Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 21 (2018) 157–164

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

15th Global Conference on Sustainable Manufacturing

On the track of human errors - Procedure and results of an innovative assembly planning method

Prof. Dr.-Ing. Robert Refflinghaus, Dipl.-Logist. Christian Kern*

University of Kassel, Department of Quality and Process Management, Heinrich-Plett-Str. 40, 34132 Kassel, Germany

Abstract

Manual assembly operations are the endmost place of the production process and with it represent a melting pot for organizational, time-related and qualitative errors of manufacturing. Because competitive advantages are increasingly determined in the manual assembly, the creation of economical and reliable work steps is of fundamental importance for future business success. For that reason, at the institute of the authors, a procedure has been developed to use the knowledge of the Expert System for Task Taxonomy that was originally developed to evaluate the error rate of control and surveillance activities in safety critical areas for creating a computer-aided expert system that allows predicting human error probabilities for manual assembly operations. Applying this expert system, production processes can already be optimized during the phase of product design by avoiding critical process steps at an early stage of the planning process. On the basis of a case study, this paper introduces the conception of an Excel-based software tool that allows an automated application of the developed assembly planning method and thereby, generates reliable risk analyses of manual work tasks with little expenditure of personnel and time.

Peer-review under responsibility of the scientific committee of the 15th Global Conference on Sustainable Manufacturing (GCSM).

Keywords: Human Reliability; Manual Assembly Operations; Human Error Probability; Excel-basded software tool

1. Introduction

The change in sales markets from seller to buyer markets presents major challenges for domestic industry that result in a strong competition with international competitors [1]. In order to be able to assert itself against the growing competition on the world market, there is currently a trend for manufacturers to increase the number of

* Corresponding author. Tel.: +049-561-8044675; fax: +49-561-8044673.
E-mail address: kern@uni-kassel.de

2351-9789
Peer-review under responsibility of the scientific committee of the 15th Global Conference on Sustainable Manufacturing (GCSM).
10.1016/j.promfg.2018.02.106

variants with a simultaneous reduction of product life time [20]. In spite of the progressing automation of manufacturing processes, a considerable proportion of the arising assembly tasks are still carried out by humans or by a cooperation of human and machines in assembly lines (cf. [2, 19]). In order to be able to compete, companies must generate stable and efficient production and assembly processes. Also, with the help of proactive quality measures quality-related test and error costs need to be kept as low as possible [3]. However, especially at the beginning stages of a manual assembly line, unstable processes often effect variations of quality which cause high quality-related costs. If the error causes are only discovered during operation, they can only be remedied with a high financial and/or a high time effort for optimizing quality-critical work steps.

In order to already analyse performance reliability of manual assembly processes in the planning phase of a new assembly line, the Department of Quality and Process Management at University of Kassel has developed a process-oriented assembly planning method MTQM (Methods Time and Quality Measurement) which combines aspects of work planning for the time-optimized interpretation of manual assembly tasks with aspects of quality planning for the assessment, evaluation and reduction of quality risks caused by anthropogenic error handling. As a result, the developed method enables the user to perform a prospective evaluation of human errors that can possibly occur while executing typical manual assembly operations (cf. [4]).

After a brief overview of concept and functionality of the assembly planning method MTQM is given, this paper deals with its practical application to the assembly line of a profile manufacturer within a case study. It is shown how human-caused errors can be forecasted and measures for optimizing the investigated assembly station can be derived from results of the risk analysis.

2. The MTQM-method

Although the early recognition of quality-critical manual work tasks constitutes a key element of creating stable and efficient production processes for cross-sectoral manufacturing companies, the prospective examination of human reliability in the assembly process has been neglected in both research and business practice to the recent past. In order to counter this situation, the developed assembly planning concept, which has been developed in cooperation with several industry partners e.g. the automotive and electronics industry on the examples of typical manual assembly tasks from series production (fitting a brake piston, fitting a valve, connecting a control unit etc.), contains the three successive fields of error analysis, reliability analysis and measure development. Figure 1 illustrates the substantial elements of the developed MTQM method and gives an overview of both needed inputs as well as outcomes resulting from method application.

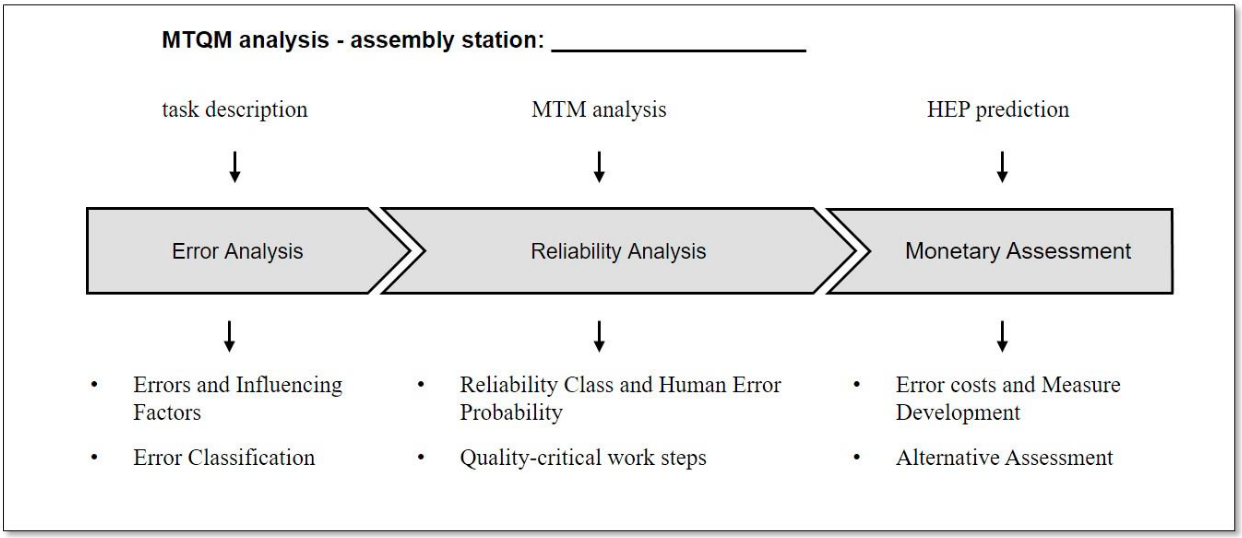

Fig. 1. Methods Time and Quality Measurement - application areas

The MTQM method is based on a reliability model, according to which the human reliability depends not only on the work task itself, but also on the personnel performance prerequisites of the operator as well as the circumstances of the work system (cf. [17]). In order to meet the requirements of the selected reliability model, the reliability analysis is based on the Expert System for Task Taxonomy (ESAT), an established HRA (Human Reliability Analysis) method for quantifying human reliability of safety-critical work tasks (cf. [5]).

In the course of method development, the ESAT method was combined with the MTM procedure (Methods Time Measurement), an established system of predetermined motion times for creating work-analytical time and motion surveys. Furthermore, by modifications within the stress vector as well as by the ongoing expansion of the risk prognosis database, the ESAT method was adapted to the scope of manual assembly [6, 7].

3. Example of a practical application of the MTQM-method

The following case study illustrates the use of the MTQM method in the final assembly line of a medium-sized German profile manufacturer that belongs to the internationally operating Tillmann-Group. Cold-rolled profiles, different press-, bending-, and stretch-bending-components, as well as complex assembly modules are part of the company`s range of products. The company's most important customers belong to the automobile-, electronic-, and furniture industry.

Based on the results of historical error data and on-location observations of the industry partner's assembly line, the manual assembly of a cargo rail shown in figure 2 was determined to be the object of reflection of the practical application of the MTQM-method.

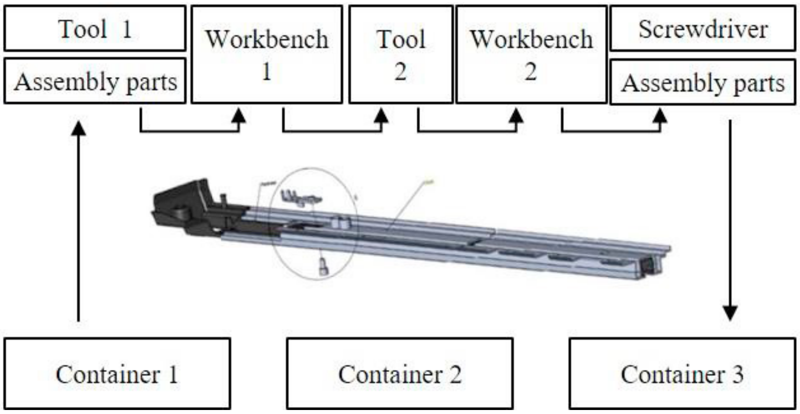

Fig. 2. Workstation and object of reflection

The considered cargo rail is part of a fixing set which gets installed in the trunk of a vehicle to secure and fasten the baggage using the interaction of hooks and straps. The assembly of the cargo rail takes place at an assembly station consisting of several workplaces which are put in a row (cf. figure 2). The assembly process begins with the removal of an aluminium rack from container 1, the insertion of the aluminium rack into the tool 1 and the grouting of two spacers. Afterwards, the technician removes a blade inlay from container 2, inserts it into the aluminium profile and establishes a connection between the two components with the help of tool 2. In the next step, at workbench 2, a QR-code is applied onto the cargo rail in a defined order and an inserted retaining plate is bolted on the aluminium rack. After installing a plastic flap, the technician puts the completely assembled cargo rail into container 3 for shipping.

3.1. Error Analysis - Identification of potentially occurring human errors

In order to reduce human error, an analysis of potentially occurring errors as well as an analysis of the cause of these errors is unavoidable. Creating a basis for the determination of error risks within the error analysis, possible handling errors must be determined by the contained movements and assembly components that need to be done for carrying out the work task "Assemble a cargo rail". For an entirely capturing of errors, in context with this case study, error classification extended by assembly-specific error categories like mental errors or handling errors (c.f. [2]), Failure Mode and Effect Analyses (FMEA, cf. [8]), expert interviews with representatives from industry and Ishikawa-diagrams have been performed.

Since the MTQM-method focusses on human error probabilities of the assembling area, further analysis only takes error-actions into consideration which are caused by humans. Therefore, material defects, as well as quality defects caused by machinery were excluded. In course of the error analysis, human induced action errors that occur repeatedly during the assembly of the cargo rail, for example, were identified when carrying out a process FMEA. In this context, omission mistakes (missing spacer, missing retaining plate, missing label, etc.) and/or handling mistakes (wrong component supply, wrong set-up of components), as well as quality defects caused by an inattentive way of working (damage of the aluminium rack due to incorrect placing of the rack into the clinching tool, incorrect run of a visual check, etc.) were detected. Unfortunately, due to an obligation of secrecy, the risk priority values that correspond with the detected errors cannot be shown in this paper.

3.2. Reliability Analysis – Forecast of Human Error Probabilities

The reliability prediction, that occurs on the basis of a modified application of ESAT (cf. [5]), represents the central element of the MTQM method. Hence, it should be indicated that the ESAT procedure delineates an HRA method which was originally developed for nuclear industry and aerospace industry. In the recent past, the method has also been used successfully in alternative application fields like picking tasks and preparing tasks. Therefore, it is suitable to evaluate the human reliability of any work task that could be carried out in a man-machine-system [6].

In this case study, the reliability analysis was carried out according to the four main process steps of the ESAT procedure (task description, time determination, shaping of the stress vector, calculation of reliability class und human error probability, cf. [6]). Hence, it begins with the creation of a standardized task description. Taking the company`s existing assembly instructions into account, the aim is to create a clear, temporally sequential process sequence for carrying out the work task by capturing all actions, mental operations, tools and test steps required to accomplish the work task. Afterwards, the individual process steps were further subdivided into task elements (grab aluminium rack, place retaining plate, pull lever downwards, turn rack by 180 degrees, etc.) and assigned to tabulated standard terms. The transfer of the task description into a standardized process language was based on the standard terms of the ESAT database (cf. [5]) which - in the course of method development - have been expanded by numerous standard terms from the field of manual assembly (e.g. joining, bolting, small items, exact position, approximate position, cf. [9]). After transferring the task description into a standardized process language execution times and corresponding pre-weightings that, in the further analysis course, allow assessing the difficulty of single task items (cf. [5]) were assigned to each task element. Since the time and pre-weighting values contained in the ESAT database are based on time measurements of control and monitoring activities that are rarely carried out, they were not suitable for the present application (manual assembly tasks of series production). For this reason, the determination of times and pre-weightings was carried out on the basis of time recordings and movement studies of the investigated assembly process which were compiled by using the system of predetermined motion times MTM (Methods Time Measurement, cf. [12]). In total, the resulting task description for the assembly of the cargo rail consisted of 75 task elements and had a total execution time of 61 seconds, as well as a total pre-weighting value of 805. After determining times and pre-weightings, the shaping of the so-called stress vector which aims to consider all performance shaping factors (PSF) potentially having a negative influence on the human reliability of the task execution takes place. To ensure an entire consideration of all performance-influencing factors relevant for typical manual assembly operations, based on the analysis of influencing factors established in several famous HRA methods (e.g. THERP (cf. [10]), CAHR (cf. [11]), etc.), significant subject-specific contributions (cf. [17]) and predetermined motion time systems (MTM (cf. [12]), WF (cf. [13]), etc.), an assembly-specific stress vector has been generated which is composed of 45 components in total (cf. [7]). The stress vector for the considered assembly operation is modelled by allocating values between 0 (no negative influence on the reliability of the considered work task) and 1 (very strong negative influence on the reliability of the considered work task) to each single component of the stress vector.

Creating the stress vector for the considered assembly operation, 31 components of the stress vector were subjectively assessed by experts (e.g. psychological tiredness potential = 0.3; time pressure = 0.2, etc.) and 14 components were objectively calculated (e.g. noise (volume, duration) = 0.23; check intensity = 0.14, etc.) by using formulas and subject-specific standards. After evaluating all performance shaping factors the stress vector is calculated by adding the individual values of its components. For the considered assembly operation, the shaping of all components of the stress vector resulted in a total stress rate of 3.71 (taking into account solely the PSF-components that were objectively assessed on the basis of formulas and standards) respectively 4.12 (taking into account both subjective and objective assessed PSF-components).

Based on the calculation of the stress vector in the last phase of the MTQM method the risk potential of the considered assembly task can be predicted. Taking the number of task items (75), the total execution time (61s), the sum of the pre-weightings (805) and the total stress rate (3.71 or 4.12) into account, at first the work task - under consideration of empirically validated calculation formula (cf. [6]) – is organized in one of twenty reliability classes (RC), before the Human Error Probability (HEP) that corresponds with the analyzed work task can finally be calculated.

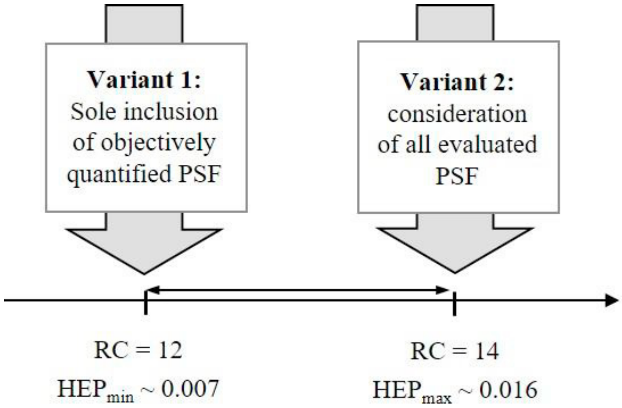

Fig. 3. HEP interval for limiting the predicted error probability

Figure 3 illustrates the results of the reliability analysis of the examined manual assembly task "Assemble a cargo rail". The risk prognosis has both, a lower error probability value, which results from the sole inclusion of all objectively quantified PSF components, and an upper error probability value, which results from the consideration of all quantified PSF components.

3.3. Monetary Assessment and Development of measures for process optimization

A comparison of different variations of carrying out assembly tasks concerning possible error risks requires a trade-off between the expenditure related to the alternative design of the assembly system and the proceeds realized by a lower error risk. Besides the described approach for determining the risk potential of a manual assembly task, a model was turned out in the course of method development which, based on a failure Process Matrix (FPM, cf. [14]) of the considered assembly process, enables the setting of prospective costs caused by assembly errors. In this context, the cost model focuses on the quantification of internal error costs (e.g. rejects, rework). The establishment of resulting error costs occurs on the basis of rework times which were documented in the company in the past. Using the example of the manual assembly operation "Assemble a cargo rail", figure 4 illustrates procedure and results of the modified failure process matrix. Based on the conducted error analysis and the MTQM-assisted quantification of error happening, the right part of the modified failure process matrix has been filled in (columns "Error", "Component" and "Slip through error"). Afterwards, the failure process matrix has been replenished with data of operationally accrued guarantee, rework and reject costs of the past years documented by the industrial partner of this contribution (cf. left part of the failure process matrix).

Reject and Rework (total cost per year)	Reject cost (cost per component)	Rework cost (cost per component)	Required rework time	Errors to the customer (components per year)	Errors in the company (components per year)	Slip through error?		
€	€	€	s			J/N	Component	Error
21,32	0	0,29	30	1	49	J	spacer	forgotten
509,52	10,18	0,29	30	3	48	J	Blade inlay	not pushed far enough
122,16	10,18	0,00	0	0	12	N	Blade inlay	inserted incorrectly
4120,63	8,24	0,29	30	25	475	J	Aluminium rack	damaged
265,38	10,18	0,29	30	25	25	J	Aluminium rack / blade inlay	clinching incorrectly
21,23	10,18	0,29	30	2	2	J	Aluminium rack / blade inlay	clinching forgotten
85,68	0	0,24	25	13	238	J	QR-Code	forgotten
21,32	0	0,29	30	1	49	J	retaining plate	forgotten

Fig. 4. Failure Process Matrix of the considered assembly operation (extract)

The column "reject and rework (total cost per year)", figure 4 shows the totalized deviation costs that are caused by the identified errors per year. The subsequent development of process improvement measures aims to eliminate those errors causing the highest deviation costs or at least reduce their appearance. As Figure 4 shows, damage to the aluminium rack causes the highest deviation costs. Damage to the aluminium rack always occurs when the operator carelessly inserts the aluminium rack into the tool for tox connection which causes an unintended collision of the aluminium rack and the tox tool. For error elimination, a larger distance between punch and die of the tox tool and an additional padding of sharp edges has been proposed. In order to avoid cost-intensive execution errors (steel inlay incorrectly inserted, tox connection failed) during the MTQM application, a test device has been developed which controls both the conciseness of aluminium rack and steel inlay, as well as the correct realization of tox connection by means of sensors at the end of the assembly process. The suggestions for process optimization developed within the MTQM application were considered as expedient by the industrial partner and have mostly already been implemented in the company.

4. Software-based identification of quality-critical work steps

The implementation of the assembly planning method MTQM (cf. [2, 4, 6, 7, 9]) requires an in-depth knowledge of predetermined motion time systems (cf. [12, 13]) and established procedures of human reliability analysis (cf. [15, 16]). Due to the high needs of time and personnel, the MTQM method is mainly used in major companies and is designed for the optimization of assembly processes in large series production. Since the necessary method knowledge in small and medium-sized companies often exists inadequately, a systematic planning of manual assembly operations can currently be conducted only on high financial and temporal (training) expenditure or with the help of an external consultant in these companies. In order to also enable small and medium-sized companies to analyse manual assembly operations under time and risk aspects an Excel-based software tool is currently being developed at the Department of Quality and Process Management at the University of Kassel. The software tool allows to evaluate typical, frequently occurring assembly operations with a standardized description and to automatically determine their susceptibility to human failure. Generating an economic analysis tool which can be used with low training expense, the analysis tool is based on the globally well-known software MS Excel. This inter alia offers the considerable advantage that simple arithmetic operations can be directly reproduced in Excel.

The structure of the developed Excel tool is based on the knowledge of the Expert System for Task Taxonomy (cf. [5]), the MTQM method (cf. [2,4,6,7,9]) and the MTM-system (c.f. [12]). For the implementation of the computer-aided Excel tool, an assembly-specific database was created which currently contains about 40 assembly-specific analysis modules (e.g. take and place item, prove with gauge, produce a screwing connection). Each single motion sequence and task item of a variety of typical, frequently occurring manual assembly operations can be depicted by drag and drop. Thus, purpose of the standardized analysis modules is to prospectively depict any manual work content automatically and to directly use the parameters dedicated to the analysis modules (time values; pre-weightings; performance shaping factors) for the computer-aided determination of the human error probability of the considered assembly operation. In this way, the user automatically reconsiders the integrated method knowledge of both HRA procedures and the MTM method during the analysis. In program modules based on each other (e.g. task description, time and risk prediction, simulation of planning variations), the deposited method knowledge and the visualization of work operations, the user is directed through the analysis step by step. Figure 5 illustrates an extract of the task description of the assembly operation “assemble a cargo rail” created with the help of the MTQM software tool.

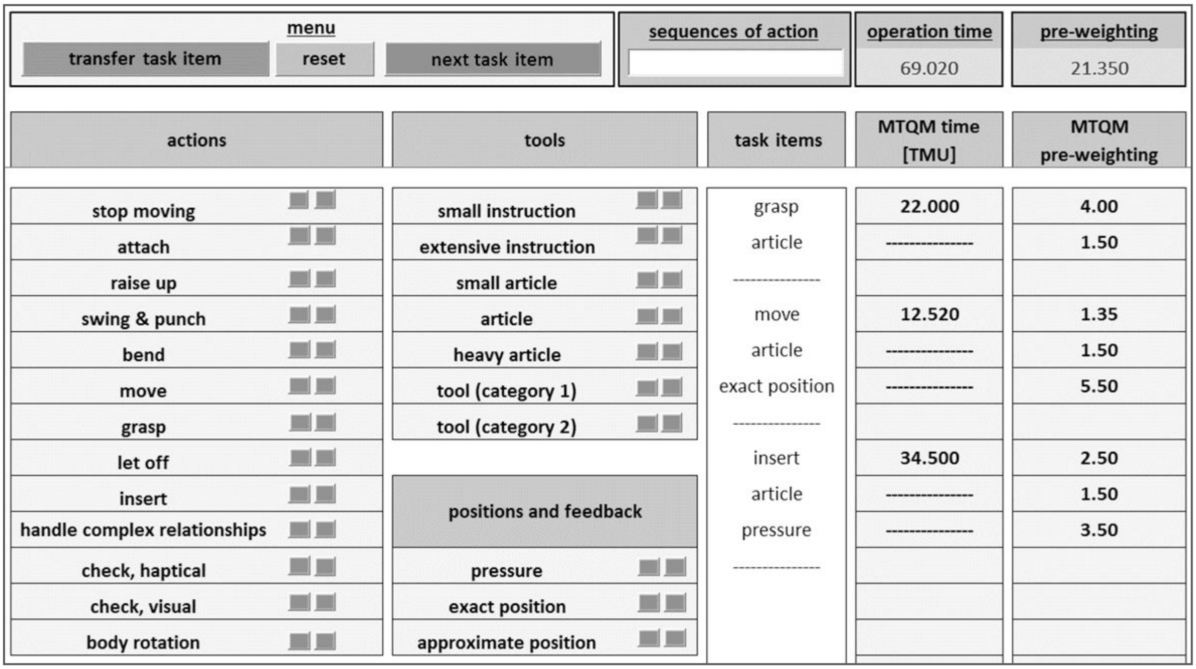

Fig. 5. Automated Creation of a MTQM task description (extract)

In order to assign further analysis modules to specific elements of the task description the analysis modules of the categories “actions“, “tools“ and “positions and feedback“ deposited in the database can be chosen by drag and drop and allocated to the task description of the considered assembly operation. Here, the allocation of analysis modules occurs with automatic recourse to the previously created database. Once the analysis module is transferred to the column “task items”, the corresponding time values and pre-weightings are automatically transmitted to the provided columns in the right part of the analysis section. In that way, a completely systematic illustration of the task description of the considered assembly operation can be created step by step.

The MTQM method is steadily further developed and regularly expanded by data of already carried out risk analyses. Moreover, the software is open-designed as in [18] but only authorized administrators can add further analysis modules at any time. Hence, authorized users can already identify quality-critical process steps in the planning phase of manual assembly operations, evaluate alternative solution concepts on less expenditure and finally realize the time and risk-optimized assembly process in the operating environment.

5. Summary

Content of this paper is the introduction and practical application of the assembly planning method MTQM (Methods Time and Quality Measurement). After an explanation of the range of services, the practical application of the MTQM method in the assembly line of a profile manufacturer is discussed. In doing so, two different variations of the HEP-calculation are considered to set a HEP-value-interval in which both, objective and subjective PSF-components contribute to the calculation process in different ways. Based on the generated results, process-improving measures are presented which were worked out in cooperation with the industry partner. Furthermore, this paper shows how the MTQM method can be transferred into a computer-aided methodology, which enables an automatically conducting and evaluating of time and risk analyses for manual assembly operations. Hence, the MTQM-method can prospectively be used to analyze manual assembly processes which are still at the planning stage. As a result, proactive human error probabilities for quality-critical work steps can be determined easily and enable the user to develop time- and quality-optimized assembly processes at an early stage of the planning process.

Acknowledgements

This IGF Project 18878N of the Research Community for Quality (FQS), August-Schanz-Str. 21A, 60433 Frankfurt/Main is supported via AiF within the programme for promoting the Industrial Collective Research (IGF) of the German Ministry of Economics and Energy (BMWi), based on a resolution of the German Parliament.

References

[1] R. Jochem, Was kostet Qualität? Wirtschaftlichkeit von Qualität ermitteln, Hanser Verlag, München, 2010.
[2] C. Kern, R. Refflinghaus, E. Bossmann, T. Bittmann, in: S. Gröger, T. Eiselt, J. Schuldt (Eds.), Prospektive Ermittlung und Reduzierung potenzieller Fehler für manuelle Montagelinien, Shaker Verlag, Aachen 2014, pp. 67-92.
[3] B. Lotter, H.-P. Wiendahl, Montage in der industriellen Produktion, second ed., Springer Verlag, Berlin/Heidelberg, 2012.
[4] C. Kern, R. Refflinghaus, Expert System for evaluating human reliability in manual assembly operations, Proceedings of the 18th International Conference on Quality and Service Science, Palermo/Italy, 2015.
[5] K. Brauser, Aufgabentaxonomie - Ein Verfahren zur Ermittlung der menschlichen Leistung bei der Durchführung von Aufgaben, Messerschmidt-Bölkow-Blohm, Ottobrunn, 1990.
[6] C. Kern, R. Refflinghaus, Modification of the HRA-method ESAT for improving human reliability in manual assembly, Proceedings of the 2016 ESREL Conference on European Safety and Reliability, Glasgow/UK, 2016.
[7] C. Kern, R. Refflinghaus, Process optimization in manual assembly by software-based identification of quality-critical work steps, Proceedings of the 19th International Conference on Quality and Service Science, Huelva/Spain, 2016.
[8] R. Jochem, M. Alshekh, The Three Stages Model for Optimizing The Failure Mode and Effects Analysis (FMEA): Crossed Impact Based FMEA (CFMEA), Quality and Innovation in Engineering and Management, 2012.
[9] C. Kern, R. Refflinghaus, Assembly-specific database for predicting human reliability in assembly operations, Total Quality Management & Business Excellence, Vol. 26, No. 10, Taylor & Francis, 2015.
[10] A.D. Swain, H.E. Guttmann, Handbook of human reliability with emphasis on nuclear power plant applications - Final report. Sandia National Laboratories, Washington, 1983.
[11] O. Sträter, Beurteilung der menschlichen Zuverlässigkeit auf der Basis von Betriebserfahrung, GRS-138, GRS, Köln, 1997.
[12] B. Britzke, MTM in einer globalisierten Wirtschaft, FinanzBuch Verlag, München, 2013.
[13] WFC-2015, Work Factor Council - Results, Available online at http://www.work-factor.nl.nu, 2015.
[14] A. Schloske, Mit der Fehler-Prozess-Matrix (FPM) komplexe Montageprozesse nach Kosten, Qualität u. Produktivität optimieren, Fraunhofer IPA, Karlsruhe, 2016.
[15] O. Sträter et al., Status and Needs on Human Reliability Assessment of Complex Systems, SRESA Journal of Life Cycle Reliability and Safety Engineering, Vol. 1, No 1., 2012.
[16] F.V. Haase , R. Woll, Application of reliability methods - an empirical study, Proceedings of the 2015 ESREL Conference on European Safety and Reliability, Zürich/Switzerland, 2015.
[17] H. Wang, S.J. Hu, Manufacturing complexity in assembly systems with hybrid configurations and its impact on throughput, CIRP Annuals - Manufacturing Technology 59 (2010) 53-56, Elsevier, 2010.
[18] S.J. Hu, Evolving paradigms of manufacturing: from mass production to mass customization and personalization, Procedia CIRP 7 (2013) 3-8, Elsevier, 2013.
[19] J. Krüger, T.K. Lien, A. Verl, Cooperation of human and machines in assembly lines, CIRP Annuals - Manufacturing Technology 58 (2009) 628-646, Elsevier, 2009.
[20] S.J. Hu et al., Assembly system design and operations for product variety, CIRP Annuals - Manufacturing Technology 60 (2011) 715-733, Elsevier, 2011.