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Digital real-time feedback of quality-related information to inspection and installation areas of vehicle assembly

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Abstract

The article presents an information technology model for the transparent feedback of quality-related information on the vehicle assembly production process in real time. This system integrates huge amounts of heterogeneous data sets, gathered through quality gates in the assembly line, to provide new user-focused information for controlling production quality. All information is prepared to cater to the specific needs of three different types of users and then reported back via four levels of quality feedback to the recipients as a defect occurrence in quality. This ensures that quality-related process information is provided immediately as essential to make progress towards achieving first-time quality and improving production quality.

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1. Introduction

A manufacturing company faces various challenges which decisively influence production. In addition to the increasing complexity and variance of assembly through a wide range of customer requirements and the change from mass production to mass customization [1-6], the high flexibility demands through the dynamic, crisis-prone environment [7-9], coupled with the increasing challenge of data, information and process transparency [1, 9, 10] due to JIS production, the compatibility with cost targets in particular poses a major challenge for businesses [11].

Quality, differentiated between product quality and production quality, is thus a decisive factor in market competitiveness. In addition to production at competitive costs and delivery within a reasonable time, a company needs to offer products with flawless quality – to maximize the product quality. An enterprise endeavors to manufacture the products from the outset with zero defects under the challenging conditions in accordance with the zero-defect principle [12] – to maximize production quality. In automotive production, the assembly step is characterized by various manual activities[1] which entails an increased defect risk along with the associated rework costs [1]. Maximization of product and production quality and minimization of the quality costs for necessary rework requires digital feedback of quality information in real time to the responsible individuals and locations within the context of "Quality 4.0" [13].

1.1. Challenges of quality feedback

The compatibility between cost minimization, especially of rework costs, and quality maximization poses a major challenge for manufacturing companies [8, 14].[2] One measure is to implement a *Quality Feedback Model* (QFM) in order to report information as quickly as possible back to all the relevant actors and locations to augment quality awareness and knowledge.

[1] Assembly accounts for approx. 20-70% of direct labor costs [2, 14]
[2] Cf. magic triangle: compatibility of time, costs and quality

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Nonetheless, the implementation of a targeted QFM proves just as challenging as ensuring the compatibility of cost and quality targets. A consistent closed-loop must be developed to control quality information by fully recording necessary data and thus generating reliable information – extracting smart data out of big data [15]. Moreover, data processing must be defined such that the defect prevention process can be initiated at the end of the process. Such control requires technologies of the emerging Industrial Internet of Things (IIoT) [16] such that the necessary information frequency and accuracy can be ensured – right information in the right place at the right time.

While many approaches to quality feedback focus on technical aspects of innovation, one important factor is often overlooked [8]: the individual who is responsible for delivering high-quality products in the value chain. Hence, a *QFM* needs to involve all those individuals taking part in the process in order to respond rapidly to dynamic changes in the human-system collaboration [2, 17].

1.2. Current status of quality feedback in vehicle assembly

The level of intensity and usability of quality feedback varies widely among automotive manufacturers [18-20]. Certain manufacturers have completely automated quality feedback in real-time embedded in the production line, while others only manually digitize defect recording, but continue to implement the reporting without any digitization, automation or real-time constraints. In particular, various system and media incompatibilities as well as a lack of user orientation through non-standardized information hamper optimum quality feedback. Consequently, the information chain of the quality feedback process is impeded, slowed down and its quality impaired at this point. [21]

These kinds of manual and analog quality feedback processes make the system highly prone to errors and potentially delay reporting. This causes a variation in quality in the corresponding quality section inspections, delays defect prevention and gives rise to other defects at the source and generates quality costs. The delay in feedback causes fluctuations in the system and creates inertia. For this reason, the creation of consistent quality feedback processes in real time with high user orientation is a basic prerequisite for moving toward first-time quality and maximizing production quality.

1.3. Aims of the QFM

The introduction of a QFM should primarily help an enterprise to achieve its defined quality targets, but also reduce the costs of quality production and assurance. Likewise, the objectives of improving production systems and added-value chains [22] also coincide with the perspectives of Industry 4.0. It meets the demand of Industry 4.0 application scenarios to access relevant information at the suitable production points across the entire added-value process on the assembly line [23]. Following objectives are met in addition:

- Laying the foundations for robust processes [24, 25]
- Creating a tool for consistent reporting [8]
- Ensuring quality is delivered by minimizing quality slip
- Reducing repeat defects by identifying systematic defects
- Provisioning rapid quality feedback loops by involving workers in the quality production process (awareness) [8]
- Maximizing product and production quality
- Minimizing quality costs
- Implementing a learning hybrid quality system[3]

2. Requirements

2.1. Quality requirements

For a common understanding, the term quality has to be defined and specified by its individual attributes. Quality is standardized by the ISO as the degree to which a set of inherent characteristics of an object fulfils requirements [26]. It is evaluated through the conformity to the desired condition of its (inherent) quality characteristics. Thus, quality characteristics are distinguishing features [26] of a specific object which represent the quality categorized by Table 1:

Table 1. Categorization of Quality Characteristics

	Qualitative Characteristic		Quantitative Characteristic	
Type	nominal	ordinal	discrete	continuous
Scalability	naming	evaluating	counting	measuring

The *measurability of quality* is important to evaluate quality through its individual *quantifiable and measurable characteristics*. These characteristics with its degree of consistency between target and actual state shall be reported back to the concerned persons which results in the requirement for *visualization of quality* through quality characteristics. Only by this way, the degree of fulfillment of the object requirements and the quality achievement can be determined which leads to the ability for quality production.

In order to achieve these requirements, the quality characteristics shall be represented in a user- and process-oriented manner through a *quantifiable quality model*. Moreover, it is necessary to *transform these information* about the degree of consistency between target and actual state *into a minimization of inconsistency* – in general to transform into quality information. Through the quantifiable quality model and the scalable quality features, it is possible to achieve that:

- the degree of consistency between target and actual quality can be precisely controlled,
- the deficiencies of the quality characteristics can be minimized, and
- the desired scalable quality by the quality characteristics can be produced.

2.2. System requirements

The QFM system shall provide users with *information on quality* as a prerequisite for the user requirement regarding the

[3] Hybrid system means a collaboration of human and (IT) system

knowledge of quality. This information shall be *extracted and aggregated* [13] from the available data to provide efficient analysis and be *processed in line with user needs* so it can be used effectively. Further requirements include *automated quality feedback* within the system as well as *real-time feedback* to respond quickly [27] to quality deviations.

Further requirements encompass the creation of *transparency through visualization* and the provisioning of *interfaces to other systems*. The system shall support *rapid, system-side input of quality defects*. Associated with this is the demand for a *learning quality system* for focused defect recording and visualization. In this way a complete, realistic database for quality feedback processes can be generated.

2.3. User requirements

In order to avoid inadequate involvement of the persons taking part in the quality feedback (section 1.1), there are requirements on system users and other actors [2, 28].

The *knowledge of quality* constitutes one major requirement. All users shall be trained to deliver quality and made aware of the quality-critical factors. Users obtain this knowledge by various systems and the QFM providing them with quality information. Thus, high quality can be delivered and validated including the provision of an adequate feedback.

This requires, on the one hand, *quality delivery skills* so as to transform the information about the defects and deviations of the specific quality characteristics reported-back directly into quality by avoiding the same defects and deviations in upcoming assembly processes. On the other hand, it takes *quality inspection skills* in order to inspect quality correctly by analyzing the specific quality characteristics and report back the correct quality information about the defect attributes and the degree of consistency between target and actual state of this individual characteristic.

Linked to this is the compulsory requirement and the motivation for users to *input quality defects* into the system, in order to ensure a consistent database and full transparency.

Once the quality has been reported back, quality defects identified from the quality inspection shall be eliminated by means of *defect prevention skills*. This is the only way of achieving higher product and production quality while also reducing the quality costs.

2.4. Process requirements

The quality feedback process shall be kept *manageable and lean* for expedient control. In this respect, actors, locations and feedback levels should be specified in particular and selected in line with the objectives according to the maxim "as much as necessary, as little as possible." In addition to ensuring complete *automation* and *real-time feedback* at process level, the process shall also facilitate, and, at the same time, ensure that the quality defects are fully recorded.

3. Users

The individuals involved in the process constitute the core elements of the QFM. Particularly the inspecting quality sensor, the quality controller and the value-creating quality actuator provide the focus [11, 29]. Thus this model represents a socio-technical quality control loop [30].

3.1. Quality gate

The task of the quality gate (QG) is to systematically compare the actual status of quality characteristics with the target specifications of a product or process. Deviations on the vehicle and its components should be identified, documented as quality defects and details reported back to the system. In assembly, a human quality inspector or a technical quality inspection system carries out the role of the QG; the theory of feedback loops talks about a quality sensor.

3.2. Defect prevention manager

The task of the defect prevention manager (DPM) is to identify and analyze the cause of a deviation from quality targets – in particular the scalable inconsistency between target and actual state of the quality characteristics. The defect prevention process should be initiated by means of the analysis findings. In the defect prevention process chain, the DPM is the first management entity which takes decisions about the measures to be taken on the basis of the quality information from the upstream QG – a supervisor, process or quality engineer carries out the role of the DPM; it is the quality controller in the theory of quality feedback loops.

3.3. Defect manager

The scope of the tasks of the defect manager (DM) covers the coordination, implementation and performance of self-checks on the measures that deliver a maximum convergence to the desired scalable value of the quality characteristics. Implementing the items commissioned by the DPM directly delivers quality and creates value with regard to the product and/or process. In assembly, a worker, assistant or reworker assumes the role of the DM; this is the quality actuator in the theory of quality feedback loops.

4. Conception of the QFM

A quality control loop relies upon quality information [31]. This loop must feature a backward quality information flow [32] in order to report back to the locations that deliver and inspect quality [33]. The QFM is characterized as a horizontal quality control loop [29, 33] and is divided up into four individual levels. These constitute a dedicated information flow between the actors, but interact together to facilitate the fastest possible quality feedback.

4.1. Quality feedback at the actual quality gate

QGs are quality sensors for quality assurance purposes of an assembly section. This includes the quality inspection and the recording of quality deviations. However, identifying key defect areas proves problematic since statistical digital real-time feedback of the findings to the QGs is often not provided.

A variable percentage of defects slips by the QG and may end up as a quality defect that is recognized by the end customer.

The first level of the quality feedback resolves this information gap by means of an overview of defect occurrences and the key defects, grouped and accumulated in descending order according to a certain defect pattern (consisting of the model series, component and defect type). The recorded quality data is processed for the QG in real time in line with user requirements to provide reliable information (smart data) and visualized by means of graphical CAD data. This extends the transparency across production quality in the actual assembly section. To ensure that complete quality assurance can be guaranteed in the form of a small quality feedback loop and the variation in quality minimized, a camera system can also be incorporated as a technical QG for quality monitoring and feedback to the human QG [10].

Through this level, the key defects can be shown to the actual assembly area; on the one hand, the human QG can be encouraged to inspect the quality characteristics more closely and, on the other hand, the specific rework focused on the key defects. Similarly, collaboration between human and technical QGs can be used to minimize the variation in quality, thus bolstering the QG quality control loop.

4.2. Quality feedback to the responsible quality gate

Experience from industry shows that defect-free quality assurance in the assembly section cannot be guaranteed despite human and technical QGs. Defects go undetected at the QG and constitute a variation in quality (slips). In order to prevent this, the QG must be informed about this variation in quality. This prevents further vehicles with identical defects from slipping through in the same assembly section.

This is implemented via the second level of quality feedback. A QG discovers a defect and enters this into the system. This defect, providing that it must have been identified previously on the basis of its defect pattern, constitutes a variation in quality of an upstream QG and is reported back by the system in real time to the responsible QG. While established defects still have to be recorded manually by the QG or, where applicable, recorded automatically by a technical QGs, that information is now reported back automatically in real time to the responsible QG without any media or system incompatibilities.

The responsible QG is thus made aware of the increased need for closer inspection of the evident variation in quality. In this way, the responsible QGs can be reinforced through real time-oriented information flows and defects identified early on through increased transparency. The quality control loop of the QG can also be reinforced through this level.

4.3. Quality feedback to the defect prevention manager

Once a defect has been reported back in level 1 to the actual QG as defect occurrences and in level 2 reported back to the responsible QG as a variation in quality, the defect prevention manager now needs to be informed. Details of a systematic defect should not only be reported back, but, above all, prevented long term. From a certain frequency or a priority and/or a degree of severity, the defect must be reported to the Quality Controller for a permanent prevention of the defect.

This quality feedback constitutes the third level of the QFM. In the event of extraordinary and systematic quality deviations, which follow a certain frequency within a period or a trend, the responsible DPM is automatically informed in order to take immediate action and initiate the permanent defect prevention process. Quality information on group attributes such as the defect pattern, period and, where applicable, cause with potential person responsible must be suitably processed in order to initiate effective defect prevention measures in a timely manner. Only if this information is provided fully and correctly, the effectiveness of the applicable defect prevention measures can be guaranteed. Once the defect prevention process has been initiated, details of the effectiveness and sustainability of these measures must also be reported back, so more effective measures can be triggered where defects continue to occur.

4.4. Quality feedback to the defect manager

Via the fourth level the DM receives information on the defect symptom, on the defect cause and on defect prevention measures. As a result, the rework and the direct quality development are initiated by preventing the identical defect in the affected assembly station. It is important that the cause of the quality deviation is reported back since the DM acts as the learning organization in the quality control loop and consequential defects of the identical defect can be prevented.

Defects occurring at a QG can be reported back in real time to the potential originator via the fourth level. Due to the rapid feedback processes and the transparent quality presentation, further defects can be prevented directly at the source. Thus the assembly station's quality control loop can be reinforced, thereby moving much closer to delivering first-time quality.

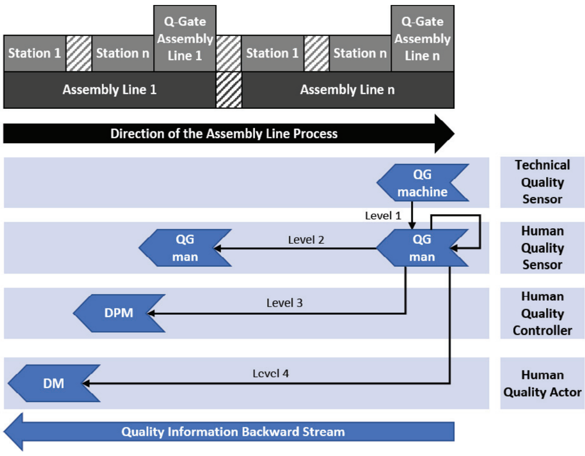

Fig. 1. QFM

5. Industrial application

The model was validated over a continuous period of exactly one year in production operation both in small-series and volume-series production of a vehicle assembly.

Implementation of the QFM enabled notable successes to be achieved in increasing the product and production quality. The throughput rate of zero-defect vehicles was increased by 7.1%; the percentage defect rate, however, rose by 13% year-on-year. The increased defect rate is attributable to the improved transparency and sensitivity regarding quality in the assembly line. Improved defect transparency in real time enables quality defects to be reworked faster in the line so that the production run is not jeopardized.

It is also noteworthy that the number of defect prevention measures in the first phase of the model has been increased by 8%. This is due to the increased defect rate and to the transparency regarding the quality defects which were found and slipped through. Quality defects, especially hot spots, were identified faster and more frequently in the direct follow-up. This identification led to faster defect prevention measures, to an increased throughput rate of zero-defect vehicles, and ultimately to improved production quality.

6. Classification in the RAMI 4.0

The Reference Architecture Model Industry 4.0 (RAMI 4.0) [34] provides essentially two basic conceptual models:

- a three-dimensional framework in which scenarios, ideas, assets and concepts may be clearly positioned across value chains and the lifetime of asset types and instances, and
- an Industry 4.0 component (I4.0 component) that provides an abstraction shell around an asset or a composition.

Quality in production is a clear objective of the Industry 4.0 initiative. As a consequence, RAMI4.0 and emerging Industry 4.0 architectural approaches, solutions and standards may be used and exploited for the implementation of the QFM.

6.1. Positioning in the RAMI4.0 Framework

The RAMI4.0 Hierarchy Levels consider and classify all the asset types that are in the scope of Industry 4.0. It is an extension of IEC 62264 and IEC 61512 in the sense that the “product” being produced is considered to be an asset itself as well as the so-called “connected world”. Hence, the Industry 4.0 scenarios that focus on the interaction between products and production plant components (“a product is seeking for a fitting machine for the next processing step”) may be modelled. Furthermore, by including the connected world, both intra-logistic and logistic aspects between enterprises (e.g. material flows in supply chains) may be modelled.

The focus of the QFM is on quality information at product level. However, during the production process, the product has relationships to other asset types such as assembly stations, quality gates and overriding working areas. In fact, in order to not only gather, assemble, aggregate and interpret product-related quality information, but also to search for quality defect causes and propose improvement, also status information about the production plant components including material flow is required. Hence, a holistic QFM would encompasses all asset hierarchy levels. However, this article focuses on product-related quality information and its structural relationship to other asset types, especially *Product*, *Station* and *Work Centers*.

The RAMI4.0 dimension *Life Cycle & Value Stream* is based upon IEC 62890 and represents the life cycle of both asset types and instances, thus representing both the design and engineering phase (generation of asset types, e.g., digital vehicle models) as well as the operation phase (generation of asset instances, e.g. vehicle manufacturing). The present QFM focuses on this axis on the *Instance Production*. Basically, of course, quality problems may also be mitigated by changing either both the product design and engineering or the production plant engineering.

The vertical RAMI4.0 *Layers* covers the architectural aspects of the IT system environment. It ranges from the digital representation of an asset, its integration into an IT environment up, communication with other components up to the informational, functional and business modelling aspects. The QFM mainly deals with the modelling of the quality aspects of an asset. It focuses upon the information layer when considering the quality information model and upon the functional layer when dealing with functions that are used to analyze quality information. Business effects of quality defect recognition and mitigation are to be considered as well.

6.2. Positioning in the I4.0 Component

The I4.0 Component is a conceptual model that allows a system architect to integrate asset of various types into an IT environment in a uniform way. It comprises an asset (or a composition of assets) and a so-called Asset Administration Shell (AAS). The purpose of the AAS is to provide the data and the functions by means of a well-defined I4.0 standard interface to other I4.0 components. This uniform abstraction, independent of the asset type underneath, enables to reduce the communication and cooperation aspects in an I4.0 system to those between its I4.0 components. The data and functional aspects are summarized in a “manifest”. The manifest data is structured according to meta-data schemes (partial models) that describe the capabilities and the behavior of the assets underneath. When mapping the QFM to an I4.0 Component, the quality information related to an asset is considered as a partial model of the manifest. Hence, in order to be compliant to I4.0, it shall be structured according the modelling rules being specified at the moment in the I4.0 working groups.

7. Conclusion

7.1. Summary

This article proposes a model for quality feedback (QFM) on the basis of four levels in transparent and process-oriented quality feedback within the assembly line in real time. All process individuals are involved in a user-oriented manner. The model is a tool for hybrid control in vehicle assembly. The model aims at providing the fastest possible quality feedback to all involved actors such that systematic defects can be found, documented and reported back early on. Once the defect has been recorded, the automated information flows facilitate complete transparency by generating reliable information (smart data) within the assembly line in real time. This provides maximum speed and aims to ensure permanent defect prevention, a long-term approximation of first-time quality and maximization of production quality. The industrial use of the model substantially reduced the defect rate while also increasing the throughput rate of zero-defect vehicles.

7.2. Outlook

The model supports the trend towards an intelligent assembly line using IIoT technologies in vehicle assembly. In collaboration with other quality-oriented systems [10], a complete integrated system that controls and improves quality in vehicle assembly can be conceived. In combination with transparent, intelligent real-time control of occurring quality defects in assembly with regard to the downstream locations and actors, a consistent quality control loop consisting of forward and backward quality information chains can be set up to achieve the quality targets.

In addition to the defect occurrences and variations in quality, the visualization of statistical information on the production quality of assembly through a quantifiable quality model based on the elements of the magic triangle constitutes a worthwhile supplement. In this way, quality-critical assembly areas can be illustrated transparently in line with user needs across the entire value chain of vehicle assembly.

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