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A novel methodology to integrate Manufacturing Execution Systems with the lean manufacturing approach

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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, two possible approaches are the adoption of lean manufacturing methodologies or the implementation of information tools: for several years, these two approaches have been assumed to be mutually exclusive. The present work aims to define a methodology to support developers and practitioners in the integration of Manufacturing Execution Systems with the lean manufacturing approach. A case-study in the field of aeronautics is presented to validate the method.

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Keywords: Manufacturing Execution Systems, Information tools, Lean manufacturing, Methodology.

1. Introduction

Nowadays 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 experiencing shortened production cycles and reduced batch sizes; on the other hand, the variety of product types and their customization are 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 initiative that a company may undertake is the implementation of *lean manufacturing* practices: this term has been introduced by Womack et al. [1] to describe the working philosophy deployed in Japanese companies, with

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particular concern for Toyota. This methodology relies on the elimination of wastes and non-productive processes, in order to focus on value added operations and produce high-quality products, at the customers demand pace, with ideally no waste. Another approach is the deployment of automation and Information Technology (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 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 and IT tools have been considered mutually opposed [2]. On one side, the philosophy of lean is "less is better": to improve company performance, inventory, variability, material handling, options and choices must be reduced as much as possible. Conversely, IT philosophy is "more is better": IT tools allow to better manage more information, increased flexibility, functions and features. However, according to [2], the two classes of instruments are complementary both in the concept and in the application: IT tools are 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, data collection and analysis is mandatory: the adoption 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. In this field, Manufacturing Execution Systems (MES) play a key role: they are in charge of collecting data, perform analyses and dispatch the resulting information. At the state of the art, a comprehensive methodology for the deployment of MES to support the implementation of lean practices is still lacking. The present paper aims to fill this gap. In Section 2 the background on both MES and lean manufacturing is presented. In Section 3, a novel methodology to integrate the functionalities of a MES with the principles of lean manufacturing is presented. A case study in the field of aeronautics is presented in Section 4. Conclusion and final remarks are presented in Section 5.

2. Background

2.1. Manufacturing Execution Systems

Manufacturing Execution Systems are IT tools commonly deployed in companies involved in traditional manufacturing. A MES enables information exchange between the organizational level, commonly supported by an Enterprise Resource Planning (ERP), and the control systems for the shop-floor, usually consisting in several, different, highly customized software applications [3]. A schematic of MES positioning in the framework of information tools supporting manufacturing is provided in Fig. 1. MES were initially deployed in industries focused in the fields of chemistry and pharmaceutics; then, the spread of such systems increased, but for long time this tool has been considered useful only for large industries. In the early 2000s, it was understood that the benefits provided by a MES can profitably support even smaller companies [4].

The tasks in charge of a MES are defined in the standards ISA95 [5] and IEC62264 [6]. A MES has two principal purposes. First, the system has to deal with the top-down data flow: the requirements and the necessities provided by the organizational level must be transformed into an optimal sequence planning meeting such targets. This sequence must be identified by best exploiting the available resources (such as staff, machines, materials, inventory) and taking into account the constraints of the process, such as processing and setup times, and workstations capacity.

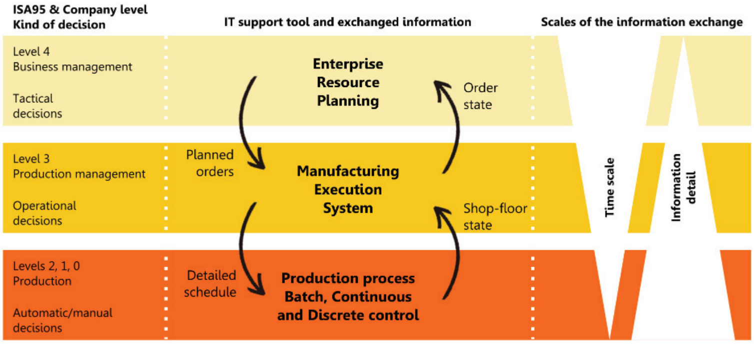

Fig. 1. MES positioning within an industrial framework.

The second aim of a MES is to manage the bottom-up data flow. Data concerning process performance and product quality can be gathered at the shop-floor level; the role of MES is to collect such data, analyze them through appropriate mathematical techniques, and extract a synthetic information to provide the business level with an exhaustive picture of the current state of the process. Possibly, the analysis should be performed in real-time, in order to make decisions to control the process with the necessary rapidity. Recently, the development of low-cost, small, easily available sensors led to a great diffusion of monitoring systems to assess product quality and process performance, and to support the improvement of production process.

2.2. 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 denote all the activities that require resources but do not add value to the process or to the product [7]. In particular, he defined seven classes of waste that typically affect a manufacturing process: (i) Overproduction; (ii) Waiting; (iii) Transport; (iv) Extra processing; (v) Inventory; (vi) Motion; (vii) Defects.

Wastes do not add value to the product: customers are not willing to pay for them, and manufacturers must be less wasteful to increase profit and improve competitiveness. A systematic method to eliminate muda is Lean Manufacturing [8]: it is an approach inspired by Japanese management methods, in particular by the Toyota Production System.

The integration between lean manufacturing and IT tools has been controversial for long time. However, a recent research [9] showed that companies need to increase the degree of use of IT tools in order to implement lean practices. The importance of MES in this field has also been shown. Cottyn [10] developed a first framework for the alignment of MES to lean objectives. He defined an automatic Value Stream Mapping (aVSM) methodology: the aVSM benefits from the information provided by the MES, since it is a rich source of information and historical data useful to define continuous improvement actions. On the other side, MES benefits from aVSM because it does not contain information concerning the value flow. The methodology is validated through the case studies of a furniture firm and a food and beverage company. In previous work [11], the support of MES to lean manufacturing has been discussed through the case study of a supplier of components for buses and coaches. Nevertheless, a methodology for fully integrating the MES capability in data analysis and dispatching with lean practices is still lacking.

3. Methodology

As stated in the previous section, MES 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 (such as 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). The methodology here developed to enable MES supporting lean manufacturing consists of three main steps:

1. Identification of the waste classes to be faced: the kinds of muda that may affect the performance of the process are identified and classified according to categories presented in Section 2.
2. Description of the process: in order to identify the sources of waste and identify possible interventions to improve the performance, a well-structured, exhaustive description of the process is necessary.
3. Data-analysis: To develop mathematical techniques for MES, 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 with the support of the manufacturer, who is aware of the real condition of the process; the latter two steps are described in the following.

3.1. General description of a manufacturing process

To define a model as general as possible, a layered representation is used. It is based on two classes of items that cooperate to perform the manufacturing process: components and resources. The former class consists in the items transformed by the manufacturing process to obtain a (semi-)finished object. The definition for resources is adopted from the standard ISO 15531 [12]: "any device, tool and means, except raw material and final product components, at the disposal of the enterprise to produce goods or services". Both the groups are made of physical objects and information, and can be further classified as input or output items.

Input components. To better address the categorization, this group can be split into the following three subgroups:

- *Suppliers*. They 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, such as 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, and reactivity to new orders). This information must be managed and dispatched by the ERP.
- *Planning*. This input class consists in information necessary to plan the production and, thus, to control the shop-floor. In a push production system, the inter-arrival time and variability for the input components 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.
- *Design*. The third class of input is related to the instructions necessary to produce the parts: materials, machines, part-programs, parameters, workpiece position in the machining area. Further, the tolerances to be satisfied and the dimensions of the finished product must be known. This information is stored in both the PLM and the MES.

Output components. Two subgroups can be identified:

- *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.
- *Quality*. Information about product quality is getting to be mandatory for manufacturers. It may result from a simple "pass or non-pass" test, or from a more complex monitoring system based on the deployment of sensors. 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 performance and quality information are managed by the MES. This system must collect data, analyze and merge them through proper mathematical techniques and provide an exhaustive and synthetic report to the business level, to verify whether the process is working in a correct and profitable way, or if an adjustment is necessary.

Input resources. The following two groups can be defined:

- *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.
- *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 same categories:

- *Reusable*. The physical output quantities are the same that were provided in input. Nevertheless, the manufacturing operation changed their state: hence, information about their state after the process must be collected.
- *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.

3.2. Methodology for data analysis

One of the aims of a MES is to embed smart mathematical techniques 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. Conversely, information is given by formatted data that can be defined as a representation of reality [13]. The most popular paradigm for the transformation of data into information is provided by the DIKW (Data - Information - Knowledge - Wisdom) hierarchy [14]: 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. Hence, the rigorous definition of a technique to analyze and organize collected data plays a key role.

The methodology for data analysis introduced in this methodology consists of the five key steps described in the following. It is an adaptation of the strategy defined by [15] 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. First, the data necessary to perform the analysis and their sources must be defined. On the shop-floor several kinds 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 stock, 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. In machining processes, the most deployed sensors are dynamometers, accelerometers, thermometers, acoustic emission and current sensors [15, 16]. 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); of course, sensors collecting different kind of data can be used and their information can be integrated to have a more exhaustive picture.

Data processing and Feature generation. The second step consists in choosing the mathematical technique to analyze the collected data. The aim of data processing is to transform data, regardless of the source, into 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.

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 sensor set.

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.

3.3. A schematic tool for the methodology

The three steps described in the previous Sections have been synthesized into a unique schematic. It is the structure shown in Fig. 2a, and it has a twofold aim. First, it can be used as a guide to integrate MES and lean approach in a specific process. 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 user with a synthetic, exhaustive overview of the process at stake. In the Figure, black fonts represent information; green is used for physical quantities.

4. Case study

Step 1. Process and wastes. To validate the methodology presented in section 3, a manufacturing process in the field of aeronautics is presented. Here, a description of the process is provided; the graphical tool synthesizing the methodology is presented in Fig. 2a.

The process of gear grinding is considered. This is a critical process, because these workpieces must be manufactured with great accuracy. However, since grinding is a costly operation (with respect to other machining processes), it should be utilized under optimal conditions [17]. The established manual operation consists of two steps. First, a pre-processing task is made to identify the workpiece axis that minimizes the geometrical distortions. This action is performed by finishing the two countersinks of the gear, which are used to place the part into the grinding machine. Then, gear grinding is performed. The operators highlighted an excessive rate of defective parts; this led to expensive reworking operations and to process variability resulting, in turn, in excessive waiting times and inventory parts accumulating through the process. The latter two waste sources were confirmed by the Value Stream Mapping analysis. Therefore, a novel system to perform gear centering prior to the grinding operation has been studied.

Step 2. Process description. After having identified the wastes affecting the process, a thorough description of the grinding process has been made. The input components are the gears leaving the upstream heat treatment process; gears belong to a finite set of well-known part families, and are grinded one-by-one. The quality of the output parts is measured through functional tolerances: residual concentricity for the bearing seats and the gear, and total axial runout of the side surface; the range of such tolerances – defined in the ISO 1101 standard [18] – is in the order of 0.05-0.1 mm. A representation of the workpiece and the tolerances is shown in Fig. 2b. The performance of the process is measured through well-established indicators: cycle-time, work in process, throughput and rate of

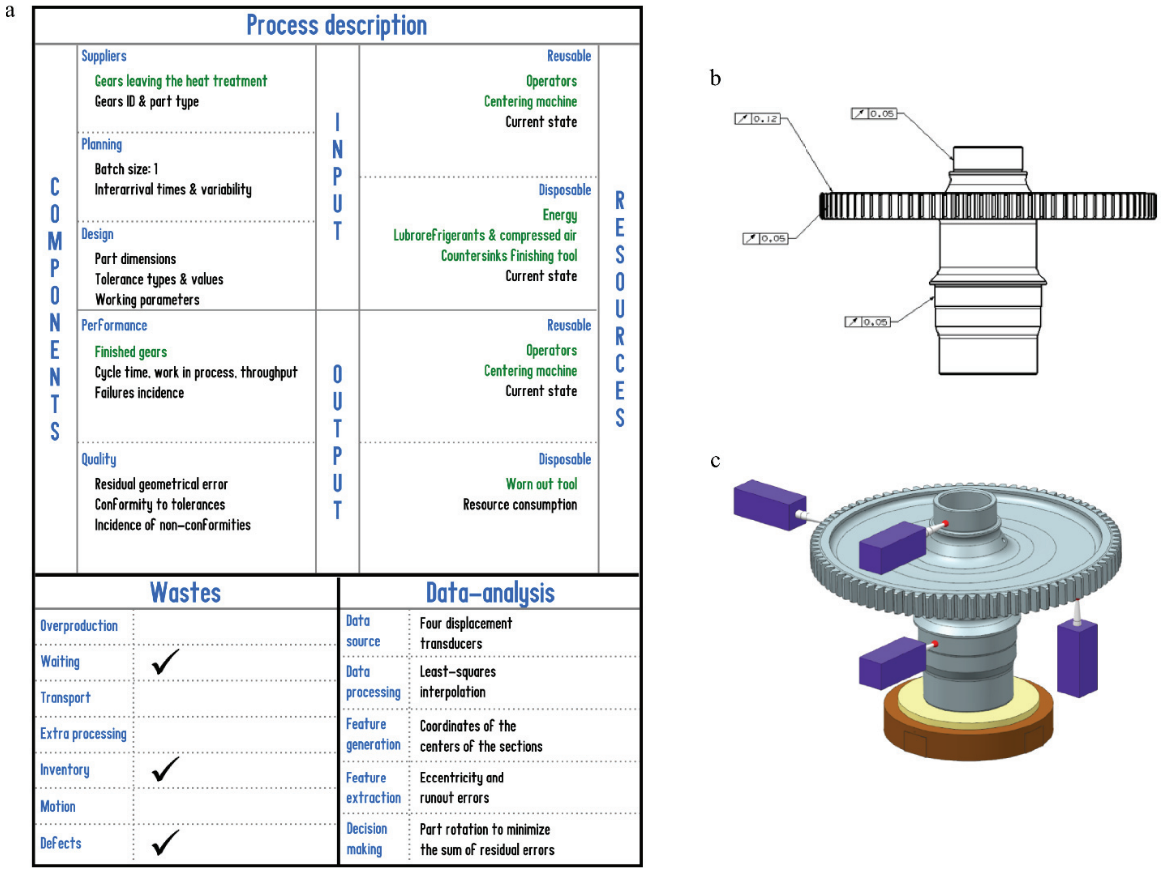

Fig. 2. (a) The methodology developed in Section 3 applied to the case-study. (b) The workpiece to be manufactured and the definition of the functional tolerances. (c) A representation of the monitoring system for data acquisition.

failures. In order to perform the process, a skilled operator is necessary to perform the correct positioning of the workpiece in the machine.

In order to improve the performance of the grinding process and the quality of the machined gears, a novel system to support piece positioning has been developed, supported by a proper mathematical technique. Mainly, the gear is placed into a manufacturing machine to finish two surfaces – at the top and bottom extremities of the piece – with the aim of defining a new reference system for the part that minimizes the residual geometrical error. Such surfaces are used in the subsequent grinding operation to easily place the gear into the machine.

Step 3. Data-analysis. First, the sources for data acquisition have been selected. Given the strict quality needs, displacement transducers are used to measure the profile of the gear where the tolerances are set, as shown in Fig. 2c. To perform the measurement, a rotation of the gear about the axis of the machine is made. Since the tolerances are tight, sensors with high reproducibility (30 μm) have been used and a high acquisition rate is set (3600 points/revolution). After the acquisition, data are processed: to minimize the impact of measurement noise and errors, a least-squares interpolation is made for each of the gathered profiles. In particular, the three radial sections (i.e. the gear and the bearing seats) are interpolated through least-squares ellipses, and the coordinates of their centers are extracted.

Given the cost of the manufactured parts, the manufacturer is interested in exploiting as much as possible the functional tolerances, in order to minimize the quantity of rejected parts. Hence, an objective function has been defined: it collects the current positioning errors, eventually weighted according to the tolerances values. This function is based on two independent variables, corresponding to the two part rotations that can be made to correct the position of the gear into the machine. Finally, the objective function is minimized to reduce as much as possible the residual positioning error; the calculated values for the two feasible rotations are provided to the machine to correct the position of the gear within the machining area. Then, the two reference surfaces are finished. More details on the mathematical technique are provided in [19].

The role of MES. The integration of this 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, MES information 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.

5. Conclusions

In the present paper, a novel methodology to enable MES functionalities supporting lean manufacturing objectives is presented. At the state of the art, a few case-studies have been developed to show the possible role of MES in continuous improvement and lean practices. The methodology introduced in [10] mainly focuses on process flows; however, MES is the repository of a huge amount of information concerning both the product and the process, which have a critical role in the implementation of the lean manufacturing approach, but often is still unexplored. The methodology presented in section 3 aims to fill this gap by providing a structured approach; a graphical tool has also been developed, to support the user in correctly perform all the necessary steps.

A case-study has been presented in section 4 to validate the methodology: it is a process in the field of manufacturing with strict quality needs. The methodology enabled to design a system for workpiece positioning within a manufacturing machine with improved accuracy and 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 performed tests enable to state that a 50% reduction of parts to be rejected or reworked is feasible. Further, the lead time and the work in process are expected to be reduced by 40%.

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