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Procedia CIRP 17 (2014) 254 – 259

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Variety Management in Manufacturing. Proceedings of the 47th CIRP Conference on Manufacturing Systems

Quality Value Stream Mapping

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Abstract

Companies in the manufacturing industry today are faced with increasing challenges with respect to cost effectiveness, lead time and quality of the production system. Dealing with these contradictory goals, an important task is the selection of suitable solutions for the integration of inspection processes within the process chain, which are necessary to ensure the required production quality. For this, supportive and easily applicable planning techniques are required to analyze and design the configuration of a respective process chain. Value Stream Mapping (VSM) is a state of the art tool which is very often used for this by professionals. It, however, is not capable of addressing the issue of a suitable integration of testing processes within the process chain. Yet, this provides valuable potential to facilitate the identification of effective testing equipment, testing strategies and quality control loops. Therefore, in this article an innovative approach called Quality Value Stream Mapping (QVSM) is presented. Based on the design elements of VSM, it provides a suitable tool for the visualization, analysis and design of quality assurance measures within process chains in manufacturing. The implementation of the developed approach is exemplarily shown for a complex value chain of a manufacturer in the electronic industry.

Selection and peer-review under responsibility of the International Scientific Committee of “The 47th CIRP Conference on Manufacturing Systems” in the person of the Conference Chair Professor Hoda ElMaraghy”

Keywords: Production Systems Evaluation and Improvement, Value Stream Mapping, Quality Management, Visualization

1. Introduction

Nowadays due to changing customer requirements, there is an increase in product variances and fluctuating order volumes. These challenges are accompanied by shorter product life cycles, intensified cost pressure and rising quality requirements [1]. To remain competitive, manufacturing companies are forced to simultaneously optimize their production in terms of cost efficiency, lead time and quality. Especially in the automotive industry growing production volumes and high quality requirements involve difficult challenges in the field of quality assurance. Thus, easily applicable planning techniques are required to analyze and design the configuration of a respective process chain in order to deal with quality issues. In this article the approach of Quality Value Stream Mapping (QVSM) is introduced which combines the method of classical Value Stream Mapping with the field of quality management.

The article is structured as follows. In chapter 2 existing approaches in the field of process and quality oriented analysis and visualization of production systems are stated. Hereafter, the developed method of Quality Value Stream Mapping is elaborated in chapter 3 and an exemplary industrial application demonstrated in chapter 4. Finally, chapter 5 concludes with a summary.

2. State of the Art Methods of Process Analysis and Quality Management

2.1. Business Process Analysis

A business process is a collection of activities taking one or more kinds of input and creating an output that is of value for the customer [2]. There are various approaches in the field of Business Process Management (BPM) dealing with the analysis, design, configuration, enactment and evaluation of processes [3]. The modeling of the process flows can be realized by means of different languages, e.g. petri nets [4] or the Business Process Modeling Notation (BPMN) [5].

The approaches of business process analysis cope with the identification of weaknesses and potentials for improvement [6]. Improvement objectives of these approaches include a reduction of costs, process times and defect rates. Yet, none of the approaches specifically deals with the visualization and analysis of quality defects in production processes.

2.2. Value Stream Mapping

Value Stream Mapping (VSM) is a simple but effective method used for the illustration and redesign of value streams. The method originates from the Toyota Production System [7] and consists of two main phases: value stream analysis, in

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doi:10.1016/j.procir.2014.01.093

which the current value stream is visualized, and value stream design, in which sources of waste within the production process are uncovered and reduced.

The method targets at a lean, dynamic and customer controlled value stream, with short lead time and reduced inventories [8, 9]. It is widely used in industrial practice. However, within classical Value Stream Mapping quality defects are only addressed in a very rudimentary manner. Inspection processes, their characteristics and the present quality control loops are not considered in the visualization.

2.3. Process Failure Mode and Effects Analysis (FMEA)

Process FMEA is a systematic method to analyze defects of manufacturing and assembly processes. According to the VDA framework [10] the method consists of the five steps structure analysis, function analysis, failure analysis, measure analysis and optimization. Within the structure analysis the considered process chain is systematically structured into individual process elements. In the functional analysis, for each element of the structure analysis, activities are assigned necessary for proper function of the process chain. Within the failure analysis the occurrence of defects within the manufacturing processes is determined. In the measure analysis potential defects are classified by the concept of risk priority numbers (RPN). Depending on the RPN, optimization measures to reduce quality issues can be implemented [11].

Process FMEA is a very effective and widely used tool to identify causes of defects and appropriate prevention measures. Yet, it does not include any visualization of the process chain regarding the occurrence of defects, inspection processes or quality control loops. Neither, quality related costs are taken into account.

2.4. Process Mapping

Process Mapping is an established tool for the visualization of processes. In comparison to process models of Business Process Analysis, Process Mappings contain considerably more details [12, 13]. A Process Mapping is a graphical illustration that shows a sequence of activities using flowchart symbols. A further objective of a Process Mapping is to identify output variables (customer critical features) and input variables (impact on critical features) of each process step. Additionally, controllable factors (e.g. rotational speed) and disturbance variables (e.g. vibrations) are also regarded [12].

Process Mapping is commonly used as a tool within the Six Sigma methodology. In the DMAIC (Define-Measure-Analyze-Improve-Control) circle it is applied as a process visualization method within the Measure phase.

Process Mapping is a very valuable method for the visualization of process flows taking into account the aforementioned key figures. Yet, it does not cope with the quality-related aspects of defect rates, inspection processes, quality control loops or quality related costs.

2.5. Stream of Variations

Stream of Variations (SoV) is a generic math model for the analysis and performance prediction of multistage manufacturing processes in which product geometry and dimensional variation are of critical importance. SoV integrates key processes, product characteristics represented in CAD/CAM models, information on the process layout, the sequence of operations and the production system observability into a unified framework [14, 15].

SoV is an effective measure to improve quality by means of variation reduction. Yet, it is mathematically very complex and does not focus on process visualization. Furthermore, quality related costs are not analyzed in detail.

In sum, the state of the art shows that there are various methods for the visualization and analysis of processes. Yet, none of these approaches is capable of addressing a suitable integration of inspection processes, quality control loops and quality-related costs within a method for the visualization and analysis of multistage manufacturing processes.

3. Method of Quality Value Stream Mapping (QVSM)

The method of quality Value Stream Mapping addresses this issue. QVSM is a procedure model, complementing classical Value Stream Mapping with specific quality related elements to systematically visualize, analyze and improve quality issues within a process chain. In addition to the production processes and flow of materials, present quality defects, quality inspections and quality control loops are considered. Based on this, the status of the quality control along the process chain is evaluated in terms of key indicators with regard to quality and quality-related costs.

Similarly to conventional VSM, in the concept of QVSM the term "value" is defined as the opposite of waste. However, due to the special focus on quality control in QVSM, the reduction of defects as a type of waste and the identification of suitable measures for this are emphasized.

The presented method of QVSM consists of four phases: preparation, quality value stream analysis (QVSA), quality value stream design (QVSD) and implementation. In the following, these phases are elucidated in detail.

3.1. Preparation

Similarly to conventional value stream analysis, QVSM starts with a preparation phase providing a basis for further recording and analysis of the value stream. The preparation phase consists of three steps (Fig. 1).

First, a product or product family to be analyzed is selected to reduce complexity as far as possible. Second, fundamental process knowledge of the process chain to be considered is obtained, e.g. by means of a SIPOC analysis [16]. Third, the quality targets of the analysis are defined, e.g. a reduction of defects or a decrease of the quality-related costs.

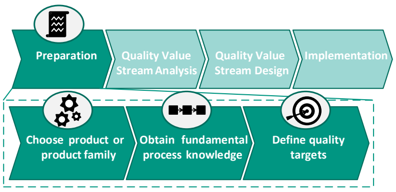

Fig. 1. Steps of preparation phase

3.2. Quality Value Stream Analysis (QVSA)

On this basis, the quality value stream analysis is carried out. This phase and the following phase of quality value stream design are the core parts of the QVSM methodology. QVSA is divided into five steps (Fig. 2).

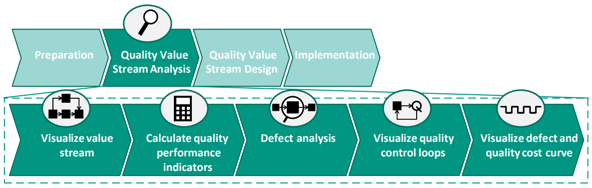

Fig. 2. Steps of quality value stream analysis phase

First, all relevant processes within the value stream of the considered production line are visualized similarly to the procedure of classical VSM. However, in contrast to VSM quality-related processes such as quality inspections, rework processes and scrapping processes are additionally mapped (Fig. 3). For inspection processes a specific symbol is introduced. Thus, all inspections according to a present inspection plan can be comprehensively included into the value stream visualization.

Second, relevant quality performance indicators are calculated and noted into an information box below the respective inspection process in the value stream visualization (Fig. 3). Important indicators are the amount of inspected parts respectively the scope of inspection of each inspection process and the respective inspection characteristics. At inspection station n, PI_n parts are inspected, having Num_{icn} inspection characteristics, and ND_{nk} defects are detected. Based on this, the defects per million opportunities ($DPMO_n$) rate with respect to inspection process n can be calculated:

$$DPMO_n = \frac{\sum_{k=1}^{Num_{icn}} ND_{nk}}{PI_n \cdot Num_{icn}} \cdot 1.000.000 \qquad (1)$$

For each of the inspection characteristics of an inspection process the inspection process capability based on a Measurement System Analysis (MSA) [17], the number of detected defects (ND) and the resulting process capability index (PCI) [18] are determined. Based on a suitable rating scale, the status of the PCI is highlighted in green, yellow or red in the value stream visualization depending on the analyzed process capability (Fig. 3). This enables a clear visualization of the inspection characteristics into the value stream and prioritization of those according to their process capability.

Third, within the defect analysis the causes of quality defects are investigated. The analysis is supported by tools such as Ishikawa analysis [19]. The resulting causes of defects are noted into information boxes below the corresponding production processes in the value stream visualization (Fig. 3). Thus, a mapping of the causes of defects within the value stream is realized.

Fourth, based on the defect analysis, quality control loops are drawn into the diagram linking the existing quality inspections with the targeting causes of defects. Each quality control loop is characterized by a risk priority number (RPN) prioritising the risks of the causes of defects. According to the procedure of Failure Mode and Effects Analysis (FMEA), the RPN depends on the relevance of the defect (R), the probability of the occurrence of the cause of the defect (O) and the probability of the detection of the defect (D) [20]. All indicators are rated from 1 to 10 on the basis of the VDA framework [10]. The relevance is a measure of the effect of a defect. It depends on the consequences for the customer, if the defect is not identified before delivery to the customer. The process capability index provides a reference for the occurrence probability. The lower the process capability index, the higher is the probability of the occurrence. The probability of detection is determined by the effectiveness of the inspection method to discover a cause of a defect. The higher the inspection process capability, the higher is the probability of detection.

The risk priority number is calculated as the product of the aforementioned three factors [10]:

$$RPN = R \cdot O \cdot D \quad ; \quad R, O, D \in [1, 10] \qquad (2)$$

The status of each quality control loop corresponding to the calculated RPN is visualized in the value stream diagram by green, yellow or red arrows (Fig. 3) based on a suitable scale, e.g. according to the VDA framework [10]. In sum, the visualization of the quality control of the entire production line provides a structured and comprehensive overview of the current state of the quality assurance.

Fifth, the overall status of the production line is evaluated with respect to both, the occurrence of defects and of quality-related costs. The evaluation is visualized by means of a defect curve and a quality cost curve below the value stream (Fig. 4). For each of the quality inspection processes (Num_{qi}) the number of defects (ND) of all inspection characteristics (Num_{ic}) is determined. Moreover, for each of the rework processes (Num_{rp}) the number of reworked defects (NR_i) and for each customer (Num_C) the number of defects identified from the customer (NC_l) are calculated. The occurrence of the defects at the inspection processes, their elimination at the rework processes as well as the customer reclamations are visualized in the defect curve below the value stream. Based on the aforementioned figures, the cumulated number of defects of the production line (ND_{cum}) can be calculated:

$$ND_{cum} = \sum_{n=1}^{Num_{qi}} \sum_{k=1}^{Num_{ic}} ND_{nk} - \sum_{i=1}^{Num_{rp}} NR_i + \sum_{l=1}^{Num_C} NC_l \qquad (3)$$

Similarly to formula (1) the cumulated DPMO rate of the production line ($DPMO_{cum}$) can be determined:

$$DPMO_{cum} = \frac{ND_{cum}}{\sum_{n=1}^{Num_{qi}} PI_n \cdot \sum_{n=1}^{Num_{qi}} Num_{ic}} \cdot 1.000.000 \qquad (4)$$

Furthermore, for each process all relevant types of quality-related costs are determined. Quality-related costs can be classified into the prevention costs (PC_n) of each of the processes (Num_{pro}), the inspection costs (IC_i) of each quality inspection (Num_{qi}), the rework costs (RC_j) of each of the rework processes (Num_R), the scrapping costs (SC_k) of each of the scrapping processes (Num_S) and the customer reclamation costs (CC_l) of each customer (Num_C). The occurrences of these cost types at each process in the value stream are visualized in the quality cost curve (Fig. 4). Thus, in sum the overall quality-related costs (QC) of the production line can be calculated as follows:

$$QC = \sum_{n=1}^{Num_{pro}} PC_n + \sum_{i=1}^{Num_{qi}} IC_i + \sum_{j=1}^{Num_R} RC_j + \sum_{k=1}^{Num_S} SC_k + \sum_{l=1}^{Num_C} CC_l \qquad (5)$$

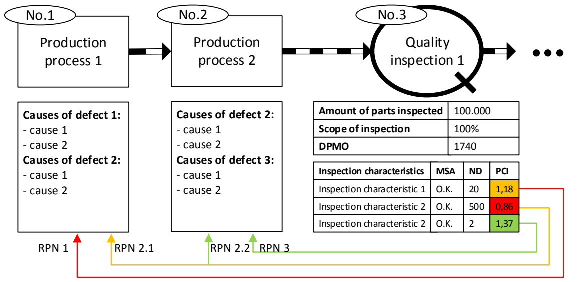

Fig. 3. Visualization of fundamental symbols and quality control loops

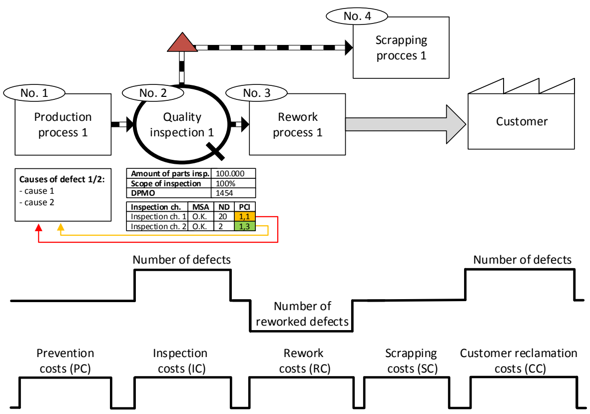

Fig. 4. Illustration of a value stream including defect and quality cost curve

3.3. Quality Value Stream Design (QVSD)

Aiming at the improvement of the quality value stream in terms of reduced rates of defects, lower RPNs of the quality control loops and lower quality-related costs, quality value stream design consists of three steps (see Fig. 5).

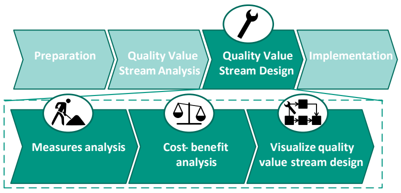

Fig. 5. Steps of quality value stream design phase

First, a measures analysis is conducted based on three design guidelines:

1. Reduce the probability of defect occurrence
2. Increase the probability of detection
3. Decrease the quality-related costs

Second, in a cost-benefit analysis it is examined, which of the considered improvement options is economically advantageous.

Third, the desired target state including all improvement measures is visualized in the QVSM diagram. Changes and corrective actions are illustrated by a kaizen flash. Fig. 8 shows an exemplary kaizen flash where the production process is extended by a poka-yoke measure.

3.4. Implementation

In the last phase of QVSM the desired target state defined in the QVSD is implemented. The implementation phase is divided into 3 steps (Fig. 6).

First, an action plan is worked out. The plan includes all important steps to implement the measures as well as milestones and responsibilities.

Second, the measures are realized step by step according to the action plan.

Third, after the implementation of the measures it is necessary to control, whether the defined measures actually lead to the desired benefit. If not, the reasons have to be analyzed and the measures may need to be adjusted.

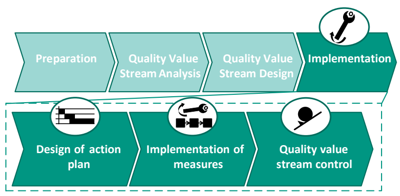

Fig. 6. Steps of implementation phase

4. Exemplary Application of Quality Value Stream Mapping

Illustrating the approach of QVSM, the methodology was exemplarily applied to a process chain of a midsize electronic company with very high quality requirements. As an OEM supplier in the automotive industry, the company produces electronic assemblies in highly-automated production lines.

4.1. Preparation

The application of QVSM is demonstrated for the analysis of a Surface-Mount-Device (SMD) production line of an air-conditioner fan control. To obtain fundamental process knowledge, first a SIPOC-Diagram was prepared. The selected target was to increase the quality level and at the same time reduce the quality-related costs.

4.2. Quality Value Stream Analysis

In the quality value stream analysis, the value stream of the SMD assembly was visualized. The production line could be divided into three sections: Data Matrix Code (DMC) labeling, soldering paste printing and SMD placement. All sections consist of production, rework and scrapping processes as well as inspection processes. Fig. 7 illustrates the SMD placement section.

After this, the relevant quality performance indicators were determined. Most data were obtained from the controlling or the quality assurance department. All information was related to a period of six months. As key figures characterizing the processes, process capability indices were calculated and a suitable color scale defined (Fig. 7).

Hereafter, based on the existing information the main causes of each defect were identified by means of Ishikawa analysis and illustrated in the corresponding text boxes underneath each production process. The dominating red and yellow colors in Fig. 7 of the process capability indices highlight the insufficiency of the quality level of the production processes in the initial state.

Next the risk priority numbers were calculated according to a FMEA analysis by means of the VDA scale [10]. On this basis the quality control loops were visualized as shown in Fig. 7 ($RPN \leq 50$ green, $RPN \geq 50$ yellow, $RPN \geq 125$ red). As most of the control loops are colored red or yellow, it is obvious that a lot of the existing quality assurance measures are not sufficient to cope with the quality requirements.

In the following, the defect curve was visualized. The total number of defects and the cumulated DPMO rate of the production line were calculated according to formulas (3) and (4) as shown in Fig. 7. During the time period of six month 3331 defects corresponding to a DPMO of 646 resulted from the production line.

For the determination of the quality costs curve all relevant quality-related costs of the SMD assembly (inspection costs, rework costs and scrapping costs) were calculated. As the SMD placement line only has an internal customer within the company, customer complaint costs were neglected. There were no prevention costs, either. The resulting quality cost curve is illustrated in Fig. 7. In total, the entire quality-related costs of the air-conditioner fan control manufactured on the production line over 6 months were 8.941€.

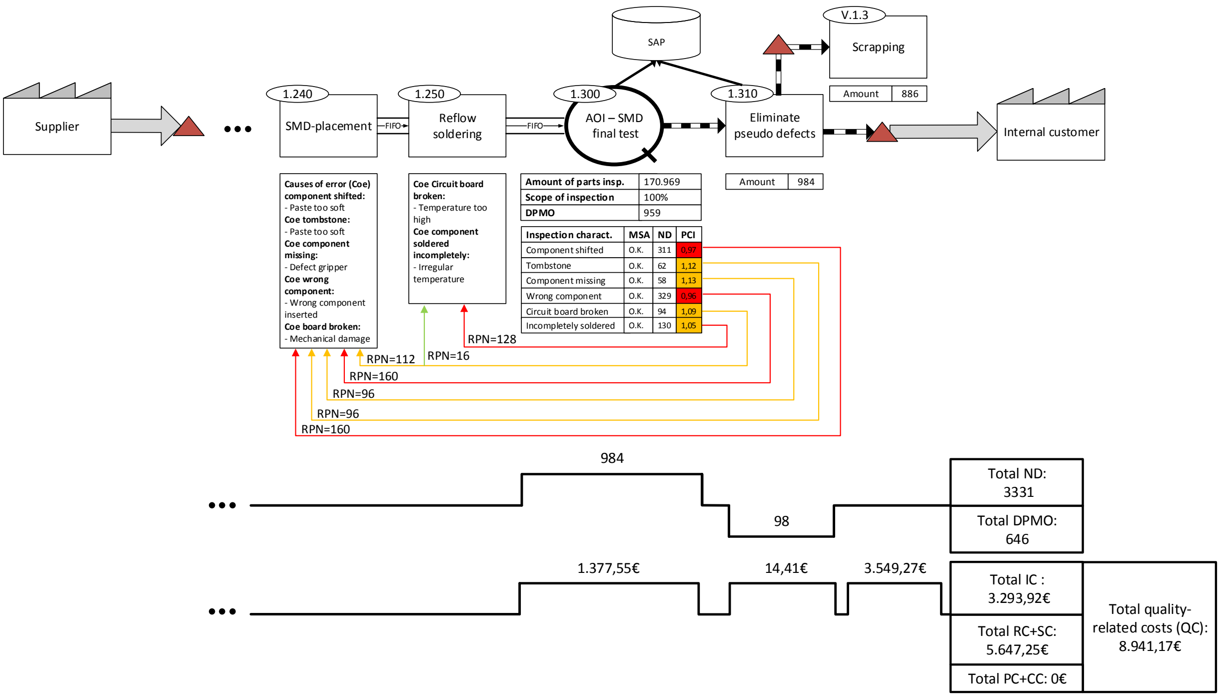

Fig. 7. Exemplary Quality Value Stream Visualisation of the status quo of the SMD placement

4.3. Quality Value Stream Design

Within the quality value stream design two of the most critical processes were identified based on the RPN of the quality control loops and the cost curve.

The first measure aimed at reducing the probability of the defect occurrence of the inspection characteristic “wrong component” at the inspection process “AOI - SMD final test”. As main cause loading of wrong components to the pick-and-place machine by the operating staff was identified. To avoid this, a constructive poka-yoke measure based on a barcode scanner was suggested leading to an approx. decrease of the defect rate of this inspection characteristic by 80% (Fig. 9).

The second measure targeted at reducing the rework costs. The inspection characteristics “component shifted” and “tombstone” at the inspection station “AOI - SMD final test” showed high RPN of the quality control loops. Yet, by means of rework processes, it was possible to eliminate the defects after the SMD placement. The time-consuming, manual rework process, however, caused high costs. Thus, the measure of an installation of an additional automated optical inspection (AOI) followed by two simple rework processes was suggested (see Fig. 8). It could be assumed that for these no additional personnel capacity was required.

After the development of the two possible improvement measures, it was checked, if these were economically reasonable. Approximating the investment costs of the poka-yoke measure as 3.000€ and of the additional AOI as 50.000€ and assuming linear depreciation, the cost-benefit analysis showed a positive cost-benefit ratio for both measures. So the implementation of both measures was advantageous.

Finally, the new quality value stream for the improved target state was visualized. After calculating the new defect and cost curve it could be seen, that the measures reduced the number of defects by 573 as well as the quality-related costs by 1463€ in the considered time period of 6 months (Fig. 9).

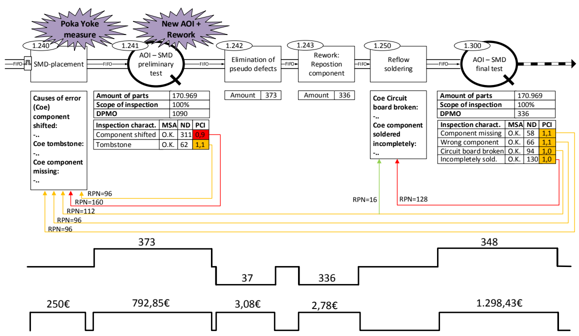

Fig. 8. Quality Value Stream Visualization of target state

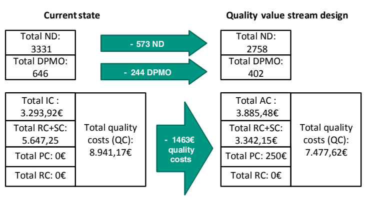

Fig. 9. Improvements by exemplary measures

4.4. Implementation

In the implementation phase, an action plan was designed, before the measures were implemented. Finally, the improvement success was controlled by a check of the key figures after implementation.

5. Conclusion

The developed method of Quality Value Stream Mapping is capable of systematically visualizing, analyzing and optimizing multistage manufacturing processes from a quality assurance viewpoint. The procedure model consists of four consecutive phases: preparation, quality value stream analysis, quality value stream design and implementation. The method enables the visualization of inspection processes, quality key indicators and quality control loops within the process flow. Moreover, the quality-related costs of the production line are illustrated. QVSM, furthermore, integrates common quality management tools such as Ishikawa analysis and FMEA in a structured way. The advantages of QVSM were demonstrated by means of an exemplary application of the method in an industrial case study. In this example both the rate of defects and the quality-related costs were reduced.

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