `ItemLot` code;
- A storage position in the rack is chosen. Different criteria can be chosen, as described below;
- The machines necessary for the storage task are identified.
  - If the resources are not free, the task is delayed;
  - If the selected machines are not already in the bay, their travel to the bay is planned with priority;
- The UL is picked from the bay and brought to the target position through the following steps:
  - The satellite, the shuttle and the lift are in the bay;
  - The satellite leaves the shuttle to pick the UL;
  - The satellite goes back above the shuttle;
  - The lift transports the shuttle to the target level;
  - The shuttle – with the satellite and the UL above – leaves the lift, moves through the aisle and stops in front of the target channel;
  - The satellite leaves the shuttle, moves through the channel and deposits the UL at the target position.
  - The satellite moves back through the channel to join the shuttle.

The **retrieval tasks** are managed in a similar way. Retrievals are created according to probability distributions: an `ItemType` and an `ItemLot` are requested; then the UL to be retrieved is identified through the selection criteria described below.

Criteria to select the storage position

The rack consists in a set of UL positions which may have different properties; for example, different levels may exhibit different sizes in order to host different kinds of ULs. The following, mutually alternative, criteria have been implemented to select the target channel (TC). The provided labels are used to quickly identify the criteria in Table 6.6.

1. Select the channel already containing the same `ItemType` and `ItemLot`, at the level closest to the bay, closest to the lift; labeled `ClosestLevelLot`.
2. Select the channel already containing the same `ItemType` and `ItemLot`, closest to the lift, at the level closest to the bay; labeled `ClosestChannelLot`
3. TC is on the level as close as possible to the bay: the TC is the channel containing the same `ItemType` and `ItemLot`, with an available position, closest to the lift; if no channel are found, the empty channel closest to the lift is chosen; otherwise, the selection is performed on the second level closest to the bay, and so on; labeled `ClosestLevel`.

The first two criteria differ in the search hierarchy. In the first one, available positions are searched through all the channels on the first level; if no one contains similar ULs, the search is extended to the second level, and so on. In the second criterion, the search is started by considering, for each level, the channel closest to the lift; if no channels fit the request, the second channel of each level is considered, and so on.

Criteria to select the item to be retrieved

When the request for an item is generated an `ItemType` and an `ItemLot` are generated; The following, mutually alternative, criteria have been implemented to select the target UL (TUL):

- Select the reachable UL with the requested `ItemType` and `ItemLot` at the level closest to the bay, in the channel closest to the lift; labeled `ClosestLevel`.
- Select the reachable UL with the requested `ItemType` and `ItemLot` at the channel closest to the lift, at the level closest to the bay; labeled `ClosestChannel`.
- Select the oldest, reachable UL, without regard for the position in the rack; labeled `Oldest`.

Criteria for machines management

In case the system consists in more than a shuttle, the one to be used for the storage task is chosen according to this priority:

- Choose the shuttle already going towards the bay (if there is one);
- Choose the shuttle already at the target level or moving towards it (if there is one), in order to avoid having more than one shuttle per aisle;
- Choose the idle shuttle closest to the bay.

To take into account for lift–shuttle uncouplings, while a shuttle is running along an aisle, the lift is set in an idle state; hence, it can be used if another shuttle needs to move through the levels.

The set of features provided as output by the simulation model is much broader than the analytical model: it consists in a report of all the activities performed by the machines, in a chronology of the events experiences by each UL, and in a picture of the current state of the rack. These data can be further processed to be transformed into more useful features, such as average values and variabilities for the transport times, the waiting times, and the utilization of the resources. The major advantage of the simulation is the possibility to explore the behavior of the system even in composite scenarios.

6.7 Results of the simulation model

The simulation tool presented in the previous Section can be used to compare the performances of different management criteria in dealing with a given scenario, and to select the one leading to the best results.

To proof this capability, the results of a set of simulations are shown in this Section. The criteria for the selection of UL position shown above have been compared by simulating two scenarios. The former represents a steady-state situation: storage and retrieval activities are almost balanced. The latter is a stressful condition: 50 items to be stored are put into the bay at the same time, and must be put into the rack as soon as possible to make free the queue.

The topology of the rack is the same introduced in Section 6.5. The parameters describing the AVS/RS are shown in Table 6.5; the shuttles are not capable to uncouple their movement from the satellites. The performances of the machines are listed in Table 6.2.

Table 6.5 Synthesis of the parameters describing the AVS/RS used as case study.

Quantity	Value
N_x	15
N_y	4
N_z	5
Spacing [m]	2
Lifts	1
Shuttles	2
Satellites	2

At the beginning of the simulation, the lift is in the bay; the two shuttles are idle at the first level ($y = 2$) and at the third level ($y = 6$). The fill rate of the rack is 50%: the stored units belong to 8 different lots. The queue of ULs waiting to enter the rack is treated according to a FIFO (First In First Out) policy.

Table 6.6 Criteria used in the simulations to identify the best UL position for storage and retrieval in the rack.

Simulation Nr.	Rack criteria	
	Storage	Retrieval
1	Closest Level Lot	Closest Level
2	Closest Channel Lot	Closest Channel
3	Closest Level	Closest Level
4	Closest Level Lot	Oldest
5	Closest Channel Lot	Oldest
6	Closest Level	Oldest

The ULs to be stored are randomly generated: the time lapsing between the creation of two consecutive items is provided by a normal distribution with average value equal to 150 s and standard deviation equal to 10 s. The `ItemLot` corresponding to each UL is generated according a uniform distribution. To keep the system balanced, the ULs to be retrieved are requested, on average, once on every 150 s, but the variability is higher: the standard deviation is equal to 20 s. The `ItemLots` are still chosen according to a uniform distribution.

A graphical representation for the content of the rack at the beginning of the simulation is provided in Appendix A.

The storage and retrieval criteria used in each simulation are listed in Table 6.6. A synthesis of the obtained results is shown in Table 6.7. For storage activities, queue times are the times in which the entering UL is waiting for a machine in the bay: the minimum time is 2 s, corresponding to the time necessary for the satellite to leave the shuttle and reach the UL. Travel times are measured from the instant in which the item is loaded from the bay and the instant in which it is stored in the rack. Travel and queue times are defined in a specular way for retrieval tasks. These data are not comparable with the cycle times obtained through the analytical model: here, after the storage of a UL, the shuttle remains idle in its position and does not go back to the bay to close the cycle.

The results listed in Table 6.7 show that allocation criteria that less use the lift provide a better performance in terms of average queue and travel times, and related variability. However, it must be highlighted that this result strongly depends on the ratio between shuttle and lift steady-state speeds, which is approximately 8:1. The criterion `Closest Channel Lot` (simulation 2) – which is the one that most uses the lift – leads to the highest queue times and the highest time variability. The criterion `Closest Level` shows better reactivity, since the queue and the travel times exhibit the minimum values among the first three criteria combinations. Nonetheless, in these cases the retrieved UL is chosen only according to its position. In case the rack is handling perishable products, the retrieved UL should be the one that has been in the rack for the longest time, among the ones matching the requested `ItemLot`. Hence, simulations 4-6 have been run to evaluate

Table 6.7 The results of the simulations performed, according to the criteria in Table 6.6.

		Simulation Nr.					
		1	2	3	4	5	6
Machines utilization	Lift	28.9%	40.2%	14.7%	32.5%	39.8%	30.2%
	Shuttle 1	28.4%	31.5%	26.3%	32.8%	34.9%	37.0%
	Shuttle 2	20.0%	21.9%	6.7%	22.9%	23.9%	17.3%
	Satellite 1	42.3%	44.9%	48.2%	46.2%	48.0%	54.2%
	Satellite 2	29.3%	31.6%	10.9%	31.9%	33.1%	24.9%
Queue time in the bay [s]	Average	20.6	24.0	11.8	28.5	26.4	26.8
	Std. Dev.	25.0	26.9	15.4	32.2	30.6	30.6
	Max	110.8	105.5	70.2	135.5	121.3	127.2
	Min	2.0	2.0	2.0	2.0	2.0	2.0
Travel time to the rack [s]	Average	36.4	39.3	30.5	37.9	40.8	36.1
	Std. Dev.	9.0	10.9	6.2	10.2	11.3	9.4
	Max	63.1	89.2	47.4	81.3	72.3	66.0
	Min	17.4	17.4	17.4	17.4	17.4	17.4
Retrieval queue time in the rack [s]	Average	33.7	37.3	20.4	38.8	41.2	38.9
	Std. Dev.	21.0	21.6	13.4	22.1	22.4	23.0
	Max	108.5	111.9	81.7	130.3	137.6	216.8
	Min	3.5	3.5	3.5	3.5	3.5	3.5
Travel time to the bay [s]	Average	34.7	38.8	29.6	37.4	39.2	34.1
	Std. Dev.	8.1	11.2	5.8	10.3	10.2	9.1
	Max	63.1	105.5	43.4	79.6	60.1	69.0
	Min	17.4	17.4	17.4	17.4	17.4	17.4

the performance of the `Oldest` retrieval criterion. The utilization of the machines, of course increases, due to the longer travels necessary to retrieve ULs. This, in turn, affects queues and travel times. The storage time also increases, since the rack positions made free by retrievals are no more the closest to the bay. Given the performances of the machines and the topology of the rack, the best storing criterion is `Closest Level`: it results in the lowest machines utilization to perform the given task. This, in turn, leads to lowest time spent traveling and to a lower energy need.

In the second tested scenario, 50 items are put into the bay at the same time and have to be stored as quick as possible. This case mimics the situation in which an external supplier deposits an amount of material. The `ItemLot` values are generated according to a uniform distribution; the initial state of the rack is the same described for the previous case.

The results of these simulations are shown in Table 6.8. The storage criteria are the same described for simulations 1-3. In this case, lift travels should be reduced as much as possible. The configuration of simulation 2 leads to the highest amount of time necessary to perform the whole storage operation; the other two criteria require comparable amounts of time, but the utilization of the machines exhibit huge differences. Hence, the criteria to be deployed can also be chosen according to the current energy level of machines batteries.

Table 6.8 Results of the performed simulations in case 50 ULs need to be stored simultaneously.

		Simulation Nr.		
		7	8	9
Machines utilization	Lift	83.6%	89.4%	50.3%
	Shuttle 1	46.9%	44.4%	60.7%
	Shuttle 2	55.4%	51.5%	23.9%
	Satellite 1	61.7%	55.6%	84.9%
	Satellite 2	68.2%	62.7%	29.5%
Travel time to the rack [s]	Average	35.4	39.0	31.6
	Std. Dev.	9.2	9.8	6.0
	Max	58.1	58.1	45.0
	Min	17.4	17.4	17.4
	Total time	2701.6	3296.0	2723.5

6.8 The role of MES

As stated in Chapter 2, performance monitoring is one of the core tasks for a MES. One way to monitor the behavior of the warehouse is the extraction of data from the PLC of the AVS/RS: data concerning the movements performed by each vehicle, their utilization and the time necessary for the performed operations can be collected and analyzed. Nevertheless, the mere extraction of average cycle-times can be an information not satisfactory. Shop-floor data allow a MES to perform deeper analyses. The analytical models shown in Section 6.4 can be integrated into the MES to compare the real behavior of the system with a set of benchmarking situations: this allows to evaluate whether the performance of the system can be improved or not, and how much effort should be done.

A more complete instrument is represented by the simulation tool. As shown, it provides more detailed information about each activity of the system. Average times, measures for variability and queues can be extracted through post-processing analyses. Furthermore, punctual information about the state of the rack can be extracted. The integration of this simulation tool with a MES establishes an extraordinary tool for activities planning and for the prevention of criticalities. The management level provides the MES with a bill of items to be stored or retrieved. A simulation for such a bill can be run to test the criteria for allocating items to rack positions and identify in advance possible issues. For example, in Section 6.7 the results provided by different allocation criteria in front of the same scenario have been compared. Since the run-time of this algorithm is a few minutes, it can be used to select in real-time the criterion that best fits with the current necessities to plan the storage and retrieval activity. Hence, the criteria to manage the AVS/RS system can vary according to the particular condition of the rack and to the specific situation in which the storage and retrieval task has to be performed.

The deployment of the simulation tool also supports the prevention of criticalities. The final content of the rack can be virtually observed; in case it is not satisfactory, an intervention is possible before starting the storage and retrieval tasks. For example, some ULs can be reallocated to reduce the operational time, or to make free some strategic positions for the new items to be stored. Furthermore, the integration of simulation into MES also allows to better deal with variability: in case a huge quantity of items must be rapidly put into the rack, the MES can manage in advance the content of the rack by making free the positions closest to the bay, in order to quickly conclude the storing activities and successfully deal with activities peaks. Similarly, in case broad quantities of items need to be retrieved, the MES can move such items as close as possible to the bay during the idle times, in order to improve the reactivity of the system.

Over longer time-scales, the MES can collect data concerning the average staytime into the rack for each item type. Hence, it can manage the allocation criteria by placing the most exchanged item types closest to the bay, in order to minimize the storage and retrieval time, thus reducing transport.

6.9 The support to lean manufacturing

The two tools that have been developed in this work allow to enrich the functionalities of a MES in the field of warehouses. This also allows to better deal with the lean manufacturing approach. The first source of waste that can be faced and reduced through these tools is *transport*: a tight monitoring and control on the allocation activity is certainly strategic to decrease useless transportation of the items. Transport reduction implies an average reduction of the cycle time, leading to improved reactivity of the system. An improved control of the allocation criteria also enables *motion* reduction: storage strategies appropriate to the current conditions of the system allow to decrease the useless motion of vehicles. Motion reduction is particularly significant: the energy necessary to move shuttles and satellites is provided by batteries; when a machine gets out of energy, it is recovered for a given time. Hence, motion reduction fosters increased availability for the machines.

Furthermore, the flexibility in redesigning functional criteria enabled by the MES can also be extended to the hierarchy of the operations to be performed. The system chosen as case study performs activities in the order they are introduced into the system. For example, consider the case in which two storing activities are planned and a retrieval operation is required while the first one is running. The system will finish the first storage activity; the machines will go unloaded to the bay; the second storing activity will be performed and, finally, the retrieval operation will be examined. The flexibility provided by the MES can support a redefinition of the hierarchies, allowing to perform – if convenient – the retrieval activity between the two storage operations; this improved planning of activities also contributes in reducing non value-added motion.

The improved flexibility and capability in dealing with variability provided by the MES also allow to reduce *waiting* and *inventory*: queues of items to be stored and temporarily stocked into the bay can be reduced, as well as the time interval necessary to lead an item in the bay after its request.

6.10 Conclusions

In this Chapter, heterogeneous techniques to evaluate the performance of an automated warehouse based on AVS/RS technology have been provided. The approaches currently available in literature are not satisfactory because mainly consider single- or double-depth racks. Conversely, the system studied in this Chapter consists in multi-depth racks. Furthermore, usually the allocation criteria is not considered to evaluate the performance of the system; nevertheless, it plays a key role in stating whether the warehouse is well exploited or not.

The importance of integrating the developed techniques into a MES (or a WES) has been discussed, as well as its role in supporting the achievement of lean manufacturing. Beside online monitoring and control, the presented techniques can also be used to support the design phase of a new system or to evaluate interventions to improve the performance of an existing AVS/RS. The analytical technique provides a preliminary estimation of the expected performance: practitioners can use it to evaluate whether the configuration of the designed system (i.e. the number of machines and their performances) is able to satisfy the needs of the customer in dealing with standard cycles. On the other hand, the DES tool is based on a virtual copy of the designed system: hence, the AVS/RS can be validated before the physical realization of the warehouse, by testing its reaction in front of the most different scenarios.

Note This work has been supported by Regione Piemonte under the research feasibility study MOMA, "Analisi delle prestazioni dei sistemi di MOvimentazione per Magazzini Automatici", in cooperation with the company Eurofork.

Chapter 7

MES for the management of automated vehicles traffic

Abstract Beside storage, another activity surrounding the manufacturing operations is the transport of items through the workstations in the shopfloor. Usually, in mass-production, workstations are placed in a serial layout, and items move through consecutive workstations by conveyors. This is an efficient solution, but the resulting flexibility of the production line is very low and even a small failure in the transportation means may result in blocking the whole line. Recently, the spread of Automated Guided Vehicles (AGVs) increased: this solution allows to improve the flexibility of the line. However, switching from a traditional conveyor to a fleet of AGVs, keeping the serial layout for the workstations, is not economically convenient; a cellular layout would enable to better exploit the advantages provided by the new transportation system. Hence, a novel methodology to identify the best cellular layout for a manufacturing process has been studied. A mathematical model has been developed for re-dimensioning the workstations and to identify their best position in the plant, in order to minimize the path traveled by each item. Then, a technique based on Discrete Events Simulation has been used to evaluate the behavior and the performance of the transport system, in order to monitor and control the behavior of the whole manufacturing process in the new layout, and predict possible criticalities. This tool can be used to online manage the process as well as to a-priori test different scenarios and support the decisions taken by the designers.

7.1 Introduction

In the case studies previously discussed, the methodology presented in Chapter 3 has been deployed to deal with already existing processes: waste classes affecting the process were identified; the exhaustive process description allowed to identify the possible sources of such wastes; then, techniques to be integrated into MES were developed to reduce wastes and improve process performance. The aim of this Chapter is slightly different: here, the purpose of the research is to provide a support to the innovation process by working hand-by-hand with the design, in order to reduce expected wastes since the very early design stages.

A case study has been provided by a system integrator settled in the Turin area. It consists in a line for the assembly of engine cylinder heads: this line is usually designed in a serial layout, and traditional conveyors are used to perform the transport of items between subsequent workstations. This is an efficient solution, but the resulting flexibility of the production line is very low and even a small failure, either in a machine or in the transportation means, may result in blocking the whole process. Hence, the company is considering the opportunity to switch from the traditional transport system to automated vehicles. Two ways to exploit this change exist. The first one is a mere replacement of the conveyors with a set of Automated Guided Vehicles (AGVs); however, due to the higher cost of the fleet of vehicles with respect to the conveyors, this strategy is not economically sustainable. The second way is a complete change in the design paradigm, enabling to fully exploit the potential benefits deriving from the deployment of flexible transportation means.

The efforts performed in this work mainly involve two areas. The first one is the layout design of the manufacturing line: the freedom provided by the AGVs allows to remove transport constraints and opens the possibility to switch from a serial workstation positioning to a cellular layout. The flexibility of the process can be dramatically improved; nonetheless, a careful analysis must be performed to minimize the impact of sources of waste. The second work area is the definition of the tasks to be performed by the automated vehicles: they can be used for the mere transport of items through workstations or, alternatively, they can take in charge an item since it is introduced into the line and accompany it through the whole process.

The remainder of the Chapter is organized as follows. In Section 7.2 the state of the art in the field of cellular manufacturing design is depicted. In Section 7.3 the process selected as case study is introduced. In Section 7.4 an innovative technique to optimize the position of workstations in a cellular layout is presented; the results are shown in Section 7.5. Then, the issue of AGVs tasks is dealt: in Section 7.6 a simulation tool is presented to compare different scenarios; results are provided in Section 7.7. Beside process design, the developed tools can have further purposes: in Section 7.8, the possible deployment of such tools to manage the process after its implementation is discussed; their support to lean manufacturing is presented in Section 7.9.

7.2 State of the art

For long time, in traditional layout configuration the issue of handling material has not been considered, since it was a manual task; alternatively, standard automation solutions were deployed. With the development of new manufacturing systems and the spread of AGVs, the flow path layout gained importance for the efficacy of the whole manufacturing process.

The first aim of this work is the optimization of a cellular layout: cellular manufacturing is a consequence of group technology, in which a manufacturing system is partitioned into several independent systems with enhanced flexibility. According to Dimopoulos and Zalzala (2000), this problem consists in three sub-problems: (i) the definition of the manufacturing cells, i.e. the machines and the operations that constitute a cell must be identified; (ii) the layout of the cells in the plant; (iii) the layout of the machines within the cells. The techniques developed in this work address the second task: the first one is currently performed by the industrial partner, according to technological constraints. The third one, at the moment, is not dealt, since cells are made of identical machines and there is not a transport of items within cells; further, the cells considered in this work only consist of one or two machines.

Different approaches are available in literature. Given the complexity of the problem, often the three tasks are not performed at the same time, thus multi-step techniques have been developed. A first attempt has been made by Gupta et al. (1996): a genetic algorithm was proposed to address the machine cell-part grouping problem. Three different objective functions were proposed with different purposes: (i) minimize the total inter- and intra-cell moves; (ii) minimize cell load variation; (iii) minimize simultaneously both the former functions. Wu et al. (2007) developed a hierarchical genetic algorithm (HGA) to simultaneously form manufacturing cells and determine the group layout of a Cellular Manufacturing System (CMS). Chang et al. (2013) developed a two stage model: first, they solve cell formation and cell layout; then, machine layout in each cell is evaluated. A linearized, constrained objective function is minimized. A similar approach has been used by Chan et al. (2008). Javadi et al. (2013) enriched the intra-cell optimization by taking into account unequal dimension of machines, machines orientation and the exact material handling costs. Kia et al. (2014) aimed at minimizing the total cost of material handling between and within cells by taking into account machine relocation, the purchase of new machines, machine overhead and processing in a multi-floor layout. Hu et al. (2006) focused on the inter-cell layout and material handling system: they aimed to minimize the inter-cells path through genetic algorithms to reduce the cost of material handling. Tavakkoli-Moghaddam et al. (2007) developed a model to simultaneously minimize the total costs of inter- and intra-cell movements, also taking into account a stochastic demand. Hafezalkotob et al. (2015) used the fuzzy goal programming to jointly minimize four independent objective functions concerning: (i) the inter-cellular traveled distance; (ii) the economic investment on machines; (iii) the workload balance of cells; (iv) the capacity of the cells.

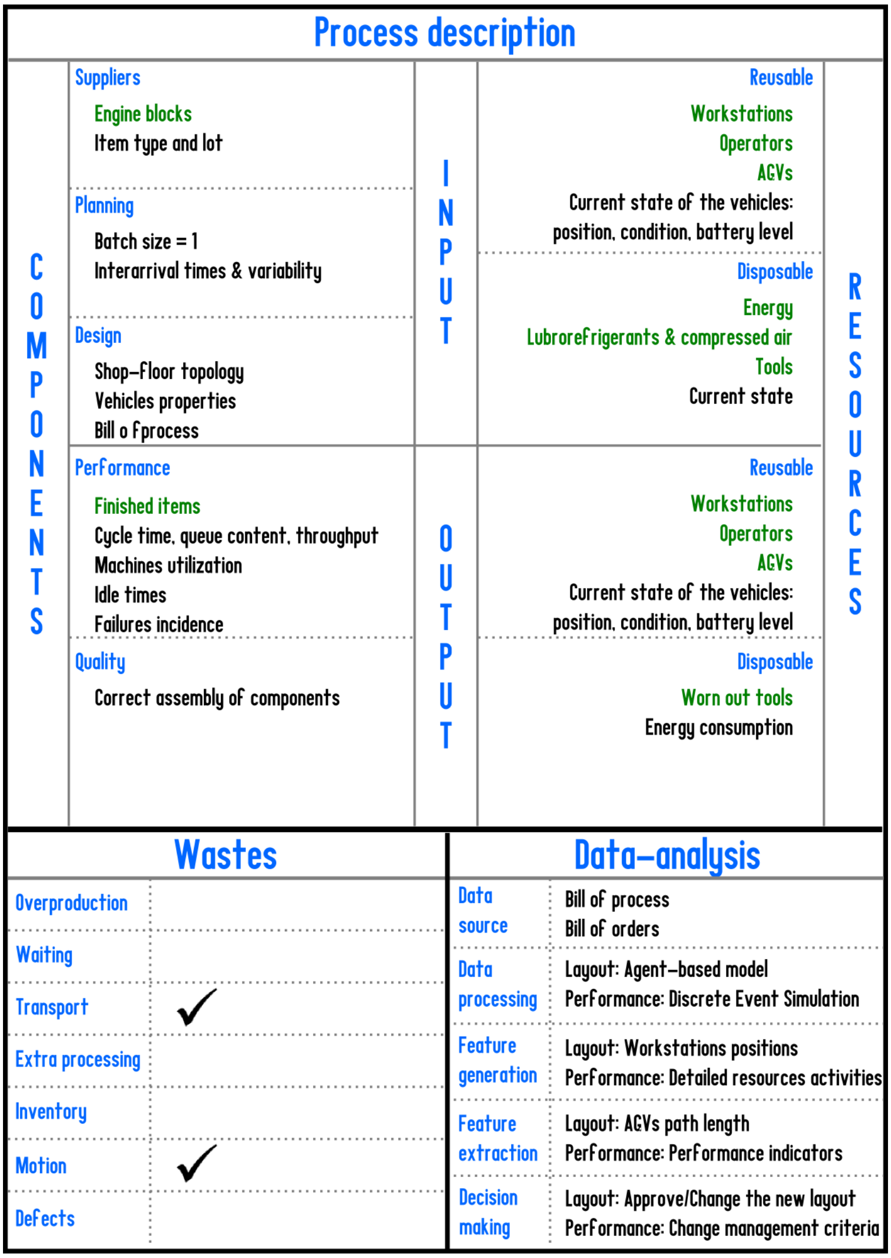
Other approaches have been inspired by physical or natural systems. Ariafar and Ismail (2009) aimed at arranging facilities in a cellular system to minimize handling material cost. They used a simulated annealing technique, which is based on physical annealing: it is a heat treatment process that gradually cools a physical system to reach the state of minimum potential energy. Jolai et al. (2012) developed an electromagnetism-like model in which each point is considered as a charged particle. Charged particles interact and influence with each other through attraction and repulsion; electromagnetism-like algorithms are designed to optimize non-linear, real-valued problems. Soto et al. (2015) used an artificial fish swarm algorithm, belonging to a class of techniques able to solve complex optimization problems. The aim of their work is the minimization of movement and material exchange between cells, to optimize time and costs.

7.3 Description of the process

The process considered in this study consists in a line devoted to the assembly of engine cylinder heads. This line is made of the 19 operations listed in Table 7.1. In the Table, a short description of these operations is provided, together with the corresponding process and setup times. Automatic, semi-automatic and manual operations are performed; each of them is supposed to take place into a different workstation. The transport of items through the process is supported by conveyors joining the workstations in a serial layout. When switching to the AGV fleet, the design must be optimized to minimize *transport* and *motion*. The schematic in Figure 7.1 synthesizes how the methodology defined in Chapter 3 has been used to develop the research work in this case study.

7.4 Technique to optimize a cellular layout

As stated in Section 7.1, the aim of this Chapter is to develop tools able to optimize the position of the workstations into a cellular layout. Currently, the approach to design a serial layout is mainly based on the experience of



Process description

COMPONENTS

INPUT

Suppliers
Engine blocks
Item type and lot

Planning
Batch size = 1
Interarrival times & variability

Design
Shop–floor topology
Vehicles properties
Bill of process

RESOURCES

Reusable
Workstations
Operators
AGVs
Current state of the vehicles:
position, condition, battery level

Disposable
Energy
Lubrorefrigerants & compressed air
Tools
Current state

OUTPUT

Performance
Finished items
Cycle time, queue content, throughput
Machines utilization
Idle times
Failures incidence

Quality
Correct assembly of components

Reusable
Workstations
Operators
AGVs
Current state of the vehicles:
position, condition, battery level

Disposable
Worn out tools
Energy consumption

Wastes	
Overproduction	
Waiting	
Transport	✓
Extra processing	
Inventory	
Motion	✓
Defects	

Data–analysis	
Data source	Bill of process Bill of orders
Data processing	Layout: Agent–based model Performance: Discrete Event Simulation
Feature generation	Layout: Workstations positions Performance: Detailed resources activities
Feature extraction	Layout: AGVs path length Performance: Performance indicators
Decision making	Layout: Approve/Change the new layout Performance: Change management criteria

Fig. 7.1 The schematic of the methodology used to develop this work.

Table 7.1 Bill of operations of the current process for cylinder head assembly.

ID	Cluster	Description	Avg. process time [s]	Avg. setup time [s]
1	Load	Load cylinder head to pallet	10	8
2	Sealant and lubrication	Lubricate valve guide bores or valves	15	8
3	Insertion	Install intake and exhaust valves	25	4
4	Leak test	Valve blow-by leak test	25	8
5	Rollover	Turnover 180 degrees	10	8
6	Load	Load camshafts to pallet	15	8
7	Load	Load camshaft caps and bolts to pallet	20	8
8	Insertion	Assemble valve stem seal	25	4
9	Press	Press valve stem seals	15	8
10	Insertion	Assemble valve springs, valve spring retain	25	4
11	Press	Key-up	15	8
12	Sealant and lubrication	Apply sealant	25	4
13	Load	Assemble camshafts, camshaft caps, bolts and pre-torque	10	4
14	Tightening	Torque camshaft cap bolts	20	8
15	Measure	Torque to turn	25	8
16	Press	Press camshaft seal ring	15	8
17	Tightening	Torque,intake, exhaust and/or injector studs	25	8
18	Marking	Cylinder head label	15	8
19	Load	Unload cylinder head assembly	10	8

the designer: approaches such as Knowledge Based Engineering (KBE) are at study, aiming to identify tools capable to formalize this knowledge and make it available for all the designers working into a company. Nonetheless, KBE can provide hints concerning good practices, particular requests or habits of a particular customer. When switching from a serial to a cellular layout, optimization tools are necessary to design a process involving the lowest number of components and able to provide the best performance.

In this Section, an algorithm to evaluate the best workstations position in the shop-floor is presented. It is based on the analogy with a mechanical system consisting in a set of bodies connected with each other through springs. Each spring has given stiffness and equilibrium length. The equilibrium configuration of this system results in the lowest residual energy. The mechanical system is transposed to the manufacturing layout as follows. The workstations act as the connected bodies; the springs represent the travels to be performed according to the bill of process: the stiffness of the springs is proportional to the number of travels performed through each couple of cells. In this way, each working cell is considered as an agent that interacts with other agents, which position is due to a balance of forces.

Hence, a lattice-free agent-based model to simulate the interactions among cells and determine the equilibrium configuration has been formulated. The morphology of the cells is not explicitly introduced: in the model, agents are described as circular objects: this simplification allows to model interactions as acting only on the radial direction, rather than the x and y coordinates. Each cell is given two characteristic radii: R^{in} is the radius of the area physically occupied by the workstation; R^{out} depicts the area necessary to move around the workstation (for example, to permit AGVs transit or to supply components to the machines).

In Figure 7.2, an example of the interacting forces is shown: the black area is the circle with radius R^{in}; the lilac area is the circle with radius R^{out}. Two kinds of forces act between the cells i and j: the attraction force tends to lead the length of the spring towards the equilibrium length (i.e. the distance at which the two external circles are tangential with each other); the repulsion force avoids overlapping between adjacent stations. Such interactions involve the centers of the two cells. The following variables can be introduced:

$$\mathbf{d}_{ij} = \mathbf{x}_i - \mathbf{x}_j$$

$$\ell_{ij}^{eq} = R_i^{out} + R_j^{out} \tag{7.1}$$

The two forces are modeled through a unique spring with variable stiffness: when the length of the spring is higher than the equilibrium length, the stiffness is equal to the number of travels performed through the stations i and j to produce one unit, denoted by T_{ij}; hence, the highest is the number of travels, the highest is K_{ij}, the lowest is the final distance between the two cells. The overlapping between cells is discouraged through a quadratic relationship, as shown in Equation 7.2.

$$\begin{gathered} K_{ij} = T_{ij}(|\mathbf{d}_{ij}| > \ell_{ij}^{eq}) + 10\,T_{ij}^2(|\mathbf{d}_{ij}| \leq \ell_{ij}^{eq}) \\ \mathbf{F}_{ij} = K_{ij}\left(|\mathbf{d}_{ij}| - \ell_{ij}^{eq}\right) \cdot \frac{\mathbf{d}_{ij}}{|\mathbf{d}_{ij}|} \end{gathered} \tag{7.2}$$

The warehouse is modeled as a punctual entity, i.e. items to be manufactured and finished items enter and leave the line from the same point. It is described as an additional cell interacting with the other agents in the model according to the relationships above. Further, repulsion forces are added to avoid cells going outside the plant area:

$$\begin{aligned} \mathbf{d}_{i,wall} &= \mathbf{x}_i - \mathbf{x}_{wall} \\ \mathbf{F}_{i,wall} &= 10\left(\left|\mathbf{d}_{i,wall}\right| - R_i^{out}\right)\frac{\mathbf{d}_{i,wall}}{\left|\mathbf{d}_{i,wall}\right|}\cdot\left(\left|\mathbf{d}_{i,wall}\right| \le R_i^{out}\right) \end{aligned} \tag{7.3}$$

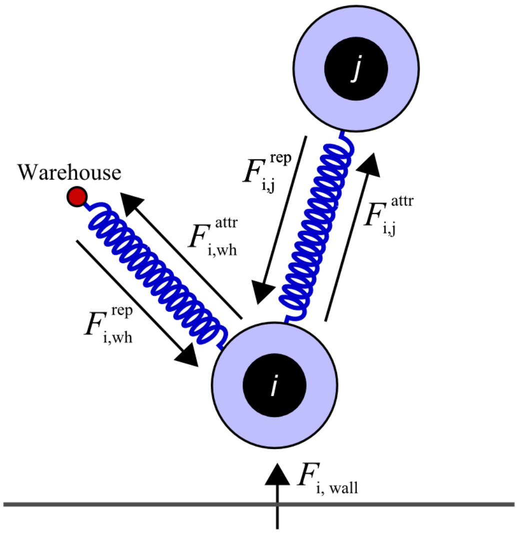


Fig. 7.2 Example of the interaction forces involving the cell i.

A balance of forces is performed for each of the N agents in the model. The inertialess assumption can be made, since the cells can be freely placed and moved into the shop-floor. At the equilibrium configuration, for each cell $\sum \mathbf{F} = 0$. Nevertheless, the balance of forces described above allows to evaluate the distances among cells, but not their position into the shop-floor. Hence, an artificial movement due to drag forces is introduced:

$$\mathbf{F}_i^{drag} = -\nu\dot{\mathbf{x}}_i \tag{7.4}$$

The parameter ν can be set equal to 1. In this way, the balance of forces is given by the following equation:

$$\dot{\mathbf{x}}_i = \sum_{\substack{j=1 \\ j\neq i}}^{N} \mathbf{F}_{ij} + \mathbf{F}_{i,wall}, \quad i = 1,\ldots,N \tag{7.5}$$

This expression must be solved for all the agents that can be freely moved along the plant area; conversely, a given position can be set for the agents that cannot be moved (e.g. the warehouse, or cells with localization constraints).

Table 7.2 Description of the working clusters composing the cellular layout to be optimized.

Cell ID	Cluster	Operations	Avg. process and setup time [s]	Inlet flows	Nr. of machines	Utilization
1	Load A	1; 19	18.00	2	1	0.80
2	Sealant and Lubrication	2; 12	26.00	2	2	0.58
3	Insertion	3; 8; 10	29.00	3	2	0.97
4	Leak test	4	33.00	1	1	0.73
5	Rollover	5	18.00	1	1	0.40
6	Load B	6; 7; 13	21.67	3	2	0.72
7	Press	9; 11; 16	23.00	3	2	0.77
8	Tightening	14; 17	30.50	2	2	0.68
9	Measure	15	33.00	1	1	0.73
10	Marking	18	23.00	1	1	0.51

7.5 Results of the layout optimization

The algorithm shown in the previous Section has been tested to design in a cellular layout a line able to perform the bill of operations presented in Table 7.1.

The ultimate goal of the cellular layout is to have cells composed of flexible machines able to perform operations similar with each other, rather than having heavily focused machines. Hence, the listed operations have been clustered in order to identify cells performing similar tasks: the column "cluster" has been used to group similar operations. The only exception is given by the *Load* cluster: the first and the last operations must be performed close to the warehouse, due to the weight of the part to be loaded; conversely, in operations 6, 7, and 13 lighter parts are managed. Further, since load operations are spread along the sequence, a unique cell placed close to the warehouse would generate a huge quantity of traffic and crossings between vehicles. For this reason, two *Load* cells are considered. In total, 10 working cells have been identified.

The number of machines composing each cell has been evaluated, keeping lower than one the overall utilization of the workstations. To perform this analysis, the current takt time equal to 45 seconds has been kept. The results of this analysis are synthesized in Table 7.2: the 10 cells consist in one or two machines. In the traditional layout, 19 machines are necessary to perform the whole sequence. The first result of the layout reorganization is a reduction of this number: 15 machines are sufficient to keep the process stable.

Given this clusterization, the values for the matrix T, containing the number of travels between each couple of cells can be evaluated. The direction of the travel is not taken into account: the scope of this step is to identify the movement aisles and the intensity of the traffic. The matrix T for this bill of processes is provided below; the first row and the first column are referred to the warehouse. For sake of readability, non-zero values are highlighted with bold fonts.

$$T = \begin{array}{c|ccccccccccc|cc}
 & \multicolumn{11}{c}{\text{Workstation}} & & \\
 & \text{WH} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & & \\
 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \text{WH} & \\
 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & \\
 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 2 & \\
 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 3 & 0 & 0 & 0 & 3 & \\
 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 4 & \\
 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 5 & \text{Workstation} \\
 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 6 & \\
 & 0 & 0 & 1 & 3 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 7 & \\
 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 8 & \\
 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 9 & \\
 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 10 &
\end{array}$$

Then, the dimension of each cell must be evaluated. Each machine has length equal to 4 m and width equal to 1.8 m. The distance between machines in the same workstation is 2.2 m. Hence, the radii of the area occupied by the machines are equal to 2.7 m for single-machine cells and 3.8 m for double-machine cells. The annulus surrounding the cell to support the movement of vehicles is 5 m thick.

The plant is supposed to be square; the length of the edge is 100 m. For sake of simplicity, the coordinates of the point representing the warehouse are (0,0): this point is not moved during the optimization of the layout; conversely, all the working cells can be freely placed in the available area, without further constraints.

The initial position of the agents is evaluated adding cells one-by-one in the area. First, the cell with the highest number of interactions with the warehouse is introduced (in this case, cell number 1). The other cells are introduced one by one in the model: at each step, the cell with the highest number of interactions with the agents already placed in the area is introduced in an iterative way.

Finally, the model can be run. An explicit numerical method has been used to solve the set of Equations 7.5. The model is iterated until the steady state is reached, i.e. the equilibrium configuration is achieved. The equilibrium configuration for the bill of processes used as case study is shown in Figure 7.3. Black circles represent the area occupied by the machines; lilac circles depict the annuli to support vehicles movement. The blue lines represent the traffic directions; the ticker is the line, the more is the traffic on the aisle. Critical crossings involve the aisles 2-6 and 7-3, and the aisles 8-10 and 7-9. In Table 7.3 the final positions for the cells are provided. The algorithm also evaluates the distance to be run by an AGV to transport an item through the process: the estimation is 226 m.

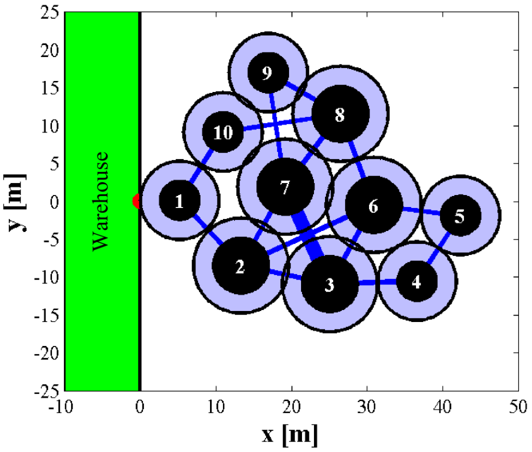


Fig. 7.3 The equilibrium configuration of the workstations for the sequence of operation chosen as case study.

Table 7.3 Equilibrium positions for the working cells.

Cell ID	x [m]	y [m]
1	2.74	1.02
2	10.81	-5.62
3	22.52	-8.12
4	34.06	-9.76
5	39.84	-1.12
6	28.38	2.33
7	16.69	4.77
8	24.01	14.37
9	14.50	17.85
10	8.49	10.04

7.6 Discrete Event Simulation for shop-floor traffic management

The first step of this project was the definition of the manufacturing cells and the identification of their position in order to minimize the *transport* of each item through the process. The second research direction, presented in this Section, is the comparison among different scenarios to evaluate the best way to exploit the AGVs. Two paradigms are compared. In the first, the vehicles are only used to transport items through the workstations; in the second, the vehicles assist an item through the whole process, since it enters the process until it leaves the line, staying idle when the item undergoes manufacturing operations. The choice among these two scenarios, performed during the design stage, can affect the flexibility of the line and its capability in dealing with takt times different with respect to the initial target.

A Discrete Event Simulation approach has been developed to mimic the behavior of the resources involved in the manufacturing process. The simulation has been implemented in FlexSim. However, this is not a restriction: the simulation can be run in any DES environment (such as Tecnomatix Plant Simulation, Arena, AutoMod,. . .). The input of the simulation model are:

1. The position of the working cells, i.e. the output of the model presented in Section 7.4.
2. The number of machines composing each cell.
3. The setup and processing times for each operation. Each machine has to perform different operations (corresponding to different setup and processing times), and the correct one must be performed at the proper stage. Hence, a numeric label is defined for each item; the initial value is equal to one, and it is increased by one unit after performing each operation; for example, an item with label equal to 10 has to experience the operation number 10.
4. The number of AGVs and their performances.
5. The task sequence for each AGV (i.e. the sequence of movements to be performed).
6. The inter-arrival time and variability of the parts entering the process.

A snapshot of the simulation environment is provided in Figure 7.4. The number of machines composing each workstation is graphically represented by the size of the station. The task executers (representing the AGVs) are initially placed in correspondence of the source of items; the dispatcher is in charge of allocating tasks within the vehicles. Different output can be extracted: in the following, performance indicators concerning the cycle time and the work in process are evaluated, the utilization of the machines and the activities performed by the AGVs.

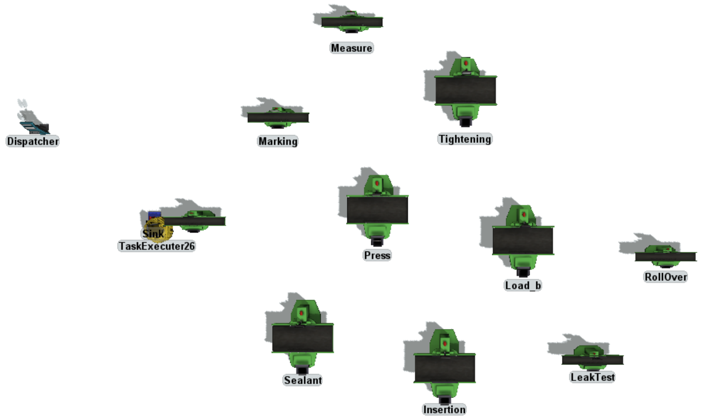


Fig. 7.4 A screenshot of the FlexSim model implemented to evaluate the performance of the AGVs fleet.

Table 7.4 Synthesis of the performance for a system in which AGVs are free to assist any item.

Nr. of AGVs	Nr. of items	Takt time [s]	Efficiency
10	1599	62.54	0.72
11	1723	58.04	0.78
12	1822	54.88	0.82
13	1894	52.80	0.85
14	1933	51.73	0.87
15	1983	50.43	0.89
16	2042	48.97	0.92
17	2104	47.53	0.95
18	2169	46.10	0.98
19	2204	45.37	0.99
20	2205	45.35	0.99
21	2205	45.35	0.99
22	2204	45.37	0.99
23	2204	45.37	0.99
24	2204	45.37	0.99
25	2204	45.37	0.99
26	2204	45.37	0.99

7.7 Results of the simulation

In the first simulated scenario, the vehicles are supposed to be used only to transport items through the workstations. The processing and setup times provided in input to the model are generated according to a uniform distribution, with the mean values in Table 7.1 and interval width equal to 2 seconds. The AGVs have steady state speed equal to 1.2 m/s and acceleration equal to 0.4 m/s^2. The interarrival time is deterministic, equal to 45 s, corresponding to the desired takt time. Simulations have been performed with different sizes for the AGVs fleet. In Table 7.4, a synthesis of the performance measures is provided: the optimal number of vehicles active in the shop-floor is 19. A quantity of AGVs lower than 19 results in efficiency (i.e. the ratio between the effective and the desired cycle time) loss, thus in higher values for the takt time and a lower demand can be satisfied. Conversely, a number of AGVs greater than this value does not lead to efficiency benefits and, as shown in Figure 7.5, idle times (hence, wastes) increase.

It must be underlined that in these simulations the energy level of the batteries has not yet been considered; hence, the fleet size discussed in the following is referred to the number of vehicles able to perform transport.

Given this active fleet size, on average, the time spent by each vehicle is composed as follows:

- the 66% is spent in idle condition, i.e. the AGVs is waiting for an item that needs to be transported;
- the 29% is spent transporting items;

- the remaining 5% is due to empty transport, i.e. transport through different positions performed without items above the vehicle.

The average cycle time is 811 s; the time due to processing and setup is equal to 465 s, hence the 42% of the cycle time is spent in transport and queue. The path traveled by each item is 255 m; a 10% difference results from the layout model, due to the increased detail level provided by DES in describing movements (e.g. AGVs rotations, alignment of machines,. . .).

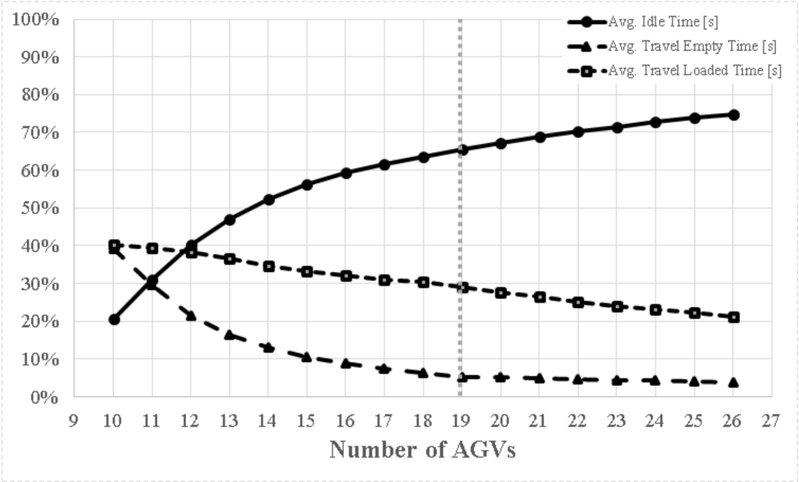


Fig. 7.5 Distribution of average time spent by each AGV in different activities for the first scenario.

In the second simulated scenario, the vehicles have been supposed to assist the same item since it enters the line until it is finished and leaves the process, in a kind of kanban system. Beside the deployment modality, this scenario implies a different AGV technology. In this case, when the item enters the machine, it is not unloaded from the AGV. Thus, on one side, the AGV must sustain the working operation; on the other side, it must have a sufficiently accurate system for positioning into the workstation. A synthesis of performance measures is provided in Table 7.5. The minimum number of AGVs to reach an efficiency equal to 98% – a value considered satisfactory for the system integrator – is equal to 18. The distribution of AGV times is shown in Figure 7.6. The ratio between different classes does not change as the number of vehicles varies, since times are determined by the events experienced by the assisted item. For a fleet size equal to 18, the distribution of times for each task is similar to the previous kind of system: 30% is spent in transport loaded; 5% is spent in empty transport; 65% is waiting. However, a further distinction can be made for the last class. In case of higher fleet sizes, the quantity of AGVs exceeding the optimal value is not used. In this kind of system, the 57% of the time is spent in processing, hence the AGV stands in each workstation for a given amount of time known a-priori.

Table 7.5 Synthesis of the performance for a system in which AGVs are constrained to assist a given item.

Nr. of AGV	Nr. of items	Takt time [s]	Efficiency
10	1298	77.04	0.58
11	1432	69.83	0.64
12	1554	64.35	0.70
13	1647	60.72	0.74
14	1759	56.85	0.79
15	1866	53.59	0.84
16	1971	50.74	0.89
17	2075	48.19	0.93
18	2174	46.00	0.98
19	2259	45.00	1.00
20	2261	45.00	1.00
21	2261	45.00	1.00
22	2261	45.00	1.00
23	2261	45.00	1.00
24	2261	45.00	1.00
25	2261	45.00	1.00
26	2261	45.00	1.00

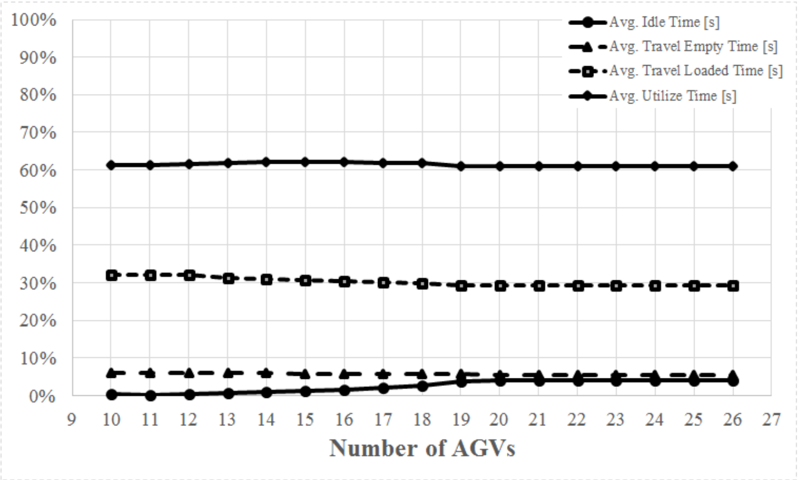


Fig. 7.6 Distribution of average time spent by each AGV in different activities for the second scenario.

The average result, for this fleet size, is similar to the previous system; however, the punctual behavior is different. In the previous system, the vehicle was free to assist different items, hence the time spent in each workstation was not fixed. Here, the waiting time is set (small fluctuations may occur due to process variability); from the AGV perspective, this is a *waiting* waste, since it cannot perform any other activity. A way to better spend this time would be the integration of a charging station into (or close to) the workstations, in order to recharge the batteries, providing the vehicle with the energy to perform a few of the following operations. This would avoid long recovery times requiring the AGV to stay out of the process. This capability can be a useful advantage for the manufacturer.

Nonetheless, the first system seems to be more flexible in case of variable demand. To avoid *overproduction*, the takt time of the line should be adapted to the demand. The AGVs deployment paradigm should be chosen also depending on the resulting flexibility of the system and the required versatility. According to the plot in Figure 7.7, in case of lower demand, the first scenario requires a lower number of active vehicles to achieve a given takt time.

Conversely, lower takt time values can be necessary to satisfy demand peaks. The plot in Figure 7.8 has been obtained by supposing a 10% increase of the demand; thus, the takt time is set equal to $40.5\,s$. In both the cases, the minimum number of AGVs to reach a 98% performance efficacy is equal to 21, hence both the scenarios lead to satisfactory performance. In case higher efficacy is necessary, the second deployment scenario is preferable.

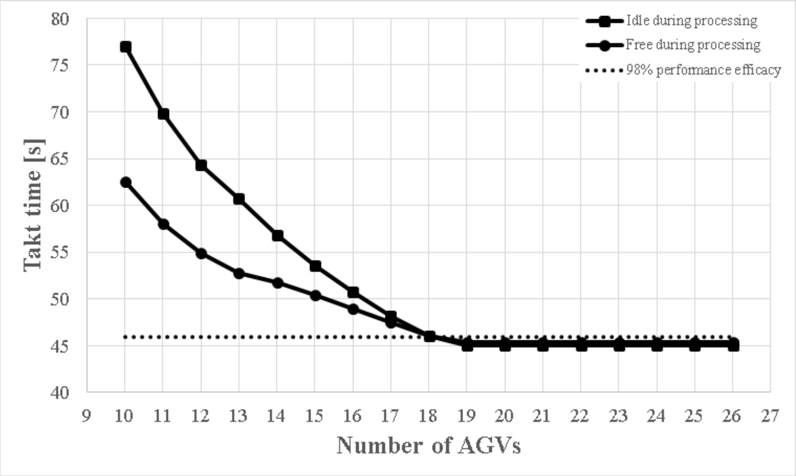


Fig. 7.7 Comparison between the takt times reachable with the two simulated scenarios.

7.8 The role of MES

The simulation tool presented and used in the previous Sections has been deployed to support the definition of a manufacturing process: it allowed to evaluate different scenarios and drive the technological choices of the design department. Nonetheless, the same tool can be used with further aims. First, MES is in charge of planning the production process. Thus the simulation tool can be used to validate a given bill of orders: the bill can be provided in input to the model, which encloses a virtual copy of the shop-

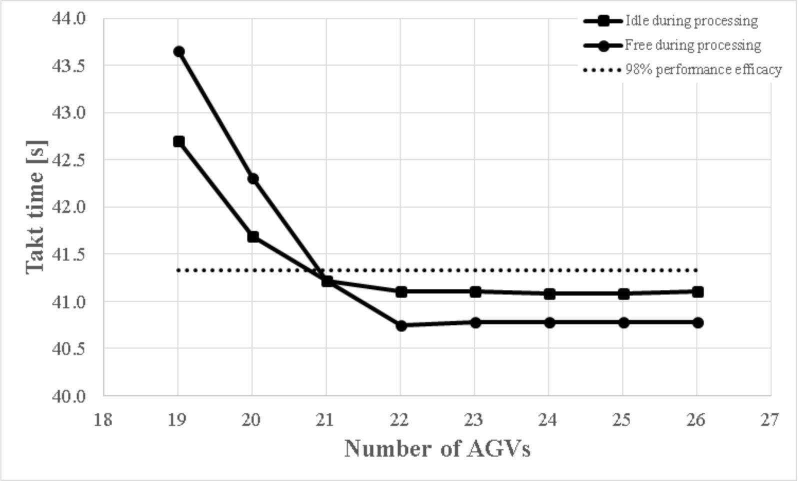


Fig. 7.8 Comparison between the takt times reachable with the two simulated scenarios.

floor. The simulation provides an evaluation of process performance and highlights possible criticalities, such as traffic density or crossings. This output can be used as a feedback for the planning functionality: the production plan can be adjusted before it is introduced, in order to minimize issues due to critical situations. For example, the inter-release time of the items can be manipulated, or signals can be sent to the shuttles to change their speed or run through different paths. This capability may lead to few advantages in case of single-product lines, like the one studied in this Chapter; nonetheless, it can be much more interesting in case different kinds of products are manufactured on the same line. The contemporary coexistence of different bills of process can be a source of issues: in this case, beside the inter-release time, a further degree of freedom to be used for planning purposes is the order at which items are released.

From the bottom-up data-flow perspective, the MES can be enriched with functionalities to take into account, beside the state of the workstations, the condition of the vehicles performing the transport. Two aspects are critical for their performance.

The first one is energy: an accurate evaluation of the current battery level and the amount of energy necessary to perform the following cycle is necessary, to avoid vehicles failing in the middle of a transport. Nonetheless, the energy issue cannot be considered only from the single vehicle perspective. A more general view is necessary: a minimum amount of vehicles must be available to prevent process performance degradation. To avoid getting below this threshold, some vehicles may be required to recharge earlier than due. Hence, the MES managing the shop-floor must also be responsible for the recharge cycle optimization, keeping the average energy level of the vehicles above a threshold.

The second critical aspect is traffic. Crossings should be avoided as much as possible, since they are a possible risk, beside a source of time waste. First, controls must be implemented in the critical points, i.e. the crossings between corridors. For example, areas that can be occupied at most by one vehicle can be identified. Further, tight precedence rules must be defined to solve criticalities, such as the “keep the right” criterion, or a grid of nodes can be used to define a set of paths alternative with each other. The capability of the MES in changing the inter-release times and the speed of the vehicles can support the solution to such criticalities.

7.9 The support to lean manufacturing

The case study presented in this Chapter is a complex process, made of 19 operations, designed to assembly automotive engines, hence high quality parts must be manufactured with tight tolerances. Different sources of waste can affect the performance of the process. Nonetheless, the system integrator is already able to provide a good control system for the workstations, leading to a negligible quantity of defective items. At the current state, the machines exhibit very limited process time variability, thus waiting and inventory through the line are minimized. The main source of waste consists in transport and motion: the study presented in this Chapter aims at minimizing the efforts spent in these two *muda*.

Transport mainly depends on the layout of the line. Reductions in transport cannot be performed during the production, and are hardly difficult to be made onto an already existing line: they require a complete reorganization of the layout, thus huge investments. Hence, the layout of the manufacturing line must be optimized a-priori, in the design stage. For this reason, the algorithm shown in Section 7.4 has been developed. The technique has been used to design a single-product line, but is general enough to deal with multi-product lines. In the latter case, the matrix of travels is given by the sum of the matrices corresponding to each product, weighted by the planned production mix.

Conversely, *motion* is tied to the management of the vehicles. In the performed simulations, when an item needs to be transported the closest AGV is chosen, in order to reduce motion. Nonetheless, even in this case a global overview is necessary. The “item” perspective allows to minimize the motion related to the specific workpiece; nonetheless, a solution optimal for a single item can lead to worse performance for other parts. Hence, the MES has to perform a global optimization, considering the whole process and taking into account the short-term performance as well as the medium and long term ones.

7.10 Conclusions

In this Chapter, different techniques to support the (re-)design of a manufacturing line have been provided. The case study consists in a line for automotive engine assembly. The currently deployed conveyor system provides rigid constraints: it enables items to perform only a given path through the workstations, and its speed is tuned to achieve the target takt time. The system cannot efficiently deal with neither higher nor lower demand; in the latter case, the only solution is to switch off the line for a given period.

To improve the flexibility of the line, the deployment of a fleet of AGVs in place of the conveyors is at study: nevertheless, this is not a mere change in the transportation system, but a radical innovation in the production paradigm.

The first research effort has been performed in the evaluation of the optimal cellular layout for this manufacturing process. A topological simplification has been made since circular cells have been considered. In further research, the real shape and size of the cells should be considered. Further, the supply of components to the workstations has not been addressed and should be introduced in further work: it can be modeled as a set of further springs linking the cells with the warehouse. Another simplification was made for the warehouse: it was considered as a punctual entity; a more reliable representation can be obtained by modeling it as a set of multiple points, each of them responsible for supplying a subset of cells.

The second research theme was the implementation of a discrete event simulation model to evaluate the events taking place in the shop-floor. Further functionalities should be implemented in the model. First of all, a library of functions to take into account the energy level of the vehicles batteries is necessary, to best plan strategies and dispatch – even in real-time – the shop-floor activities. Further, more complex rules should be implemented to manage precedences and avoid collisions.

Note The work presented in this Chapter has been developed in cooperation with dr. Andrea Ascheri, Apprentice Ph.D. Candidate in Production Systems and Industrial Design in COMAU.

Chapter 8
Conclusions

Abstract In the previous Chapters, four case studies have been presented to support the research hypotheses and provide evidence that the work methodology is general enough to be used in different manufacturing fields. Nonetheless, the research cannot be considered as concluded. In this Chapter, hints for future developments arisen during this work are presented, and an overall picture for the next research towards the factory of the future are discussed.

8.1 Introduction

The aim of this research work was the definition of a methodology to enable the development of MES-oriented tools and support the path towards lean manufacturing. A methodology was defined before starting the applicative work. Four case studies were presented to validate the methodology and provide evidence that it is general enough to be used in different manufacturing fields, including machining, warehousing, and logistics. This, in turn, enabled to investigate whether MES is a tool useful to support the implementation of lean practices as well as to evaluate in which fields it is useful or not. In the following, a summary of the case studies developed in the previous Chapters is provided. In Section 8.3, conclusive remarks are discussed. Nonetheless, the present research cannot be considered as concluded: several hints for future developments arose during this work; they are discussed in Section 8.4; further suggestions for future vision are provided in Section 8.5.

8.2 Summary of the work

Traditional manufacturing: automatic workpiece positioning

In Chapter 4, a monitoring and control system developed to automatically perform the positioning of a spur gear into a finishing machine has been presented. In this process, aeronautic components are produced, hence tight tolerances are requested. The quality of the manufactured parts must be very high; consequences of poor parts may be dramatic.

In the process used as case study, the workpiece was manually centered into the machine. This led to a high rate of *defects*, since the operators were not able to perform an optimal positioning. The replacement of this procedure with an automatic monitoring and control system allowed to improve the precision and the reproducibility of gear positioning into the machine, leading to higher overall quality and reduced reworking operations. MES allows to analyze data over the medium-long term, to ensure process stability and to identify further sources of issues and wastes. Moreover, the automation of this task also enables to reduce *waiting* and *inventory* resulting from the variability of manual operations. The benefits of cooperation between MES and PLM have also been discussed. Their integration allows to dispatch shop-floor information towards design tools: this feedback information mechanism can support continuous improvement practices, enhancing the performance of the production process and the quality of the manufactured parts.

Additive manufacturing: surface quality monitoring

In Chapter 5, a technique to monitor the surface quality of a part produced through the additive technology has been shown. The process at stake exhibited *defects*, hence a mathematical technique has been developed to provide an alarm as soon as a criticality arises. This study was presented in the form of proof of concept since, at the state of the art, there is no availability for smart sensors capable to be integrated into the building chamber and monitor the process without interfering with the machine. Nonetheless, laboratory tests and simulations have been performed and the capabilities of both detecting surface defects and evaluating adherence to the expected output have been successfully validated. Also in this case, the integration of monitoring techniques into MES enables the early identification of issues and criticalities. Moreover, MES provides support to DFAM: the performed analyses can result in new knowledge for further improvement of both the design of a product and its production process.

Warehousing: management of resources and items

In Chapter 6, techniques to evaluate the performance of warehouses equipped with AVS/RS have been developed. The analytical tools existing at the state of the art exhibit a non-negligible drawback: they do not consider the criterion used to store and retrieve items from the rack, although this is a significant factor affecting the performance of the warehouse. Hence, a mathematical technique, based on probabilistic reasonings, has been developed to enrich the analysis by taking into account this factor. This model provides information about an average behavior of the system. However, more detailed information may be necessary, both from the points of view of the stored unit or the resources involved in the system. Therefore, a simulation tool able to evaluate the reaction of the system in front of a multitude of scenarios has also been developed: it is capable of testing different management criteria and to choose the one resulting in the best performance.

The deployment of these tools allows to reduce the impact of useless *transport* of items and avoidable *motion* of the vehicles; their integration into a MES allows to perform short, medium and long term optimizations, based on the past experience as well as on the tasks planned to be performed in the future. This, in turn, enables improved reactivity of the system leading to lower *waiting* times for items needing to enter or leave the warehouse and lower *inventory*.

Logistics: transport of items through workstations

In Chapter 7, the case study of a manufacturing process to be redesigned was presented. It was provided by a system integrator that designs and produces manufacturing lines. The industrial partner is willing to introduce a radical innovation into its lines: it aims at eliminating traditional conveyors and perform the transport of items through the line by AGVs. Nonetheless, this switch is not trivial, and deep analyses must be performed; hence, tools have been developed for the best integration of AGVs into the manufacturing process and minimize *motion* and *transport*.

First, the introduction of AGVs in the process removes the constraints that determine the current layout shapes, and enables infinitely many possibilities for new solutions. Thus, an algorithm to identify the best cellular workstations layout has been developed. Second, there are several ways to assign tasks to the vehicles and exploit the resulting benefits. Hence, simulation tools have been used to test different deployment scenarios, compare different technologies and evaluate their impact. These tools have been designed to support the design phase; nonetheless, the simulation model is a flexible tool and its deployment area can be extended to further purposes. It can be integrated into a MES and used even after the physical realization of the AGVs into the manufacturing line. The monitoring of vehicles activities is the input for the simulation, which can be used to evaluate future scenarios based on the current picture. This enables improved reactivity of the whole system and better exploitation of the flexibility provided by the vehicles.

8.3 Conclusive remarks

The results obtained in the case studies described above enable to state the following conclusions.

1. **The approach is validated**. The results obtained from the four case studies provide evidence that the deployment of information-based techniques enables to develop adaptive strategies for waste reduction and achievement of lean manufacturing.
   In the last few years, we assisted to an outstanding proliferation of relatively inexpensive and very smart sensors. This phenomenon strongly impacted also our daily life: smart devices are spreading at a high pace. The diffusion of sensors in manufacturing is also taking place in manufacturing, both within companies and throughout the supply chain. This technological evolution must be supported by appropriate applications, able to deal with the generated quantity of data: the key challenge is to understand and exploit their value.

MES is the platform in charge of collecting and analyze such data, and dispatch the right information at the right system, at the right time. Due to this primary role, the implementation of smart, responsive MES is mandatory; the only way to reach this result is the integration of powerful analytics. The analyses performed by the MES can foster the definition of strategies for process improvement leading to enhanced overall performance and reduced wastes; hence, MES is a powerful tool in supporting the path towards lean manufacturing.

2. **The approach is independent of the case study**. The three-steps methodology presented in Chapter 3 was an effective tool to successfully deal with the case studies studied in this work.
   The definitions for the classes of waste and for the kind of parts cooperating into a process are general enough to be used in different manufacturing technologies, as well as in services supporting the manufacturing operations. Despite this generality, they are accurate enough to provide a detailed description and deeply understand the process to be studied. The same conclusion can be stated for the list of steps supporting the design of an effective data analysis technique.
   The schematic presented in Figure 3.1 was an effective tool to develop the research work. It allows to point out the problem and identify the solution strategy by answering questions in the logical order *Why – What – How*, hence starting from an overall perspective and driving the user to a higher level of detail. The compactness of the schematic is another advantage: it allows to keep a global view of the problem in a single sheet, thus enabling the practitioner to immediately identify inconsistencies or information lacks.
3. **The approach is independent of the solving techniques**. The five steps defined to perform data-analysis have a general significance; nonetheless, their implementation must be focused on the specific case study and on the sources of waste affecting it and the desired output. In the presented case studies, different kind of data have been analyzed and different analysis techniques have been used, such as statistical analyses, probabilistic reasoning, simulations.
4. **The data-oriented approach goes beyond tight departments**. The definition of MES relies on its vertical integration with the business level and the shop floor. One of the aims of this work was the smart integration of MES with further information tools, such as design tools. Frameworks for the integration of MES with PLM and DFAM have been presented; the cooperation among such systems can enhance the integration of product and process engineering. Given this integration, data collected by the same source can be used with different purposes, with different scales of application. Nonetheless, the techniques implemented into the MES must be smart enough to extract information with the right level of detail necessary for each interlocutor.

8.4 Future work

Additive manufacturing: surface quality monitoring

At the state of the art, additive technology is experiencing a disruptive growth and is providing new paradigms in manufacturing and unprecedented design freedom. Nonetheless, this technology is not yet totally under control: there exist phenomena occurring during the process, at low time and space scales, that are not fully understood. Hence, systems for process monitoring and control would be appreciated to improve the control on the process and, in turn, its performance. The quality of the produced parts would also be enhanced. Nonetheless, a technological lack is slowing the development of these systems. A new generation of smart sensors able to detect such phenomena without interfering with the building process is required. The development of monitoring and control systems devoted to additive technologies would be much higher for applications in high value added market niches, such as aeronautics, biomedical devices or high performance products. Thus, one research direction for the next future is the development of new technologies and framework for better monitoring and control these systems.

Warehousing: management of resources and items

Two lacks have been identified in dealing with this work. The first one concerns the absence of proper standards and methods for performance evaluation. Hence, techniques able to define standard methods to evaluate the performance of a warehouse equipped with a AVS/RS system must be identified. The second lack is the absence of systems to real-time control the events taking place in the warehouse. At the state of the art, criteria for managing resources are implemented into the software governing the system. Nonetheless, this is a rigid approach that may provide non-optimal solutions in case the operating conditions are different from the ones hypothesized by the designer. Hence, flexible tools should be implemented, able to compare in real-time the performance resulting by the application of different criteria and to choose the best one. Future work should be aimed in solving these issues.

Logistics: transport of items through workstations

Even in this case, the need for tools supporting the flexible implementation of management criteria is necessary. The case study chosen to proof the concept is in the field of automotive powertrain assembly, thus a quite rigid manufacturing process. The flexibility provided by automated vehicles performing items transport through the shop floor is enhanced in case multiple products are manufactured on the same line. Given a target output (e.g. a quantity of demanded items per each kind of product), there exist a huge number of combinations to schedule the production, and the one minimizing wastes and risks (such as traffic and crossings) should be chosen. This is a scheduling problem typically faced by the MES; nonetheless, actually there are no techniques to perform this task considering traffic issues. Similarly, another factor that can play a significant role in traffic management is variability. Usually, variability is a source of waste; nonetheless, hastening or delaying the release of an item into the process may be useful to avoid crossings with other vehicles.

8.5 Vision for the Factory of the Future

The development of information technology drove the third industrial revolution, and the pace at which IT solutions are pervading manufacturing is still increasing. The next industrial revolution, based on Cyber Physical Systems (CPS), cannot disregard IT tools: they must support manufacturers to improve: (i) product quality and robustness of production processes; (ii) speed and time with regard to innovations, lead times and start-up of production plants; (iii) competitive production costs. Further, the deployed IT tools must be adaptive to a wide variety of product variants, be able to act online and provide visibility of a compound of plants or organizations, rather than a single location (Rabbani et al., 2013). Beside this, the information tools for supporting the development of Factory of the Future must be able to comply with the following keywords.

Distributed

This term can be used to characterize future factories on different scales.

From a high-level perspective, a company may have different shop-floors distributed on different geographical areas. This kind of distribution already occurred with mass production, in order to reduce the impact of finished items transport. Nonetheless, future factories will be much more distributed than today. The paradigm of *mini-factories* is emerging (Cluster Fabbrica Intelligente, 2015): the production of custom components is postponed until the "last mile" and carried out near to or at the place of delivery. This innovation requires new organizational models based on: (i) hubs for the production of standardized components; (ii) decentralized mini-factories, equipped with state-of-the-art machinery to support the aesthetic and functional personalization of the product quickly and cheaply, in order to guarantee companies the opportunity to differentiate their product by adding value to it.

The use of advanced, highly reconfigurable technologies able to adapt to the specific context is strategic for the implementation of this model. The deployment of additive technologies, which is already growing at a high pace, can support this paradigm. Additive machines are characterized by limited impact: they do not emit smoke or gas, and produce a low quantity of scraps (typically, only the support material). Further, noise is reduced and the room necessary to host a machine is usually limited. These advantages enable unprecedented freedom in machines allocation, and the deployment of several, smaller shop-floors distributed over the target markets can become economically convenient. This distribution would enhance the competitiveness and the reactivity of a company: transport time and cost are reduced, as well as the lead time for the customer.

In this perspective, an advanced concept has been developed by Amazon (2015): a solution was patented for installing additive machines on a truck to perform, at the same time, product manufacturing and delivery. A customer may order an item through the electronic market; then the delivery truck to be used is chosen by optimizing a set of criteria, such as the time necessary for part production and the time to reach the customer from its actual position. The truck receives the manufacturing instructions from a central library in which all the information concerning each item on sale is contained.

Another promising concept concerning the market of replacement parts has been patented by Boeing (2015). Actually, when a replacement part is desired, a customer requires it to the aircraft manufacturer, which should maintain an inventory to satisfy the demand in short times. Nonetheless, the delivery can take an excessive amount of time for the customer, which may keep an inventory of parts on hand to avoid waiting for delivery from the manufacturer. However, this storage can require a huge amount of resources. The deployment of additive technology can strongly support the effectiveness of the market of replacement parts. The patented concept concerns a system to uncouple the management of the inventory and the storage of replacement parts: the manufacturer maintains a library containing all the information necessary to produce each part. When a customer needs a part, he requires the corresponding file to the manufacturer and performs, by himself, the production of the part through an additive machine.

From a low-level perspective, even workstations into the shop-floor can be distributed. Recent technologies, such as the AGVs, already allow to replace rigid transport systems like conveyors. This change enables a huge variety of innovations in term of layout design, as shown in Chapter 7. However, a rigid classification for the times that an item spends in the shop-floor still exists: it is made of processing, transport and waiting. The last two classes do not add value to the product, hence must be minimized; a technological effort is necessary to transform them into productive times. One way to explore this research direction is to transform the transportation means (e.g. the AGVs) into equipped workbenches able to move and to perform at least some elementary operations at the same time; as a consequence, workstations would be used only to perform complex tasks. Such innovation can lead to a further distribution of the process: manufacturing operations would take place throughout the whole shop-floor – even in places where there are no machines – rather than in pre-determined points.

To exploit this direction, technological efforts are necessary to physically develop innovative solutions. Nonetheless, their exploitation goes hand in hand with the contribution of optimization techniques for operations management and execution. On one side, the distribution of working areas, both at the high and the low level, enables to redesign and reduce transport of physical entities. On the other side, the transport of data and information increases, and the availability of well-structured, high-performance information tools can boost the innovation in this direction; their importance increases with the complexity of the system, in order to efficiently perform the requested tasks. In this regard, MES as a platform for data transformation and sharing has a strategic role.

Virtualized

The upcoming forth industrial revolution is triggered by the Internet, which makes feasible disruptive scenarios in communication. It concerns the deployment of CPS, that allow the integration of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and viceversa (Lee, 2008). The interaction between the controller and the physical process is performed through a set of sensors and controllers. CPS can regard machines as well as storage systems or production facilities.

In order to best exploit CPS, two complementary and parallel approaches must be undertaken: cyberizing the physical and physicalizing the cyber (Reiner, 2014). The first step to undertake this research direction is the creation of a virtual copy of all the elements of the physical factory. Then, simulation models must be implemented to transform the static models towards dynamic systems; the full virtual factory should represent both the logical schemas and the behavior of real manufacturing systems.

For long time, the virtual representation has been mainly restricted to design purposes: Virtual Models (VM) for the factory were created before the implementation of the real factory to better explore different design options, evaluate their performance and virtually commission the automation systems. This approach enables to reduce the time-to-production. Nonetheless, virtual models can also be maintained and deployed throughout the whole lifetime of the production: they are an effective connection with the shop-floor and allow to exploit CPS. The integration of VM into CPS enables the fusion of virtual and physical worlds: virtual models can be fed with real data and simulate future scenarios without the need to input data manually (Westkämper and Jendoub, 2003). Complex and composite scenarios can be tested, even in real time, to evaluate their impact on the production system and take corrective actions to adapt the process and achieve the best performance. On the other hand, the evolution of the real factory must be stored in the virtual models to maintain them effective.

To fully exploit CPS, appropriate simulation tools are necessary. Today, the simulation environments for production processes are mainly used as stand-alone methods, using simplified representations of the process based on estimated data. Such simulations are mainly used to support design and for offline (re-)configuration of the production system. The functionalities of simulation tools must be extended to achieve an integrated platform able to support the optimal management of the production process throughout the entire life cycle; simulations must support closed-circuit online optimization and must be connected with CPS and the related automation for process reconfiguration (EFFRA, 2013).

Beside company resources, products, processed materials, systems, must be treated in the same way. Physical products should be transformed in uniquely identifiable information carriers, which may be whenever located to know their history, current status and alternative routes to achieve their target state.

Factory virtualization relies on data exchange between the real and the virtual realization of the factory. An effective MES implementation is strategic to efficiently perform data collection and analysis, and the appropriate information dispatching. MES is in charge of a fundamental role in the connection between the virtual and the real realizations of a process. By performing data collection and analysis, it enables the information exchange that promotes "cyberizing the physical and physicalizing the cyber".

Integrated

The term *integrated* can be analyzed from different perspectives too.

First, integration among information tools is necessary for the configuration of production systems. The design and the management of a production system involve a huge variety of skills, tools and responsibilities, and increasingly require the support of software tools implementing design and evaluation methods. In many cases, these software tools work separately, thus the efficiency of information exchange is reduced and the risk for errors or incomplete information is increased. Further, the implementation of integrated methodologies for management or configuration is not feasible. Hence, the availability of a platform supporting interoperability between various tools would be significantly appreciated. The first step towards this direction is, necessarily, a shared representation of the production system, which is continuously updated and consolidated both in the design and management phases to ensure overall coherence of the results.

A deeper integration must also be pursued within departments and plants belonging to the same company, spread in different geographical areas. The interaction between information tools and the development of virtual models enables operators and technicians physically far with each other to successfully cooperate, for example, to jointly design a product, or act on a given process to check its health state and take decisions aiming at problem solving and performance improvement. Also, the interaction between machines and humans can benefit by mobile devices and interaction devices: production and enterprise specific information can be transmitted regardless of their geographical location and adapted to the context and the specific skills or responsibilities.

The virtualization of factory environments also promotes a tighter integration among all the entities taking part in the value chain of a product: each of them can be enabled to access information concerning any stage of the path from the raw material to the finished product, and adapt its own process to the operating condition of the other companies. Further, in collaborative networks, suppliers and OEMs will be also able to sell their products as services; for example, remote service management helps to improve equipment uptime, reduce costs for servicing (e.g. travel costs), increase service efficiency (e.g. first-visit-fix-rates) and accelerate innovation processes (e.g. through remote update of device software). Further, customers may be involved in the value chain of a product: information can be extracted after sale; this information can be used to develop customized solutions for future products. The increased integration also supports the development of innovative, inclusive business models (Cluster Fabbrica Intelligente, 2015; EFFRA, 2013; IEC, 2015).

A successful integration, for each of the described levels, requires effective and reliable exchange of data and information. Thus, MES has a primary role in supporting integration.

Mindful

One of the basic concepts for the definition of a smart factory is the capability in measuring data concerning the current state of the process, in real-time sensing instability conditions and in reacting instantaneously, guided by automated systems. This kind of decision making mimics human reactions (Chui et al., 2010). Innovative IT tools must support increased autonomy of the machinery in the usage phase, in terms of both maintenance and optimization of the process parameters; this enhances profitable production of mass customized and highly personalized products, as well as faster reactions to shifts of market demands.

There are two ways to undertake this path. The most deployed strategy is the identification of local optima, i.e. solutions that are optimal over short time terms or for a specific machine. An alternative, more complex strategy is the identification of global optima, i.e. the evaluation of solutions able to solve an issue or to improve the overall process performance on a longer time horizon.

The next generation information tools must be provided with "mindfulness" capabilities, and must be able to evaluate the impact of their actions. Intelligent systems based on mechanisms for condition prediction, estimation of remaining useful life, and self-learning capabilities will lead to increased reliability, availability and safety in the entire production system. For example, maintenance will be increasingly planned before the failure occurs, and when its impact is at a minimum. Therefore, predictive data analytics techniques should be developed and integrated into the MES to aggregate and process the massive amount of data captured on the shopfloor: complex event processing techniques for cause-effect and trend analysis are required to provide the decision-makers with a holistic overview of the process. The way in which information is spread is even more important: the right amount of information must be transmitted to the right person/department at the right time.

8.5.1 The role of the human

Smart software provide manufacturing companies with the potential to reshape their industries, increasing the productivity of engineers and plant operators, and generating more efficient manufacturing processes. These applications require high skilled workers. Thus, the diffusion of IT based applications in manufacturing environments will generate more knowledge-intensive jobs and will require more knowledge workers to perform them. Three main aspects need to be addressed to define the role of humans in future factories (EFFRA, 2013):

- how people will work and learn;
- how people will interact with technology;
- how people can add value to manufacturing.

In this work, the attention was focused on the transformation of Data into Information. The next step to be addressed, according to the DIKW paradigm (Ackoff, 1989), is Knowledge: information must be appropriately treated, understood and utilized by workers, at all levels, in the manufacturing processes throughout the whole value chain. To comply with this capability, efficient learning processes are required, based on the adequate use of information models and storing mechanisms. IT solutions can also be useful for workforce training, to support the transfer of best practices to workers at the shop floor (for example, aiming to improve efficiency, productivity and reliability, or to prevent job risks). Such models and tools should support knowledge creation and learning at all levels (strategic, tactic, operation) for the entire product and factory life cycle. Another deployment area of IT is the creation of multimedia technical documentation, to support exchanges between OEMs and companies, concerning learning, deployment and recovery practices. Skilled experts are necessary both for developing the software, to implement the applications at manufacturing sites, and to deploy them in a production environment. Hence, on the one hand the level of competences required to work in manufacturing is increasing, as well as the role of human brain. On the other side, education will play a strategic role: the spread of automation will decrease the impact of labor cost on the final product price and on the overall competitiveness of a company; hence, manufacturers will be more interested in setting up units where an adequate level of education is available. This aspect can be crucial for companies reshoring.

IT systems can introduce new relations between human and the factory resources. In the past, such relations were static: a manufacturing schedule was created according to a business plan, and the necessary workforce was assembled. Workers were used to plan their life according to the manufacturing schedule, sacrificing their personal schedules and sometimes their health. Company productivity was limited by the degree to which workers could unite their minds with the factory (IEC, 2015). Future human-factory relations will become more dynamic through the use of advanced IT tools: robots can be used to improve the ergonomics in production, and automated machines can replace manpower in performing intensive, repetitive, low value added tasks; this enables workers to focus on knowledge-intensive activities. A broader interaction between humans and machines will be required to achieve manufacturing objectives. Today, static approaches are mainly deployed: on the shop-floor, some tasks are in charge of human operators; other ones are performed by automated machines or robots. Conversely, more dynamical models must be developed, together with techniques for a safe physical interaction between humans and machines. Dynamically changing systems can also adapt to temporary changes or limitations due, for example, to inexperience or inappropriate skills of an operator. The human-machine interaction may occur physically, as well as virtually: the increasing deployment of virtual models allows operators to interact with machines even from remote positions, and take decisions and actions to adjust the process.

Therefore, the way in which human can add value to manufacturing is not any more limited to providing mechanical energy to the process. The image in Figure 8.1 provides a good synthesis about the importance of human in manufacturing: his knowledge and intelligence will play a key role in the development of intelligent processes and factories (Cluster Fabbrica Intelligente, 2015; EFFRA, 2013).

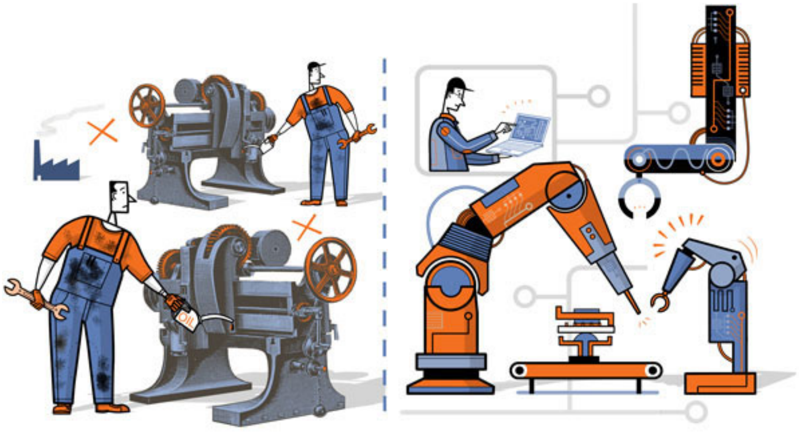


Fig. 8.1 The role of human in future factories. Picture taken from The Economist.

Appendix A

Automated warehouses: results of the simulations

In the first part of this Appendix, full lists of the operations performed during some example cycles are provided to show the generality of the analytical models presented in Section 6.4. Then, graphical representations are provided for the content of the rack at the end of the simulations described in Section 6.7. Different criteria for UL storage and retrieval have been compared: they are synthesized in the table below. Further, the reaction to two scenarios have been simulated: the first one represent a steady-state situation, in which the number of stored and retrieved ULs is similar; the second one mimics a stressful situation, in which 50 items have to be stored as soon as possible.

In the Figures, different colors represent different `ItemLots`; further, the ID of the item is provided. IDs lower than 300 are assigned to ULs already in the rack at the beginning of the simulation; ULs with an IDs greater than 300 are stored during the simulation

Table A.1 The criteria used in the simulations to identify the best UL position for storage and retrieval in the rack.

Simulation Nr.	Rack criteria		Stored ULs	Retrieved ULs
	Storage	Retrieval		
1	Closest Level Lot	Closest Level	300	284
2	Closest Channel Lot	Closest Channel	300	284
3	Closest Level	Closest Level	300	284
4	Closest Level Lot	Oldest	300	284
5	Closest Channel Lot	Oldest	300	284
6	Closest Level	Oldest	300	284
7	Closest Level Lot	None	50	–
8	Closest Channel Lot	None	50	–
9	Closest Level	None	50	–

Table A.2 Time necessary to perform a cycle for 1 storage (or 1 retrieval) with a system comprising 1 lift, 1 shuttle and 1 satellite.

Movement	Duration
Lift: from bay to avg. floor	y_M
Shuttle: from lift to avg. channel	x_M
Satellite: travel through the channel	z_M
Satellite: travel through the channel	z_M
Shuttle: from avg. channel to lift	x_M
Lift: from avg. floor to bay	y_M
Total time spent:	$2y_M + 2z_M + 2x_M$

Parameters	Value
I	1
T	0
Result from model 6.4	$2y_M + 2z_M + 2x_M$

Table A.3 Time necessary to perform a cycle for 1 storage and 1 retrieval with a system comprising 1 lift, 1 shuttle and 1 satellite.

Movement	Duration
Lift: from bay to avg. floor	y_M
Shuttle: from lift to avg. channel	x_M
Satellite: travel through the channel	z_M
Satellite: travel through the channel	z_M
Shuttle: move through the aisle	δx
Satellite: travel through the channel	z_M
Satellite: travel through the channel	z_M
Shuttle: from avg. channel to lift	x_M
Lift: from avg. floor to bay	y_M
Total time spent:	$2y_M + 4z_M + 2x_M + \delta x$

Parameters	Value
I	2
T	1
Result from model 6.4	$2y_M + 4z_M + 2x_M + \delta x$

Table A.4 Time necessary to perform a cycle for 2 storages (or 2 retrievals) with a system comprising 1 lift, 1 shuttle and 1 satellite, with the capability of uncoupling the movements of the shuttle and the satellite.

Movement	Duration
Lift: from bay to avg. floor	y_M
Shuttle: from lift to avg. channel	x_M
Shuttle and satellite work in parallel	S_{xz}
Shuttle: move through the aisle	δx
Satellite: travel through the channel	z_M
Satellite: travel through the channel	z_M
Shuttle: from avg. channel to lift	x_M
Lift: from avg. floor to bay	y_M
Total time spent:	$2y_M + 2z_M + 2x_M + \delta x + S_{xz}$

Parameters	Value
I	2
T	0
S	1
Result from model 6.5	$2y_M + 2z_M + 2x_M + \delta x + S_{xz}$

Table A.5 Time necessary to perform a cycle for 2 storages and 2 retrievals with a system comprising 1 lift, 1 shuttle and 1 satellite, with the capability of uncoupling the movements of the shuttle and the satellite.

Movement	Duration
Lift: from bay to avg. floor	y_M
Shuttle: from lift to avg. channel	x_M
Shuttle and satellite work in parallel	S_{xz}
Shuttle: move through the aisle	δx
Satellite: travel through the channel	z_M
Satellite: travel through the channel	z_M
Shuttle: move through the aisle	δx
Satellite: travel through the channel	z_M
Satellite: travel through the channel	z_M
Shuttle: from avg. channel to lift	x_M
Lift: from avg. floor to bay	y_M
Total time spent:	$2y_M + 4z_M + 2x_M + 2\delta x + S_{xz}$

Parameters	Value
I	3
T	1
S	1
Result from model 6.5	$2y_M + 4z_M + 2x_M + 2\delta x + S_{xz}$

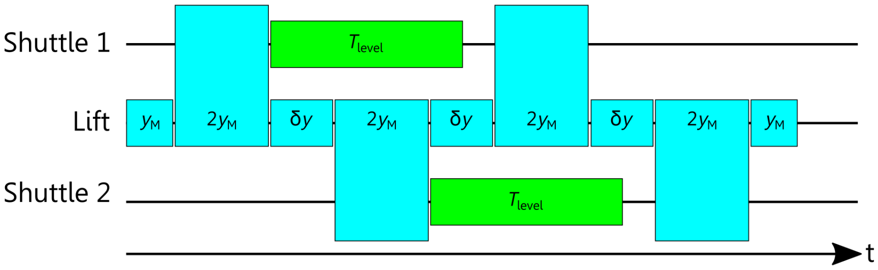


Fig. A.1 Graphical representation for a system comprising one lift and two shuttles, in case the lift is the bottleneck (Eq. 6.8).

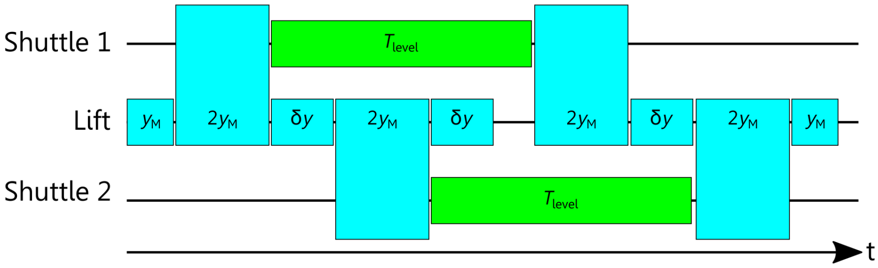


Fig. A.2 Graphical representation for a system comprising one lift and two shuttles, in case the shuttle is the bottleneck (Eq. 6.8).

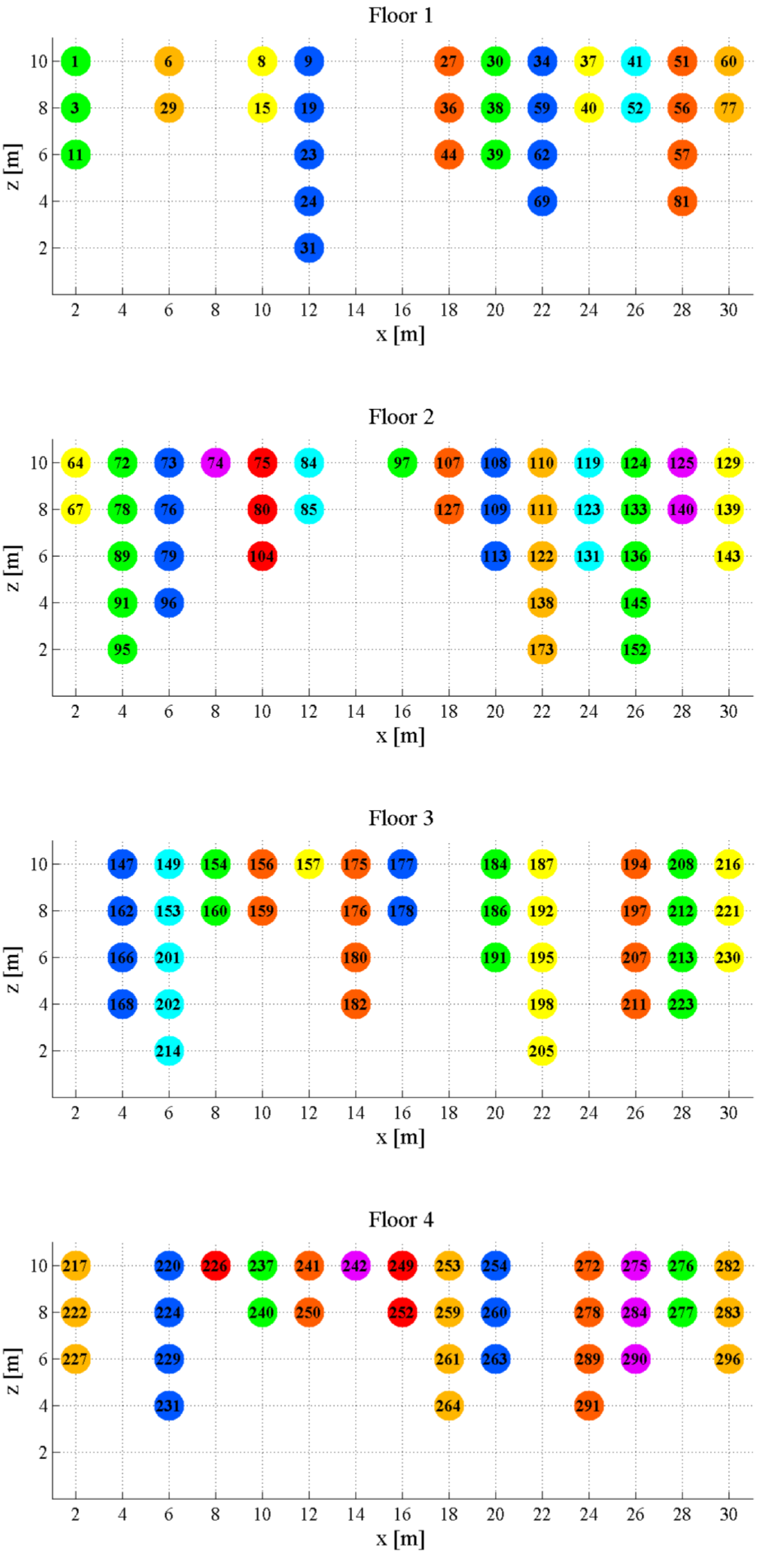


Fig. A.3 Content of the rack at the beginning of the simulation.

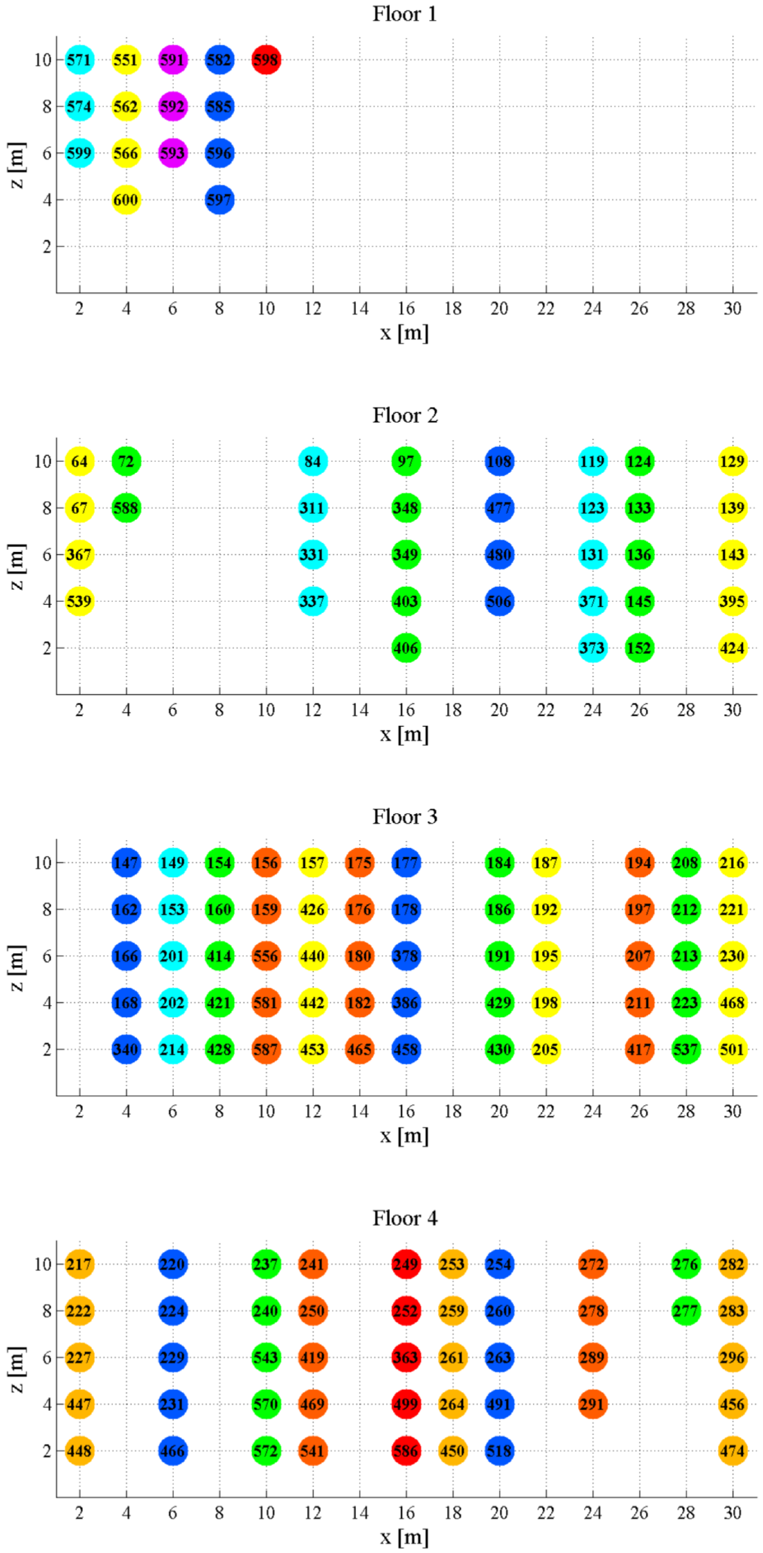


Fig. A.4 Content of the rack at the end of simulation nr. 1. Different colors denote different item lots.

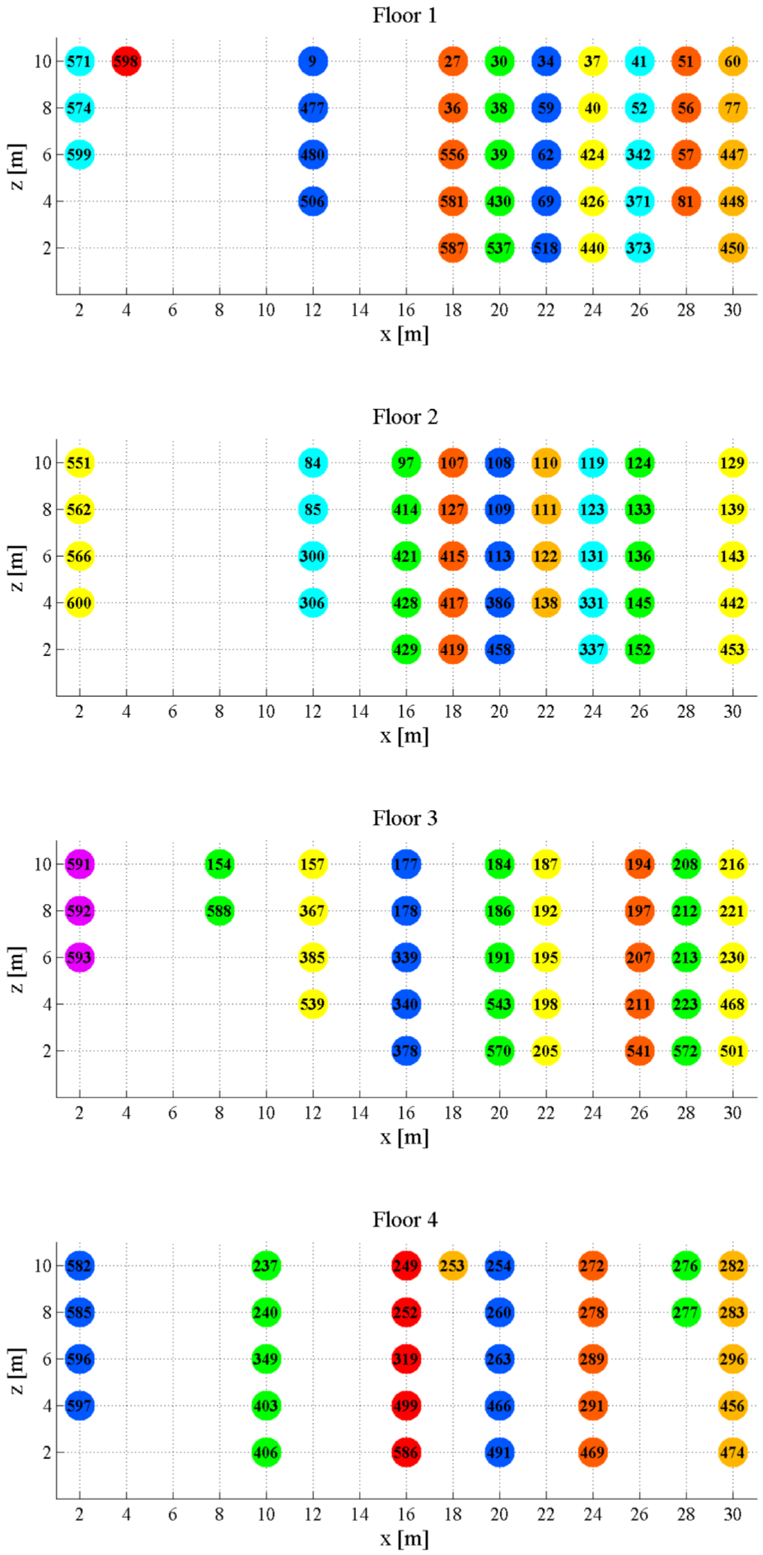


Fig. A.5 Content of the rack at the end of simulation nr. 2. Different colors denote different item lots.

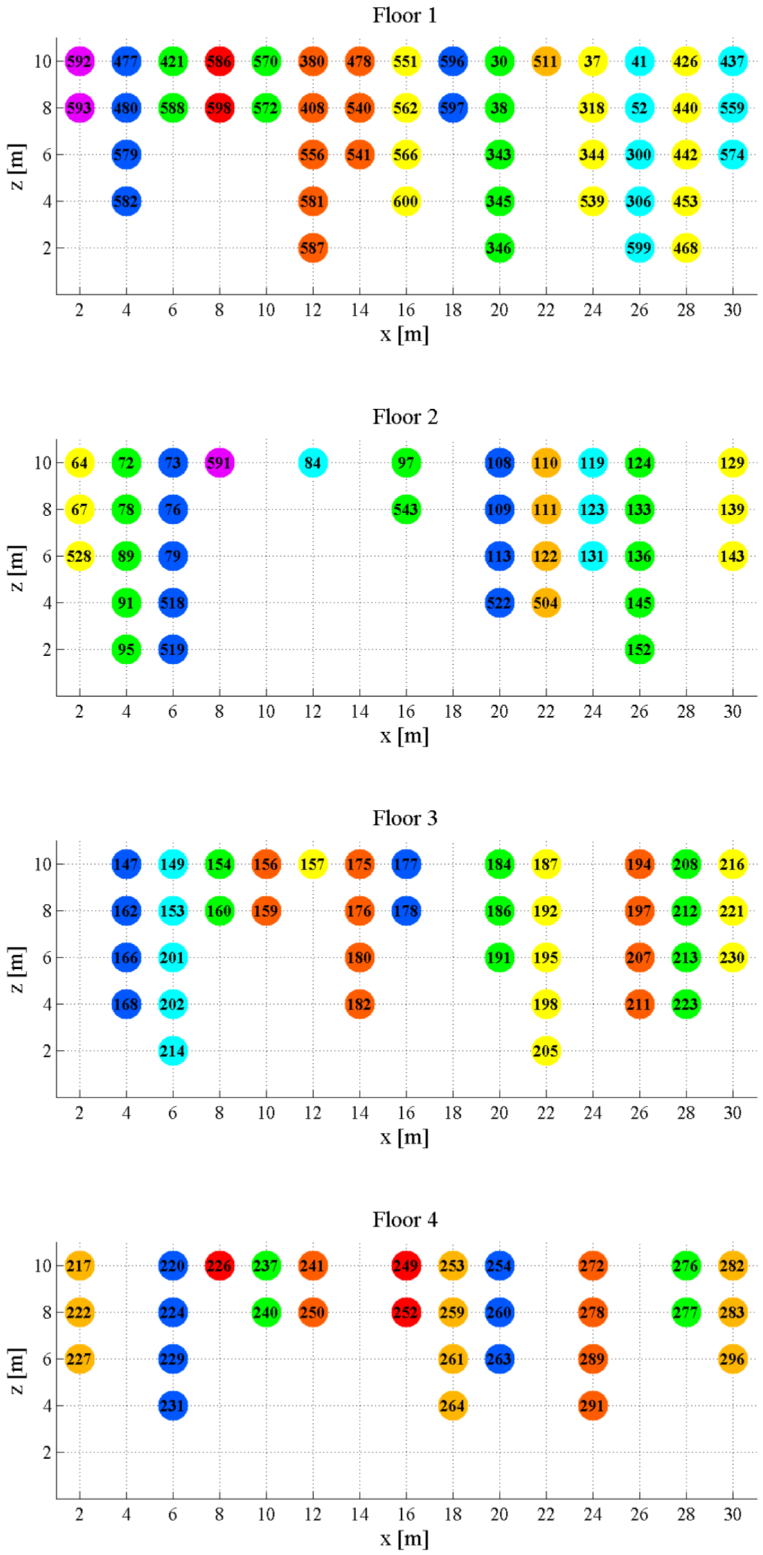


Fig. A.6 Content of the rack at the end of simulation nr. 3. Different colors denote different item lots.

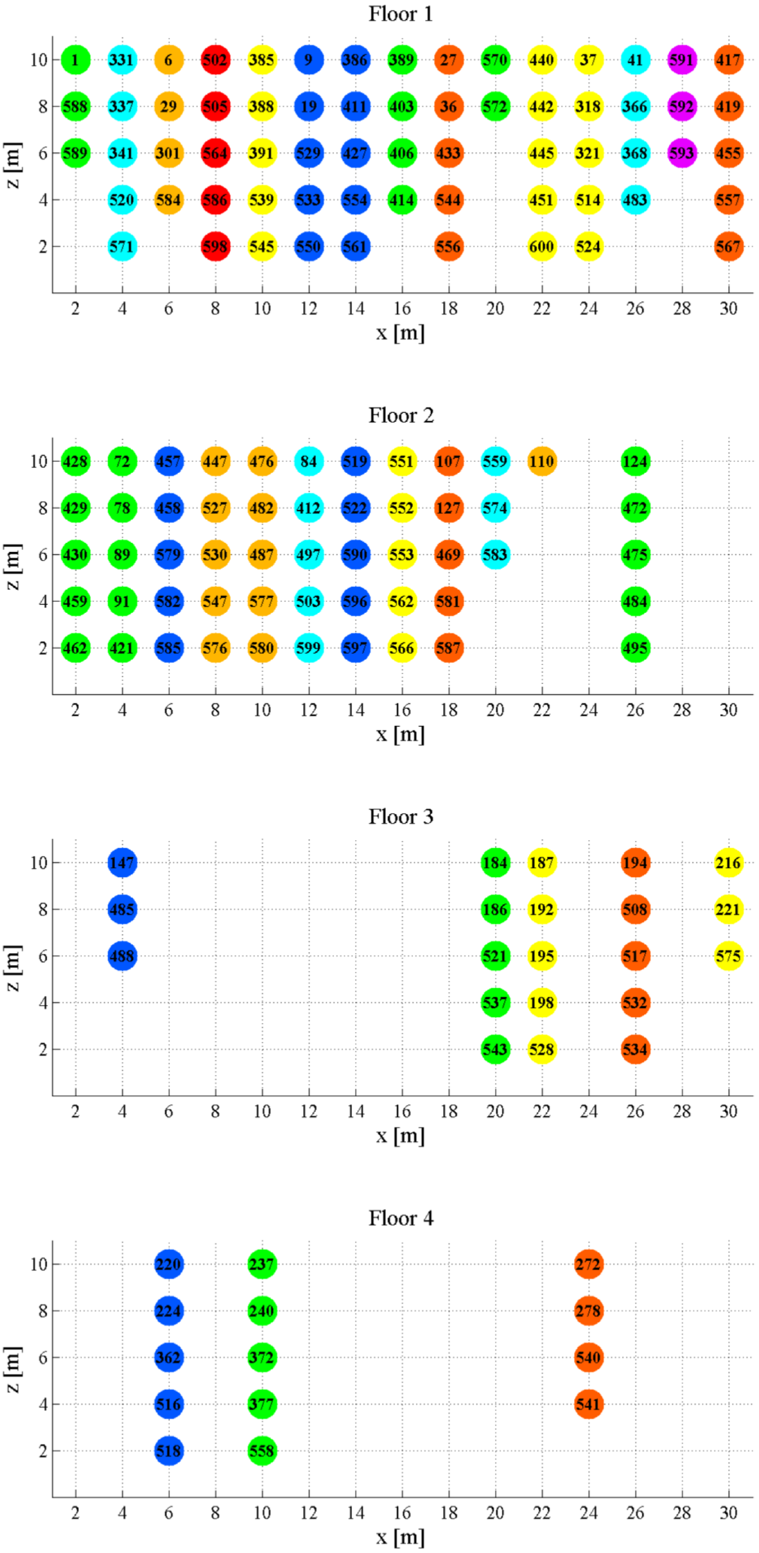


Fig. A.7 Content of the rack at the end of simulation nr. 4. Different colors denote different item lots.

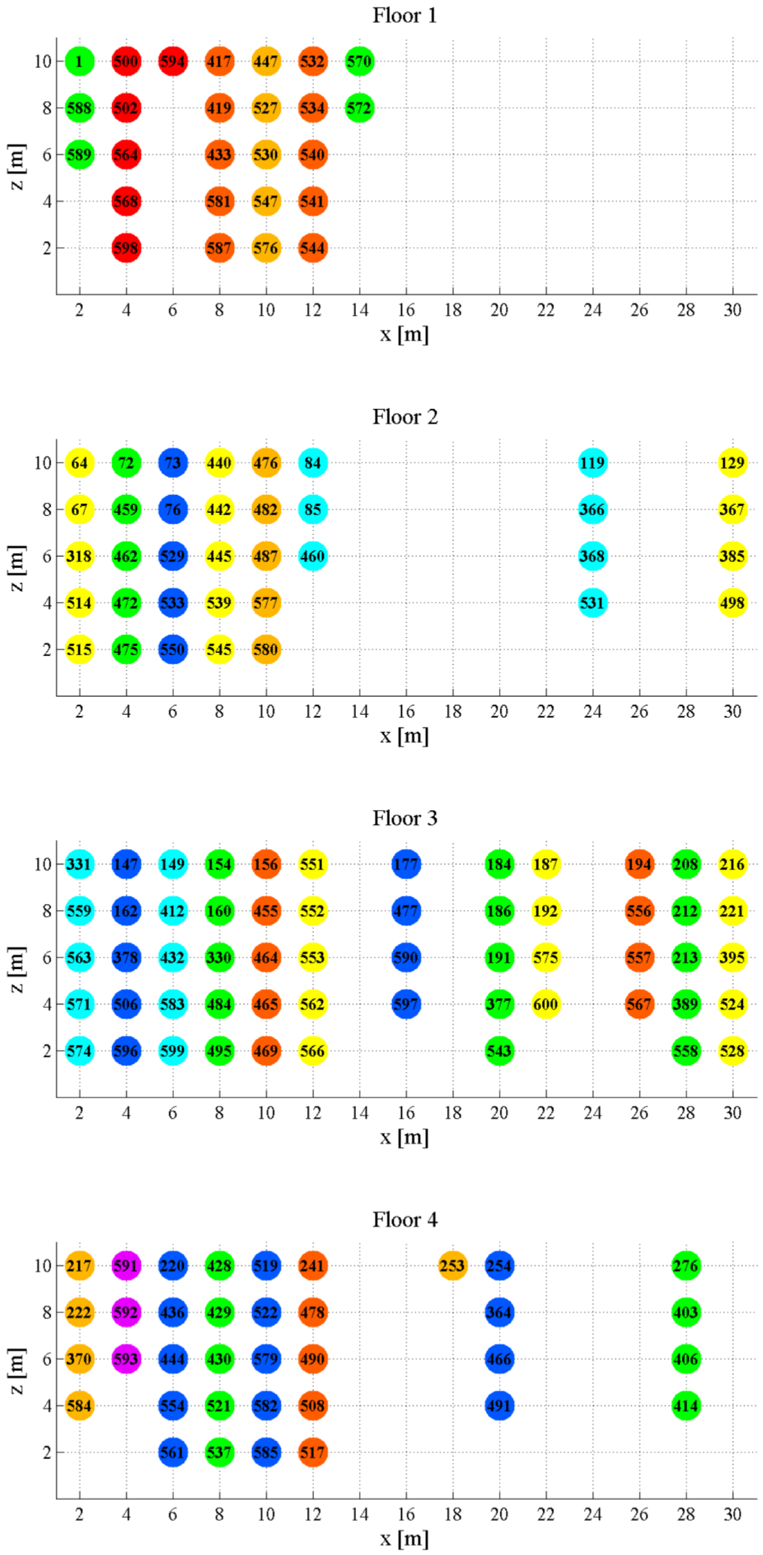


Fig. A.8 Content of the rack at the end of simulation nr. 5. Different colors denote different item lots.

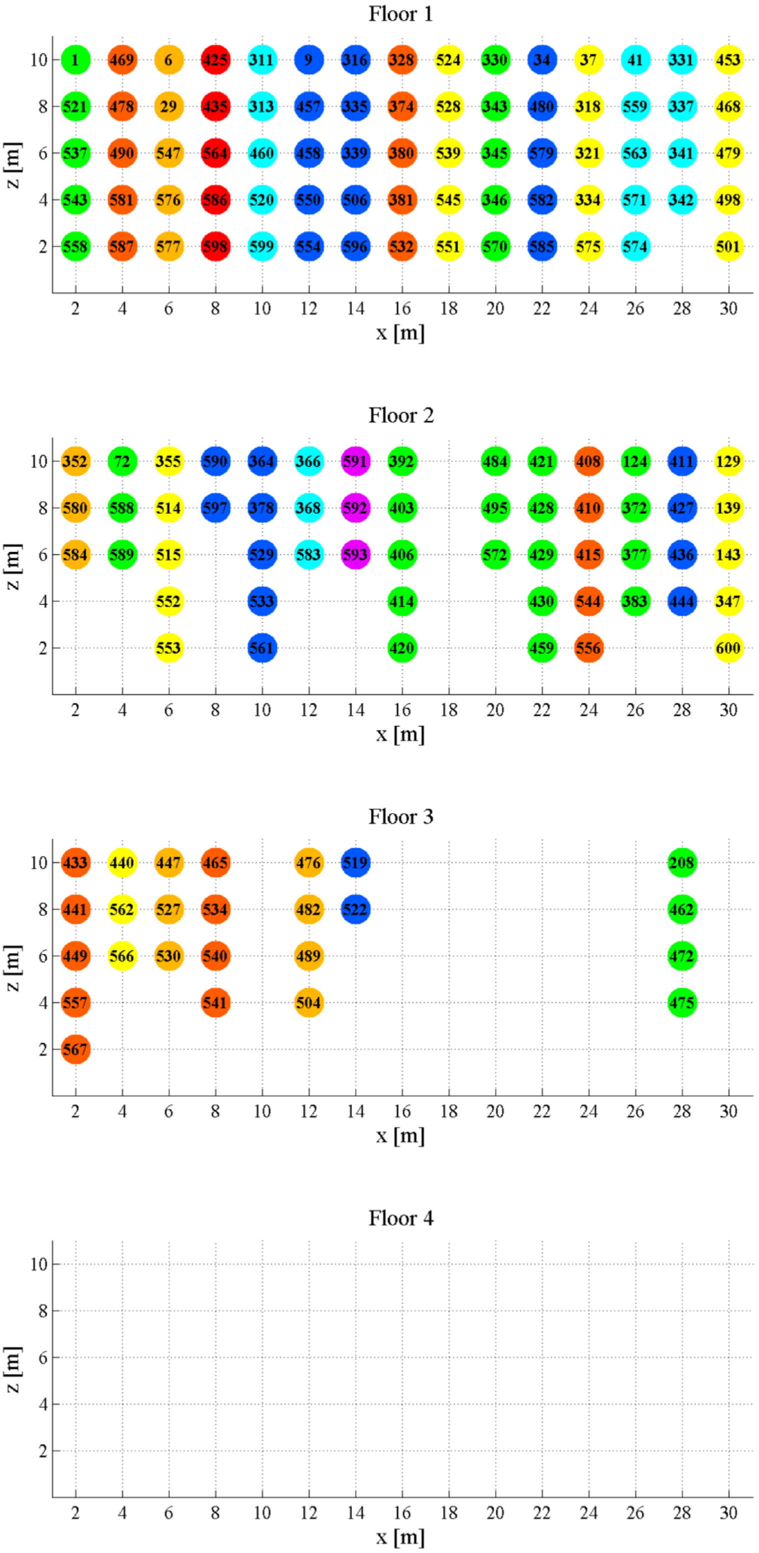


Fig. A.9 Content of the rack at the end of simulation nr. 6. Different colors denote different item lots.

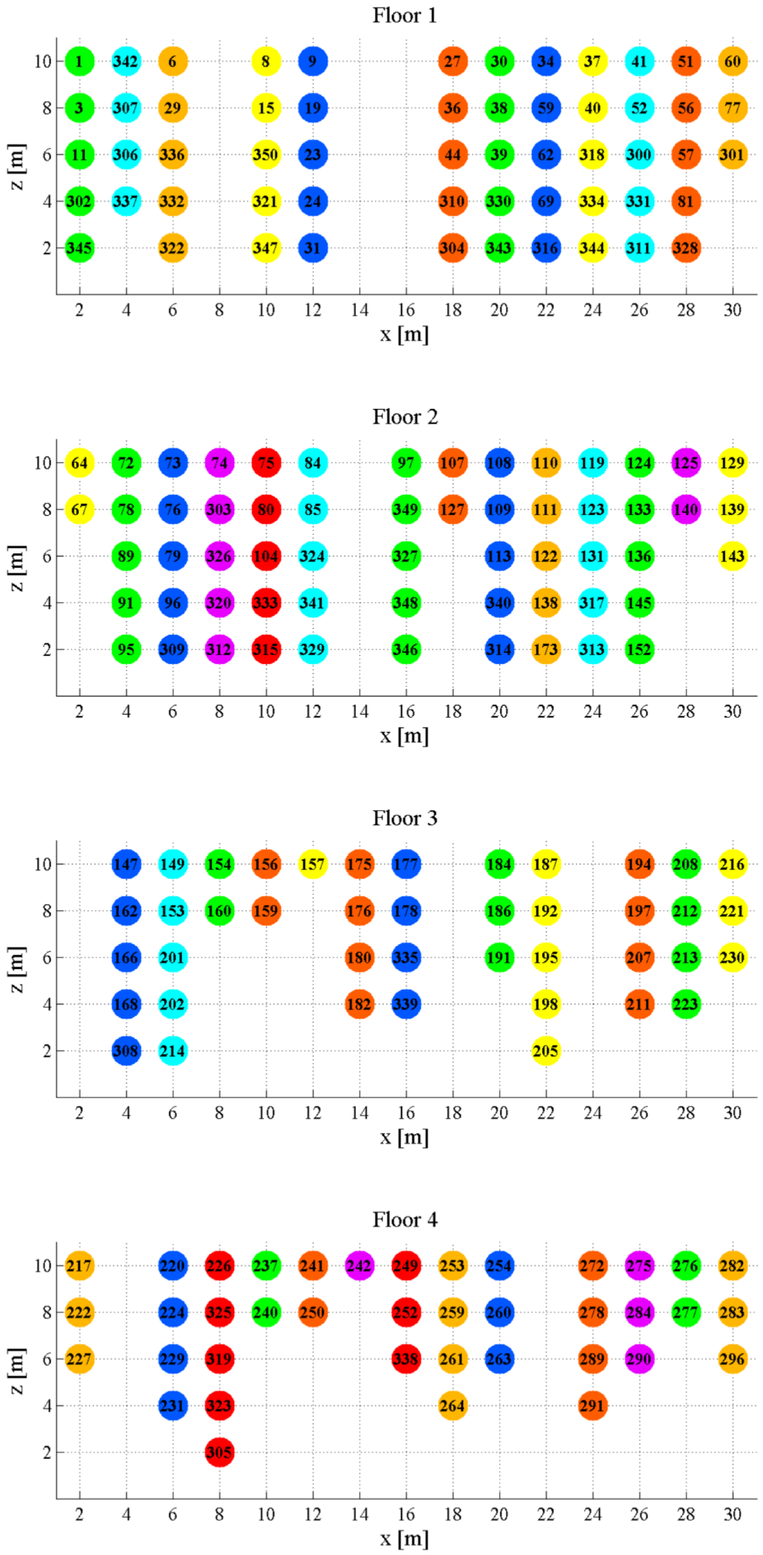


Fig. A.10 Content of the rack at the end of simulation nr. 7. Different colors denote different item lots.

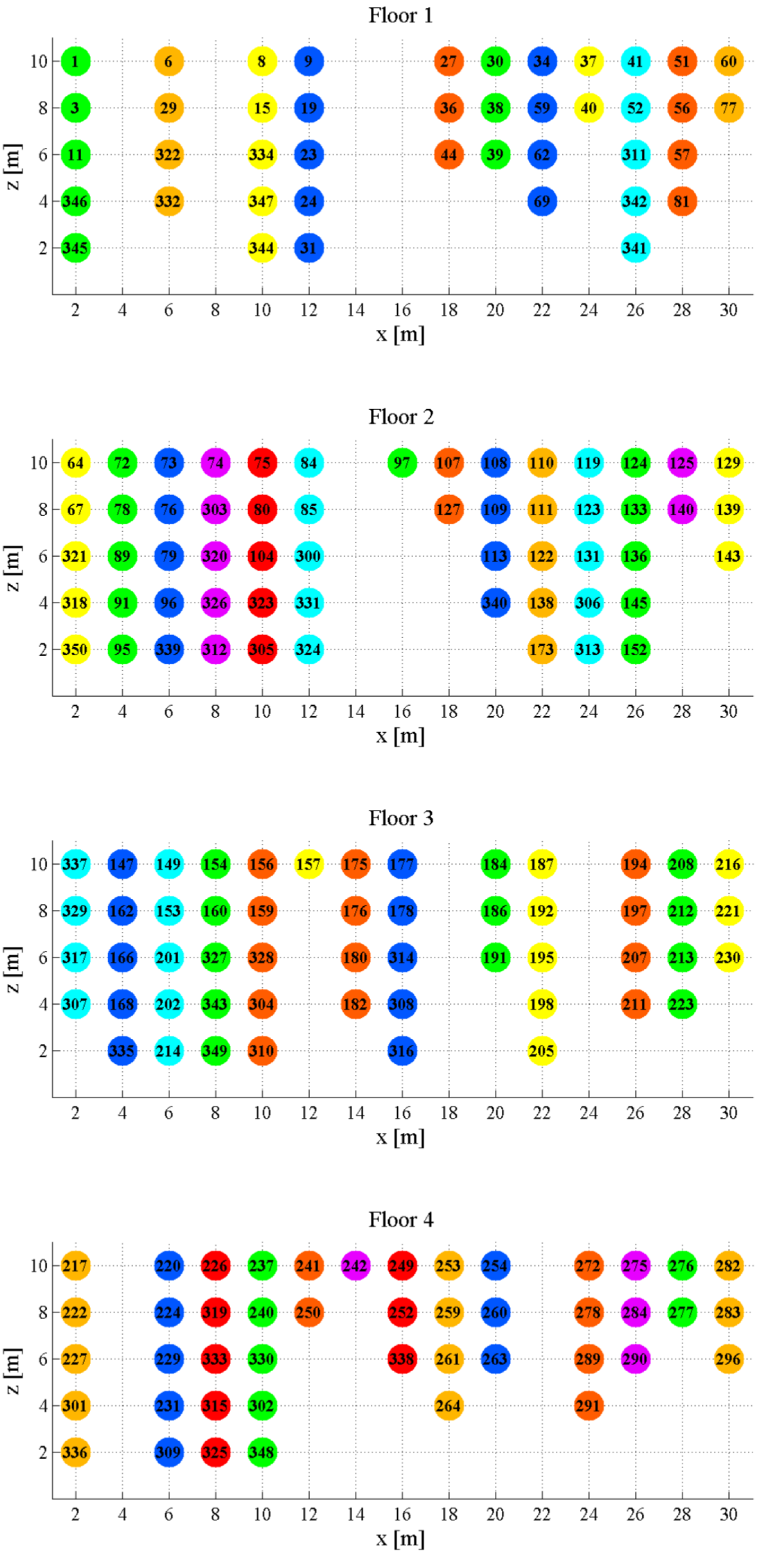


Fig. A.11 Content of the rack at the end of simulation nr. 8. Different colors denote different item lots.

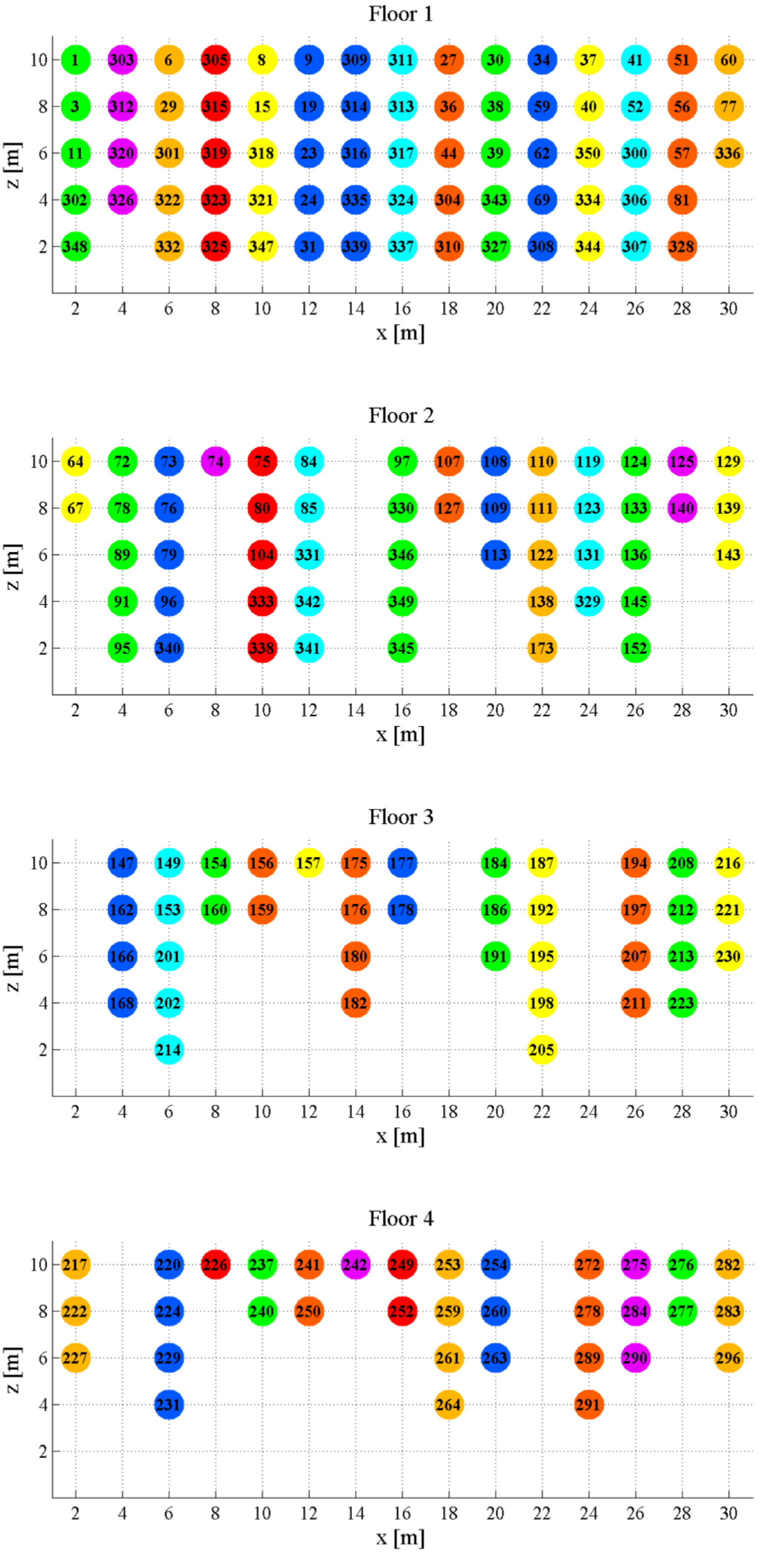


Fig. A.12 Content of the rack at the end of simulation nr. 9. Different colors denote different item lots.

Appendix B
List of abbreviations

Acronym	Description
AGV	Automated Guided Vehicles
AM	Additive Manufacturing
AS/RS	Automated Storage and Retrieval Systems
AVS/RS	Autonomous Vehicle Storage and Retrieval System
BS	Bearing Seat
CAGR	Compound Annual Growth Rate
CIM	Computer Integrated Manufacturing
C-MES	Collaborative Manufacturing Execution System
CMM	Coordinate Measuring Machine
CMS	Cellular Manufacturing System
CPS	Cyber Physical Systems
DES	Discrete Event Simulation
DFM	Design For Manufacturing
DFAM	Design For Additive Manufacturing
DIKW	Data - Information - Knowledge - Wisdom
ERP	Enterprise Resource Planning
FIFO	First In First Out
ICP	Iterative Closest Point
IT	Information Technology
KBE	Knowledge Based Engineering
LIFO	Last In First Out
LS	Least-Squares
MDA	Machine Data Acquisition
MES	Manufacturing Execution System
MRP	Material Requirements Planning
MRP II	Manufacturing Resources Planning
PDCA	Plan – Do – Check – Act
PDM	Product Data Management
PLC	Programmable Logic Controller
PLM	Product Lifecycle Management

RFID	Radio-Frequency IDentification
SME	Small-Medium Enterprise
SMED	Single Minute Exchange of Dies
SPC	Statistical Process Control
SQC	Statistical Quality Control
TC	Target Channel
UL	Unit Load
VM	Virtual Models
VSM	Value Stream Mapping
WIP	Work In Process
WCS	Warehouse Control System
WES	Warehouse Execution System
WMS	Warehouse Management System

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