International Journal of Computer Integrated Manufacturing

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Published online: 14 Jun 2013.


To link to this article: http://dx.doi.org/10.1080/0951192X.2013.802370

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An integrated technique for the internal logistics analysis and management in discrete manufacturing systems

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(Received 22 October 2012; final version received 30 April 2013)

A novel hierarchical and iterative technique is presented for the analysis and management of the internal logistics of manufacturing systems. The method effectively integrates the value stream mapping (VSM) tool, the analytic hierarchy process (AHP) approach, and discrete event simulation. Starting from a concise description of the manufacturing system obtained by the VSM graphical approach, so as to identify nonvalue-adding activities, a detailed and standardised description is obtained by the unified modelling language (UML). Then the AHP technique is used to rank the system anomalies, singling out the major ones. Further application of the VSM tool produces an overall picture of the desired manufacturing system internal flow, and the UML description details the to-be system activities. Finally, the use of discrete event simulation allows the quantitative verification of the effects of the changes in the production system. The proposed technique is a tool to systematically improve the internal logistics of complex production systems while assessing the system dynamics and corresponding performance improvements. An application of the method to a real case study enlightens its effectiveness.

Keywords: manufacturing systems; internal logistics; value stream mapping; unified modelling language; analytic hierarchy process; discrete event simulation

1. Introduction

1.1. Motivation

In the manufacturing environment, there has been a gradual shift in the control of the product market from producers to customers and then to final consumers. With the increased customer demand, for most manufacturing industries it has become increasingly important to optimise the performance of the industrial process (Yan, Zhou, and Sebastian 1998; Yan, Zhou, and Sebastian 1999; Yan et al. 2001; Yan and Zhou 2003; Gourgand, Lacomme, and Traoré 2003; Koh, Chung, and Gunasekaran 2006; Li and McMahon 2007; Agyapong-Kodua, Ajaefobi, and Weston 2009). In the context of manufacturing systems management, a decisive role is played by logistics, which may be defined as process planning and organisation aimed at optimising the flow of material and information within and outside the company to maximise profit (Christopher 2010; Costantino et al. 2012). The most common tools for analysing and managing the internal logistics of a manufacturing system are: (1) cellular manufacturing, based on organising processes into cells including all necessary resources; (2) just-in-time (JIT), where the demand is initiated by a customer and is transmitted backward, ‘pulling’ production; (3) Kanbans, a signalling system for implementing JIT production; (4) total preventive maintenance (TPM), where workers carry out regular equipment maintenance to prevent breakdowns; (5) setup time reduction, where system engineers continuously try to reduce machine setup times; (6) total quality management (TQM), a continuous improvement system that is centred on the needs of customers and employs participative management; (7) 5S, focusing on effective workplace organisation and standardised work procedures; and (8) value stream mapping (VSM) that depicts the overall value stream to identify waste (Hines and Rich 1997; Seth and Gupta 2005; Abdulmalek and Rajgopal 2007). Basically, the major goal of these manufacturing optimisation tools is to reduce cost by eliminating waste, namely, over-production, waiting time, transportation, over-processing, inventory, motion and scrap (Womack and Jones 2003). The most notable and common of the cited techniques is undoubtedly VSM, thanks to its straightforwardness of application and ability to produce a compact view of the overall system. Indeed, VSM allows visualising in an integrated manner the material and information flow of the selected value stream, identifying the system anomalies, i.e., activities that do not add value to the manufacturing process.

Despite the numerous contributions appearing in the literature proposing manufacturing logistics management tools (for instance Bonney and Jaber 2012; Álvarez et al. 2009; Ramesh, Sreenivasa Prasad, and Srinivas 2008), few attempts were made to propose systematic techniques that,
while improving the manufacturing system internal logistics and the related performance, are able to assess the manufacturing dynamics and corresponding improvement. In this context, simulation can be a valuable tool to determine the system dynamics under different scenarios and improve the design based on what-if analyses (Papakostas, Alexopoulos, and Kopanakis 2011).

This article aims at filling this gap proposing a novel technique for manufacturing systems analysis and management that integrates the well-known VSM tool with the analytic hierarchy process (AHP), discrete event simulation, and the unified modelling language (UML) (Miles and Hamilton 2006).

1.2. Contribution

A general and systematic technique is proposed for the internal logistics of manufacturing systems that allows improving the system behaviour quantitatively and iteratively. More precisely, four different methodologies are applied in an integrated and systematic way to describe, assess and improve the logistics of the production processes: the AHP decision-making approach (Saaty 2008) and the discrete event simulation framework (Banks 2005) are employed as a support to VSM and UML to systematically improve the manufacturing system behaviour while rigorously assessing the macroscopic improvement actions.

The proposed method is mainly based on VSM, which is chosen among the available manufacturing optimisation tools in the literature as it is a simple and effective approach to identify and reduce waste, while improving the overall operational control (Hines and Rich 1997; Seth and Gupta 2005). More precisely, the systematic and hierarchical technique performs seven steps and starts from the VSM picture of the overall process activities, identifying the system anomalies in the value stream and subsequently representing the system activities in a detailed and standardised way by the UML representation. If some anomalies are detected, in the third step AHP ranks their severity so as to allow the system optimisation through the eventually partial resolution of the identified problems, starting from the major ones. Based on the AHP results, the VSM approach is then used to establish the future vision of the value stream, with a reduced impact of non-value-added activities. Hence, in the fifth step, UML is employed to re-design the manufacturing system, removing the main system anomalies and detailing the to-be system. Subsequently, to verify and assess the obtained improvements, the UML model is translated into a discrete event simulation model to determine the future system dynamics (which cannot be provided by the static VSM view) and quantitatively compare several key performance indicators of the to-be manufacturing system scenario with the real as-is condition. Finally, the designed changes are implemented in the real production system. The technique is iterative and repeated at least annually to ensure that improvement is continuously achieved.

The proposed technique is applied to a case study, namely a manufacturing process of an engineering company, OM Carrelli Elevatori SpA, a leading manufacturer of forklift trucks that is located in the mechanics industrial district of Bari (Italy). The production process refers to the flow of semi-worked pieces that, after being painted, enter the assembly line of forklift trucks. The internal logistics currently generates many wastes, numerous missing parts, and a working condition that is not fully in line with ergonomic principles. The application of the proposed technique to this case study leads to the improvement of several key performance indicators in the company, enlightening the approach effectiveness.

1.3. Related literature and discussion on the technique advantages

This subsection addresses the relationship of the proposed technique with two classical approaches for manufacturing systems analysis and management: VSM and discrete event simulation. Accordingly, the major advantages of the proposed technique are highlighted.

First, it is to recall that the related literature includes several application examples of VSM to discrete manufacturing systems (for instance, Ramesh, Sreenivasa Prasad, and Srinivas 2008). However, it is well known that the traditional VSM tool is properly effective only for linear flow manufacturing systems (Braglia, Carmignani, and Zammori 2006), while mapping a complex manufacturing system and identifying its critical issues is not straightforward (McManus and Millard 2002). It is to remark that, with respect to the classical VSM technique, the proposed technique offers several advantages: (1) it can be effectively applied to complex manufacturing systems (thanks to the integration of different techniques); (2) it allows detailing the process activities (thanks to the use of the UML formalism) while depicting the overall value stream in a high-level picture (using the VSM conciseness); (3) it leads to a quantitative verification of the proposed improvements (thanks to the use of discrete event simulation); (4) it allows ranking the system criticalities and eventually focusing on removing only the major ones, for feasibility or cost reasons (thanks to the use of AHP).

Second, it is to recall that discrete event simulation allows representing in detail the system dynamics while capturing its state variables changes only at those discrete points in time at which events occur (Banks 2005). As a result, discrete event simulation is able to accurately represent the manufacturing system dynamics that is typically characterised by millions of parts and hence would require an enormous number of equations to be represented in a differential or difference equation setting. However, existing approaches in this context mainly consist in single case
studies referring to the integrated application of optimisation tools and simulation. For instance, Detty and Yingling (2000) use simulation to assist in the decision to implement lean manufacturing principles at an existing assembly operation thanks to the ability to measure the system resource requirements and performance. In addition, Deif (2010) uses computer simulation to explore the impact of applying just in time lean policy on a traditional inventory based production system. Moreover, Melouk et al. (2013) present a simulation-based optimisation model for steel manufacturing system optimisation. The reader is referred to (Melouk et al. 2013) for a discussion on the topic of simulation-based optimisation of manufacturing systems. It is to remark that the presented technique, starting from the VSM study, allows guiding discrete event simulation to analyse the future manufacturing system scenario, by avoiding time-consuming and unsystematic what-if investigations.

Third, with regard to the relationship of the presented technique with existing approaches integrating VSM and simulation, it is to recall that McDonald, Van Aken, and Rentes (2002) apply VSM to an assembly process using discrete event simulation to define the basic system parameters. Moreover, Narasimhan, Parthasarathy, and Narayan (2007) propose simulation-aided VSM for quick and efficient data analysis and apply it to an engine product development environment. In addition, Lian and Van Landeghem (2007) propose a formalism that, using what they call VSM objects, is able to translate them into a simulation model that yields future scenarios. However, in the cited approaches the resulting simulation models are excessively concise since they are directly obtained from the VSM and do not incorporate general performance indices that can evaluate continuous improvement in a systematic way. Our technique overcomes such limitations.

Fourth, to the authors’ knowledge, the only existing contribution in the literature integrating simulation of manufacturing systems with the AHP optimisation tool in a lean context by Rabelo et al. (2007) does not consider the detailed manufacturing system level but only addresses the problem in the higher level and more general setting of the overall supply chain, considering strategic problems of the chain design such as, e.g., partner selection and facilities location.

Finally, it is to be remarked that the proposed technique, although not being automatic, can be systematically applied to a generic complex manufacturing system for rigorous optimisation and quantitative verification.

Summing up, the proposed technique is a systematic and general tool for complex manufacturing systems optimisation. It exhibits the advantages of concisely depicting the overall value stream of the manufacturing systems (thanks to the VSM approach), quantitatively assessing the system anomalies (thanks to AHP), allowing to design in a detailed way the to-be system (thanks to UML), and evaluating the performance of the improved system by an eventually partial removal of such waste (thanks to the discrete event simulation).

2. The manufacturing system logistics management technique

This section describes the proposed manufacturing analysis and management technique for the internal logistics that is hierarchical and based on seven steps shown by the flowchart in Figure 1. Moreover, in the following subsections the steps of the proposed technique are described in detail.

2.1. Step 1: VSM of the as-is manufacturing system

The first step of the proposed technique in Figure 1 relies on providing an overall picture of the system to identify the nonvalue-adding activities or system anomalies. To this aim, VSM (Abdulmalek and Rajgopal 2007) is
employed, a well-known tool for strategic/tactical planning of manufacturing systems providing a visual mapping of all processes and activities that contribute to the production of a piece or part. In essence, the goal of the VSM analysis is the identification of waste. Thanks to its visual approach, the VSM methodology helps companies depict the whole flow of a single product and visualise where the production process is being slowed down due to such waste. Note that using VSM leads to representing the system activities without detailing their sub-processes actors (which is done by the subsequent UML representation of Step 2). Nevertheless, such a high-level picture allows visualising in a straightforward and concise manner the main system anomalies.

The VSM procedure typical elements are the following (Pan, Feng, and Jiang 2010):

1. Identifying the product or service to map: the value stream to be improved is determined, with its start and end points;
2. Drawing the current state map: the current situation (state) of the flow of material and information in the value stream is described, including all available information (tasks, costs, time for each task, delays in between stages of the process, etc.). To produce the current state map, a team observes the manufacturing processes and documents facts (cycle times, buffer sizes, personnel requirements, etc.) which are described in the map with standardised icons (Braglia, Carmignani, and Zammori 2006);
3. Assessing the current state map: the procedure analyses qualitatively whether each process activity is adding value, so that the system anomalies are identified. The detected imperfections in the flow are signalised by icons called bombs. These are obtained by interviewing the manufacturing system operators to detect all anomalies and obtain their description and location in the VSM current state map.

2.2. Step 2: UML model of the as-is manufacturing system

Once concisely described in the first step, in this second step the technique in Figure 1 provides a detailed representation of the system activities using UML (Miles and Hamilton 2006), a graphic and textual modelling formalism suitable to understand and describe systems both from structural and behavioural viewpoints. In particular, UML allows describing in a standardised and detailed way the process activities and the corresponding actors. Note that such a framework is chosen to detail the manufacturing system representation rather than more complex approaches (such as, e.g., Petri nets, in Dotoli et al. 2008; Dotoli and Fant 2004, 2005) since the UML activity diagrams framework may be straightforwardly translated into a discrete event simulation model (see the subsequent Section 2.6). From the behavioural point of view, a system can be described in UML by activity diagrams that provide an overview of the system dynamics. The main elements of these diagrams are the following (Miles and Hamilton 2006): the initial activity (denoted by a solid circle); the final activity (denoted by a bull’s eye symbol); other activities, represented by a rectangle with rounded edges; arcs, representing flows, connecting activities; forks and joins, depicted by a horizontal split, used for representing concurrent activities and actions respectively beginning and ending at the same time; decisions, representing alternative flows and depicted by a diamond, with options written on either sides of the arrows emerging from the diamond; signals representing activities sending or receiving a message, which can be of two types: input signals (message receiving activities), shown by a concave polygon, and output signals (message sending activities), shown by a convex polygon. Moreover, activities may involve different participants in a system. Hence, partitions or swim lanes are used to show which actor is responsible for which actions and divide the diagram into columns or swim lanes.

2.3. Step 3: Assessment of the manufacturing system anomalies by the AHP

The third step of the proposed technique in Figure 1 allows the quantitative assessment of the system anomalies that have been identified in the previous steps. To perform such an assessment, AHP, a well-known multi-objective decision-making technique (Saaty 2008) is employed. Indeed, AHP is particularly suited to rank a number of alternatives according to a set of conflicting criteria of various degrees of importance. Thanks to alternative pairwise comparison, AHP allows ranking the system anomalies, eventually indicating the top and most urgent waste to address.

In our manufacturing optimisation technique, the AHP method consists of the following elements (adapted from Saaty 2008):

1. Structuring the decision problem as a two-level hierarchy. The first AHP level is defined by n criteria or key performance indicators (KPI) that are relevant metrics to assess the detected imperfections in the material and information flow, e.g., resource utilisation, inventory, etc. Hence, the second AHP level is composed by the m identified system anomalies that are to be ranked against the previous AHP level criteria or KPI.

The procedure consists of the following steps:

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(2) **Constructing a set of pairwise comparison matrices.** A pairwise comparison matrix $c_{Mi}$ of dimension $n \times n$ is required for evaluating the importance of the $n$ criteria of the first level in reaching the overall objective and $n$ additional matrices $c_{Mj}$ of dimension $m \times m$ with $i = 1, \ldots, n$, expressing how important the removal of each identified anomaly of the second level is with respect to the $i$-th criterion of the higher level. Each element $c_{Mi}(j, k)$ of $c_{Mj}$ with $i = 0, \ldots, n$ represents the relative importance of the $i$-th anomaly compared to the $k$-th one and is determined interviewing the decision maker and associating to such an importance an integer from 1 to 9 (see Table 1). If numerical performance values are available for all options of a level, value $c_{Mi}(j, k)$ can be determined evaluating the percentage difference between values of the $j$-th and $k$-th options according to Table 2 (Triantaphyllou and Lin 1996). Less important criteria are defined by reciprocals, so that $c_{Mi}(j, k) = \frac{1}{c_{Mi}(k, j)}$.

(3) **Determining priorities and normalised performances from comparisons.** For each comparison matrix, $c_{Mi}$ with $i = 0, \ldots, n$ determine the maximum eigenvalue and the corresponding eigenvector $v_i$ with $i = 0, \ldots, n$. Obviously, $v_p$ includes $n$ elements, while all the other eigenvectors $v_i$ with $i = 1, \ldots, n$ include $m$ elements. Compute the priorities vector normalising eigenvector $v_0$ of $c_{M0}$ as follows:

$$P = \frac{v_0}{\sum_{j=1}^{n} v_0_j} = [p_1 \ldots p_n]^T,$$

where each element $p_i$ with $i = 1, \ldots, n$ of $P$ represents the normalised importance degree of the $i$-th criterion. Similarly, compute the normalised performance values of the alternatives against each $i$-th criterion as follows:

$$CRIT_i = \frac{v_i}{\sum_{k=1}^{m} v_i_k} = [CRIT_{i1} \ldots CRIT_{in}]^T$$

with $i = 1, \ldots, n$.

(4) **Determining the decision model.** For each identified system, anomaly $j$ with $j = 1, \ldots, m$, determine the weighted sum of the normalised performance values against each criterion weighted by the corresponding priority:

$$P_{j_{AHP}} = \sum_{i=1}^{n} p_i CRIT_{ij},$$

so that $P_{j_{AHP}}$ quantifies the impact or significance degree of the $j$-th anomaly with respect to the set of criteria or KPI.

(5) **Ranking alternatives.** The identified manufacturing system anomalies are ranked by their overall AHP index $P_{j_{AHP}}$. Obviously, the top anomaly is the one showing the highest index $P_{j_{AHP}}$ obtained by (3). Hence, the greater the value of such an index, i.e., the higher the anomaly position ranking, the greater the necessity to require an immediate resolution to the problem.

### 2.4. Step 4: VSM of the to-be manufacturing system

The fourth step of the technique re-designs the overall system, eliminating all or, if for cost or feasibility reasons not all waste may be removed, the top nonvalue adding activities as resulting from the previous AHP assessment. To this aim, VSM is employed to draw the to-be state map, i.e., the overall picture describing the ideal future state of the manufacturing system. Hence, the to-be state map shows the desired system after the elimination of the critical points identified in the previous step of the optimisation technique.

Note that this step is a crucial one and requires deep knowledge of the system, attention and creativity from the decision maker. Hence, the subsequent step supports in this process of creating a solution and detailing it.

### 2.5. Step 5: UML model of the to-be manufacturing system

In the subsequent step of the technique, using the UML formalism the detailed activity diagram of the re-designed manufacturing system obtained by the previous step is depicted: the sketched vision of the value stream is thus...

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**Table 1.** Saaty’s AHP scale of comparisons.

<table>
<thead>
<tr>
<th>Intensity of importance</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
</tr>
<tr>
<td>3</td>
<td>Moderate importance</td>
</tr>
<tr>
<td>5</td>
<td>Strong importance</td>
</tr>
<tr>
<td>7</td>
<td>Very strong importance</td>
</tr>
<tr>
<td>9</td>
<td>Extreme importance</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>Intermediate values between adjacent judgments</td>
</tr>
</tbody>
</table>

**Table 2.** Saaty’s AHP scale of comparisons for measurable alternatives.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>AHP scale</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>
detailed by a novel activity diagram of the manufacturing system. The UML model depicts all the activities of the to-be system and is obtained from the one determined at Step 2 of the technique leaving unchanged activities that are not affected by anomalies and suitably updating those that are characterised by waste according to the decision maker choices in the previous step. As a result, an updated behavioural model of the manufacturing system is obtained.

2.6. Step 6: Simulation of the to-be manufacturing system

In the sixth step of the technique, the designed changes in the manufacturing system are implemented in a discrete event simulation framework (Banks 2005). Differently from VSM, which provides a static view of the system, discrete event simulation allows detailing the manufacturing system dynamics and the corresponding performance based on the comprehensive and standardised view obtained by the UML representation. In this article, the manufacturing system is described as a timed discrete event dynamical system (Fanti et al. 1996), in which the state stores the information on the jobs in the system and on the paths that they have to follow. As time moves on, the state changes at any event occurrence. Note that events relevant for the system analysis are those corresponding to new jobs entering the system, jobs progressing from a resource to another one, and jobs leaving the system. Hence, in the discrete event simulation model the manufacturing system is represented by a series of events, i.e., occurrences that change the state of the system instantaneously, and by individuals, called entities, taking part in these events and characterised by properties called attributes. Simulation moves from one event to the next one in continuous time and future events are kept in a list and performed in a time order. As a result, from the discrete event simulation the key performance indicators of the updated manufacturing system are evaluated and compared with the original setting, so that the improvements are verified and assessed.

For instance, the UML description obtained by the previous step may be implemented in Arena (Kelton, Sadowski, and Swets 2009) that is a well-known discrete event simulation software particularly suited for dealing with large-scale and modular systems. Indeed, activity diagrams can be used to straightforwardly generate the Arena simulation model by the following three steps (adapted from Teilans et al. 2008):

1. Associate an Arena model to the UML activity diagram, by establishing a mapping between each UML graphical element of the activity diagram a corresponding Arena module. Indeed, even if the Arena software is not able to read UML diagrams, the activity diagrams can be quite directly translated into such a computer program;
2. Include the simulation parameters in the Arena environment, i.e., assign the activity times, the process probabilities, the resource capacities, and the average input rates. These specifications can be modified in every simulation and enable the choice of the scenarios in the case study implementation and management;
3. Single out the simulation run of the experiments and determine the performance indices with suitable traditional statistics functions that are built-in in Arena.

After such a step, the technique evaluates the simulation results and, if the obtained performances are unsatisfactory, then it re-starts from step four to remove additional anomalies in the ranked list obtained by the AHP evaluation. If this is not the case, it proceeds to implement the last step.

2.7. Step 7: Implementation of the changes in the real manufacturing system

In the seventh and final step of the optimisation technique in Figure 1, if the simulation performance indices are satisfactory the identified improvement plans are implemented in the real manufacturing system, so that the envisaged future state can be obtained.

3. Application of the logistics analysis and management technique to a real case study

3.1. The manufacturing system description

The case study is the real manufacturing plant of a world leading Italian manufacturer of forklift trucks, including several types of product families that depend on the forklift truck capacity or load. The production process has a high level of complexity, due to a large number of components, a large number of suppliers, and a large number of types of finished products. In particular, production is characterised by 11 product families and about thousands of final product types, with a high customisation level.

The company manufacturing plant includes three production lines, corresponding to three main product families: electric, diesel motorisation, and gas motorisation forklift trucks. In particular, the so-called IC 15-30 production line, assembling pallet trucks with diesel or gas motorisation and with a capacity that varies from 15 to 30 tons, produces four families of forklift trucks (indicated by F1 to F4 in the sequel) for a total of 20 models (M1 to M20). The selected production line is significantly less efficient than the other two production lines of the
company: the flow of material of the IC 15-30 line generates a large number of waste, particularly of missing parts (i.e., of errors in the management of material flows).

A scheme of the production process of the company is reported in Figure 2 with reference to the considered inefficient production line. Apart from external suppliers that are in charge of outsourcing some types of raw pieces, the main zones of the production area are the carpentry, the painting department, the 10 phases of the assembly line, and several storehouses. In particular, the carpentry area is dedicated to the custom machining of some components required for the assembly. Moreover, in the painting department all the semi-worked pieces are painted. In addition, the area devoted to assembly operations is composed by the selected production line. Two flows of painted components arrive at the assembly line: semi-worked pieces that are purchased from an outside supplier and components that are manufactured in the carpentry area. The first are mostly small components; the latter, on the contrary, are large semi-worked pieces manufactured by the company and stored in the carpentry storehouse. Both streams of semi-worked pieces, with a different supply policy, go into the painting department stock area and successively undergo the painting process.

Once components are painted, they are stored into a dedicated area in the painting department. Painted components finally arrive at the assembly line in different ways, following the previous division into large and small pieces, ruled by a specific supply policy. Here, based on the production orders, a forklift truck belonging to a specific family is produced according to 10 subsequent phases: (1) engine assembly; (2) forklift engine assembly; (3) plumbing; (4) electrical wiring; (5) driving seat assembly; (6) forklift and driving seat assembly; (7) wiring completion; (8) wheels and ballast mounting and fuel supply; (9) coupling; (10) preparation. After these 10 phases, the produced trucks are stored.

3.2. Application of the logistics analysis and management technique: Steps 1 to 5

The proposed technique application starts by analysing the manufacturing system behaviour. Accordingly, the application of VSM to the current process allows obtaining the current state map reported in Figure 3a, showing the material flow, from top to bottom, and the backward information flow. Moreover, Figure 4a depicts the component supply policy; the components provided by the external supplier are received by an employee according to a pull policy (as signalled by the so-called Pull Arrow Icon in Figure 3a) and are provided to the painting department. In addition, the semi-worked pieces arriving from the carpentry department are manually selected by the employee gathering information through visual means (as indicated by the so-called Go See Icon in Figure 3a) and according to a pull policy. After the painting, components are moved by a push policy (as signalled by the so-called Push Arrow Icon in Figure 3a) into the painted components storehouse. Parts are subsequently provided to the assembly line on the basis of the employee’s experience (as indicated by the additional Go See Icon in Figure 3a). In addition, Figure 3a shows that the information flow is managed by the SAP software, starting from the assembly line backward to the beginning of the manufacturing process. In particular, each time a complete forklift truck is assembled, an operator inserts by SAP the use of painted components originating from an external supplier, so that the corresponding storehouse receives an acknowledgement of the material use. A similar process is set up with respect to semi-worked pieces provided from the carpentry department. As the information flow is not automated, the assembly line employee directly communicates the inventory needs to the painting department. The remaining information flow in the current state map is also not automated.

Figure 3a reports the \( m = 25 \) identified system anomalies associated to nonvalue added activities, depicting each of them by the so-called bomb icon. These anomalies, the most significant of which have to be removed, are listed in Table 3 (first two columns).

Hence, Figure 4 reports the detailed activity diagram of the current production process, illustrating in a standardised way the actors, operations, and flows of the production stages in Figure 2 and of the overall picture of Figure 3a. In particular, Figure 4 specifies the actors involved in the process: storehouse employee, carpentry employee, team leader (painting department), painting employee, and phase \( i \) (with \( i = 1 \) to 10) worker. The flows and activities represented in the figure may be summarised as follows. The flow starts with the storehouse and carpentry employee supplying the respective stock area with semi-worked pieces. The team leader of the painting department composes the order list without a precise logic and delivers this list to the painting employee. Then, he loads the semi-worked pieces on the rack, paints them and transports the painted components to the stock painting area. Moreover, the storehouse employee checks the presence in the toolbox of the required painted components and delivers the components to the assembly line. In the assembly line stock area, the worker has two toolboxes for each piece: he takes the piece out of the toolbox and assembles the components. In case of absence of some pieces in one of two toolboxes, the worker removes the empty one and takes the piece out of the other toolbox. On the other hand, if both toolboxes are empty he stops the production and waits for the supply.

Both the location of the icon bombs in Figure 3a and their description in Table 3 show a high level of inefficiency.
Figure 2. The flow chart of the case study manufacturing system.
Figure 3. The as-is (a) and to-be (b) state maps of the case study.
in the assembly line and in the painting department storage area. In the subsequent step of the technique, by the AHP decision-making methodology, the identified manufacturing system anomalies are ranked with respect to \( n = 3 \) assessment criteria. More precisely, as the aim of the manufacturing process is producing a forklift truck with little or no waste or missing parts and with a high level of ergonomics, \( n = 3 \) KPIs are defined as follows: (1) number of wasted parts; (2) number of missing parts; (3) level of ergonomics. Hence, the AHP hierarchy is defined: (1) the first level is the overall goal, i.e., obtaining a complete forklift truck at the assembly line output; (2) the second level is composed by the criteria that contribute to achieving the goal, i.e., the three selected KPI; (3) the third level refers to all the identified manufacturing system anomalies. For each level of the AHP hierarchy (from bottom to top), the contribution of all the subsequent level options to the level is thus evaluated. To this aim, the pairwise comparison matrix \( C_{M0} \) of dimension \( 3 \times 3 \) is determined, evaluating the importance of the \( n = 3 \) criteria of the second level in reaching the top objective as follows:

\[
C_{M0} = \begin{bmatrix}
1 & 5 & 3 \\
\frac{1}{5} & 1 & \frac{1}{3} \\
\frac{1}{3} & 3 & 1
\end{bmatrix}
\]

(4)

Hence, all the other AHP vectors and matrices are determined (not reported for the sake of brevity). The last column of Table 3 reports in a descending order of importance according to AHP the system anomalies, showing that the top problems are those numbered 4, 10, 18, 14, and 21. It is interesting to remark that the top-five ranked criticalities in Table 3 all show that the manufacturing process needs a suitable supply policy to properly manage the material flow. Accordingly, some plant parts need specific areas for parts storage.

After the application of Step 4 of the technique in Figure 1, the to-be state map of the system is obtained,

Figure 4. The as-is activity diagram of the case study.
which is reported in Figure 3b. This is determined removing the 21 assembly line anomalies in Table 3. The remaining four anomalies (the last four lines of Table 3) have not been taken into account because they are due to the painting department that is not the focus of this case study. In particular, Figure 3b includes, with respect to the original state map in Figure 3a, a suitable policy, as signalled by the so-called Supermarket Icon, modelling a so-called 'supermarket' inventory with daily supply and a re-order logic based on a visual check performed by the assigned employee, who verifies whether the supermarket containers are empty and, if this is the case, requests the supply. Obviously, this graphical and compact picture of the system specifies the desired state but is not able to clarify in detail the system actors and activities.

Hence, Figure 5 shows the modifications of the to-be activity diagram, with respect to the as-is one of Figure 4. Note that the complete to-be activity diagram (not reported for the sake of brevity) presents the same actors and activities of the as-is diagram in Figure 4 but includes a novel supply policy between the painting department and the assembly line, that is detailed in Figure 5: in the as-is case (Figure 4) the team leader of the painting department composes the order list without a precise logic. In the to-be case (Figure 5), instead, he produces such a list upon verification of the presence in the stock-painting area of all the painted components. More in detail, the team leader of the painting department checks the presence of all the components in the painting department stock area and provides a list of missing products that is sent to the painting employee.

![Figure 5](image-url)

**Table 3. Identified system anomalies in the current state map and their AHP ranking.**

<table>
<thead>
<tr>
<th>Number</th>
<th>System anomaly</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Presence of type A mudguard in containers of type B mudguards in preparation area</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>Missing type B mudguards in mounting area</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>Lack of specific zone for providing mudguards to assembly line</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>Lack of procurement policy for mudguards</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Presence of footrests with mixed pieces in preparation area</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>Mudguard storage in areas far from mounting area</td>
<td>18</td>
</tr>
<tr>
<td>7</td>
<td>Lack of location for ballast top in XD last phase</td>
<td>12</td>
</tr>
<tr>
<td>8</td>
<td>Missing container for ballast top in XD last phase</td>
<td>14</td>
</tr>
<tr>
<td>9</td>
<td>Impossibility of identification of ballast top in XD last phase</td>
<td>22</td>
</tr>
<tr>
<td>10</td>
<td>Lack of procurement policy for ballast top</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>Lack of location for fixing radiator rod in XD first phase</td>
<td>21</td>
</tr>
<tr>
<td>12</td>
<td>Missing container for fixing radiator rod in XD first phase</td>
<td>13</td>
</tr>
<tr>
<td>13</td>
<td>Difficulty of identification of fixing radiator rod in XD first phase</td>
<td>23</td>
</tr>
<tr>
<td>14</td>
<td>Lack of procurement policy for fixing radiator rod</td>
<td>4</td>
</tr>
<tr>
<td>15</td>
<td>No marking of storage area for mounting line sides</td>
<td>11</td>
</tr>
<tr>
<td>16</td>
<td>Missing container for mounting line sides</td>
<td>10</td>
</tr>
<tr>
<td>17</td>
<td>Presence in mounting line of sides of type B in chassis</td>
<td>19</td>
</tr>
<tr>
<td>18</td>
<td>Lack of procurement policy for type B sides</td>
<td>3</td>
</tr>
<tr>
<td>19</td>
<td>Absence of location for headlight fixing rod in PG mounting area</td>
<td>8</td>
</tr>
<tr>
<td>20</td>
<td>Presence of rear fixing rod for headlight mounting on column in PG mounting area</td>
<td>5</td>
</tr>
<tr>
<td>21</td>
<td>Lack of procurement policy for headlight mounting in PG mounting area</td>
<td>7</td>
</tr>
<tr>
<td>22</td>
<td>Presence of painted mudguards on footrest in painting area</td>
<td>17</td>
</tr>
<tr>
<td>23</td>
<td>Presence of mudguards and sides in painted chassis area in painting area</td>
<td>25</td>
</tr>
<tr>
<td>24</td>
<td>Difficulty of access to ballast top rack in painting area</td>
<td>16</td>
</tr>
<tr>
<td>25</td>
<td>Difficulty of access to Kanbans in painting area</td>
<td>16</td>
</tr>
</tbody>
</table>

![Team leader (painting department)](image-url)

**Figure 5. The activity diagram modifications in the case to-be with respect to the as-is diagram of Figure 4.**
3.3. Application of the manufacturing optimisation technique: Steps 6 and 7

The sixth step in Figure 1 is simulation. Since the assembly line only is modified, addressing the 21 assembly line anomalies and disregarding the painting department waste sources, for the sake of simplicity in this step of the technique only the assembly line is simulated, while neglecting to determine the to-be dynamics of the previous phases in the painting department. Hence, the re-designed production flows are simulated in a discrete event framework, starting from the engine assembling phase (phase 1) and ending with the preparation phase (phase 10). The model described in the to-be UML activity diagram is implemented in the ARENA environment (Kelton, Sadowski, and Swets 2009) by the three step approach recalled in Section 2.6.

The considered simulation analysis takes into account the assembly process of 10 forklifts per day and focuses on the flow of material from the arrival of a production order to the assembly of a complete forklift truck and the availability of the final product. The inter-arrival time of production orders is modelled by an exponential distribution with an average value of 0.1 days. Furthermore, for each new order the kind of forklift to produce is randomly generated on the basis of the corresponding product family, model and equipment (optional or standard) of the forklift truck. Table 4 reports the production rates provided by the company. In particular, the system may produce 20 different kinds of forklift models, and we report on the second row of Table 4 the probability for each kind of model. Note that for each type of family and model the standard (optional) equipment production rate equals 90% (10%). In addition, Table 5 shows the working time for each phases of assembly line and forklift model for the standard and optional configuration.

Further, Table 6 reports all the data used in the simulation for phase 1 with the standard and optional configuration. In particular, all operation times are modelled by a triangular distribution. Indeed, the triangular distribution is

<table>
<thead>
<tr>
<th>Family</th>
<th>Prod. rate</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>19%</td>
<td>42%</td>
<td>23%</td>
<td>16%</td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td></td>
<td>M1</td>
<td>M2</td>
<td>M3</td>
<td>M4</td>
</tr>
<tr>
<td>Prod. rate (%)</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 4. Production rates of product families and models.

<table>
<thead>
<tr>
<th>Product family</th>
<th>Standard equipment [min]</th>
<th>Optional equipment [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>512</td>
<td>487</td>
</tr>
<tr>
<td>F2</td>
<td>527</td>
<td>553</td>
</tr>
<tr>
<td>F3</td>
<td>540</td>
<td>484</td>
</tr>
<tr>
<td>F4</td>
<td>531</td>
<td>522</td>
</tr>
</tbody>
</table>

Table 5. Average forklift working times.

<table>
<thead>
<tr>
<th>Family</th>
<th>Standard equipt. [min]</th>
<th>Optional equipt. [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M1</td>
<td>M2</td>
</tr>
<tr>
<td></td>
<td>68</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>68</td>
<td>90</td>
</tr>
</tbody>
</table>

Table 6. Modal values δ for forklift configurations.
commonly used in situations in which the exact form of the distribution is not known, but estimates of the minimum, maximum and most likely values are available (Kelton, Sadowski, and Swets 2009). In the case study, the working times are estimated by the company; therefore, the minimum and modal values of the distribution coincide because a phase cannot take less than the estimated time, i.e., only a delay is possibly allowed. Table 6 reports the modal values $\delta$, while the maximum and minimum values are equal to $1.2\, \delta$ and $\delta$, respectively. Finally, Table 7 reports all the resources and their capacity in the ARENA model.

The performance indices assumed as relevant measures for the discrete event simulation of the future state and its comparison with the current state are the following:

1. the makespan, i.e., the average time necessary to produce a forklift truck belonging to one of the four product families: it is evaluated as the elapsed time from the beginning of phase 1 until the end of phase 10;
2. the resource utilisation, i.e., the percentage time the workmen resources are busy, considering the utilisation for the engine assembly (phase 1), driving seat assembly (phase 5), main assembling phase (phases 2, 3, 4, 6, 7, and 8), coupling (phase 9) and preparation and delivery (phase 10).

Table 7. Resources and capacities.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
<th>Phase 4</th>
<th>Phase 5</th>
<th>Phase 6</th>
<th>Phase 7</th>
<th>Phase 8</th>
<th>Phase 9</th>
<th>Phase 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workers number</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Buffers number</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Note that all the model assumptions and data are gathered from the historical data provided and reviewed by the company. All the indices are evaluated by a long simulation run of 800 working days with a transient period of 50 days.

More precisely, as each working day includes 8 working hours, the simulation run equals 384,000 time units (where the minute is the time unit) with a transient period of 14,400 time units. The estimates of the performance indices are deduced by 50 independent replications with a 95% confidence interval. Besides, the percentage value of the confidence interval width is evaluated about 2.35%, showing the accuracy of the indices estimation.

Figures 6 and 7 show the simulation results. In particular, Figure 6 compares the makespan of the to-be simulated configuration with respect to the as-is real one and shows that the introduction of a suitable supply policy between the painting department and the assembly line leads to a noteworthy decrease (about 30%) of the lead time. Notice that product family F3 obtains the best improvement. In addition, Figure 7 shows that the resource utilisation of the case study is also improved: in particular, the utilisation of the main assembling phase (i.e., phases 2-3-4-6-7-8) exhibits an overall increase of about 37%. Summing up, by this step of
the technique the improvement of the case study performance is verified and quantified, specifically reducing the lead time and delivery time and increasing the resource utilisation.

The final step of the logistics management technique in Figure 1, i.e., the implementation of the system changes, required about three weeks for full application, and Figure 8 shows the results of the three weeks monitoring of the assembly line with the implemented changes. Figure 8 shows that the introduction of a suitable supply policy between the painting department and the assembly line leads to about a 40% reduction both of waste and missing parts, already after the first week of the monitoring. Remarkably, these KPI are equal to zero after two more weeks. The improvement of the ergonomics level of the system (not reported for the sake of

![Figure 7. The resource percentage utilisation of the simulated case study.](image)

![Figure 8. The KPI resulting from the implementation of the improvement plans.](image)
brevity), which was evaluated by interviews to employees, also shows that the implementation of the technique was successful in improving work places quality, thus reducing accident risks. Summing up, applying the proposed optimisation technique to the case study leads to rationalising the internal logistics, while reducing waste and costs.

4. Conclusions

The article presents a novel systematic technique for performance analysis and improvement of the internal logistics of complex discrete manufacturing systems. The approach is iterative and hierarchical, relying on the integration of tools belonging to several frameworks. In particular, the UML is employed to obtain a standardised and detailed representation of the system, the VSM is used to synthesise the overall picture of the value stream with the system anomalies, the AHP is employed to assess and rank such criticalities, and discrete event simulation is used to verify the dynamics and the resulting performance of the re-designed system when the (major) anomalies are removed. The combination of such techniques allows detecting and assessing the criticalities of the internal logistics of the manufacturing system, leading to evaluate the performance of the re-designed system to obtain the desired improvement.

The novelty of the technique lies in the rigorous integration of well-known manufacturing system optimisation tools, leading to a systematic technique that benefits simultaneously from the advantages of each of them. With respect to the classical VSM technique, the proposed method offers several advantages: straightforward application to complex manufacturing systems, detailing of the process activities while depicting the overall value stream in a high-level picture, quantitative verification of the proposed improvements, ranking the system criticalities and focusing on removing the major ones, for feasibility or cost reasons. The case study is employed to demonstrate the significance of the technique analysis. The lessons learned from the case study indicate that the proposed approach may be useful for decision support.

Future research will deal with two directions. First, the proposed methodology is to be implemented in a decision support tool for automatic and systematic optimisation of the internal logistics of complex discrete manufacturing systems while assessing the system dynamics and corresponding performance improvements. Second, the plan is to adapt the technique to the presence of uncertainty in the manufacturing system data and performance parameters, so as to enable the treatment of randomness or fuzziness that often characterise the model representing a manufacturing system.

Acknowledgements

This work was partially supported by the SMARTT ‘Ritorno al Futuro’ project funded by Apulia Region (Italy). The authors also wish to thank OM Carrelli Elevatori SpA staff, above all Eng. Salvatore Carluccio, for his support in the preparation of this article.

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