Process optimization in manual assembly by software-based identification of quality-critical work steps

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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. Since 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 modelling and evaluating manual assembly processes under time and quality aspects, the assembly planning method MTQM presented at the conference last year enables a prospective determining of human error probabilities and therefore increasingly is applied in industrial practice. Currently, the MTQM method still requires a manual implementation of time and risk analyses and therefore is associated with a high expenditure of time and personnel requirements. Because until now also an in-depth knowledge of various work and quality planning techniques is a mandatory requirement of the methods application, this paper introduces the conception of an Excel-based MTQM software tool that allows an automated application of the MTQM method and thereby generates reliable time and risk analyses of manual work tasks with less expenditure.

As a result the application of the MTQM method in future not only leads to time and quality optimization but also to an economic improvement.

Keywords

manual assembly operations; process optimization; forecast of human failure; automated application; computer aided evaluation

1. Introduction

Assembly activities are a fundamental element of the supply chain. With regard to the service provision, the manual assembly is the endmost place of the supply chain and with it represents a melting pot for organizational, time-related and qualitative errors of the entire product development process. The fulfillment of the enormous quality standard of manual assembly resulting of this business matter is considerably influenced by employee qualification, by exclusion of error-privileged situations and by complexity of the assembly task.

Hence, the planning of execution steps is of fundamental importance to an efficient working process. For modeling manual assembly activities, in industrial practice predetermined motion time systems are used (cf. (Britzke, 2013)). Although the utilization of predetermined motion time systems leads to a time-optimized arrangement of manual assembly processes, they do not offer sufficient methods for a preventative quality management. In this context it is often not considered, that handling errors of persons involved may lead to inadequate stability of the assembly system. Because the occurrence of staff errors so far has been taken into account insufficiently, the development of robust and efficient manual assembly processes until now often fails. For this reason, on the basis of the modeled processes it is worth striving to quantitatively depict the occurrence of errors of the staff operating in the production system. Against this background a method for planning assembly processes is desirable, which considers the dynamically developing factors of industrial production and simultaneously generates an endurance and risk analysis already in the planning stage.

A promising approach for solving the presented problems is the assembly planning method MTQM (Methods Time and Quality Measurement) that was presented at the conference last year. This method enables the user to perform a prospective evaluation of human errors that potentially could occur while executing typical manual assembly operations (cf. (Kern, 2015)).

The implementation of the assembly planning method MTQM developed by the authors of this paper (cf. (Kern, 2013); (Kern, 2015)) until now requires an in-depth knowledge of predetermined motion time systems (cf. (Bokranz, 2012)) and established procedures of human reliability analysis (cf. (Sträter, 2012); (Haase, 2015)). On account of the high needs for time and personnel, the MTQM method is therefore mainly used in major companies and is designed for the optimization of assembly processes in large series production. Since in small and medium-sized companies the necessary method knowledge often exists inadequately, in these companies 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. The same applies for the production of small series, where a holistic, time and quality related consideration of the assembly process can only be reached by an uneconomically high planning expenditure.

Hence, the central target of this paper is to present a solution approach, which enables to simplify the implementation of the MTQM method for evaluating human misconducts in manual assembly, so that in future the MTQM method can also be used by companies having limited method knowledge. This should be reached by creating an Excel-based software tool, in which single work steps of the MTQM method can be carried out automated.

In this paper it is shown, how the MTQM method inclusive the needed method knowledge can be transferred to a computer-aided methodology enabling an automated conducting and evaluating of time and risk analyses for manual assembly tasks. Additionally, on the basis of the generated results, treatment recommendations for the error minimal arrangement of the considered assembly processes can be derived.

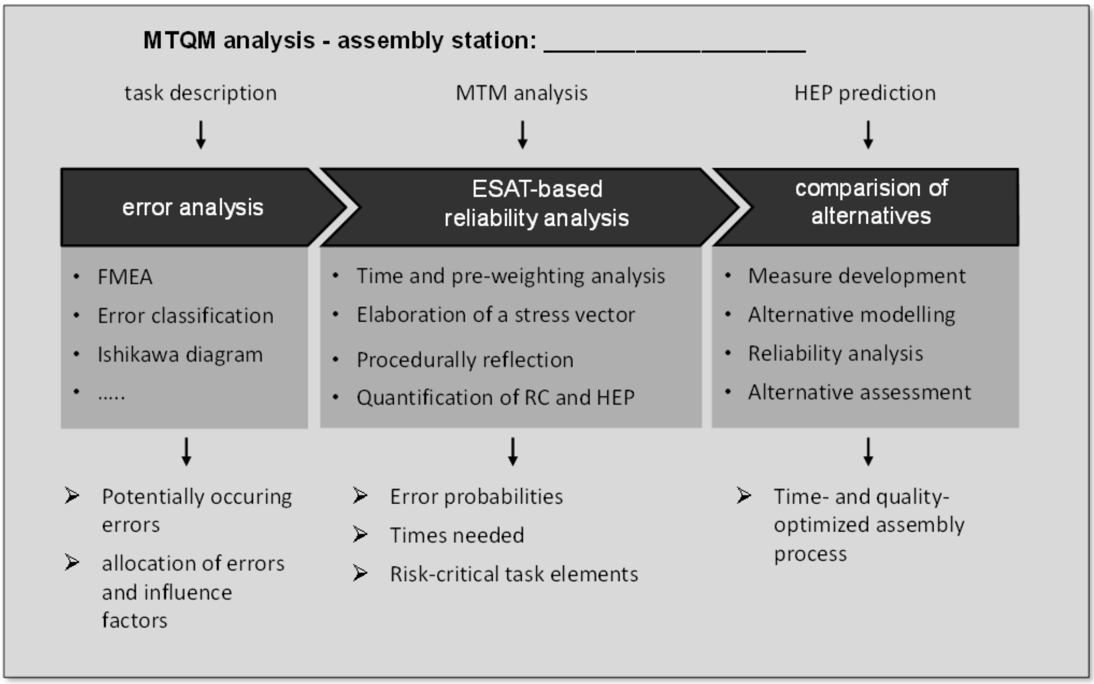
Thus, by using the MTQM software tool in future it will be possible to re-assess error probabilities of personnel acting (Human Error Probability - HEP) in manual assembly processes automated so that reliable, qualitative and quantitative risk analyses can be drawn up easily. Based on these findings, critical process steps can already be avoided at an early stage of the planning process and production processes can be optimized already during the phase of product design.

2. A brief review of the MTQM method

In practical application, a prospective analysis of human reliability in the manual assembly until now has been neglected. Since for manufacturing companies across all sectors the early recognition of quality-critical work steps constitute a key element for generating stable and efficient production processes, at the Department of Quality and Process Management at the University of Kassel the process-oriented method MTQM has been developed, which assists to predict human reliability in the manual assembly.

The created method consists of three areas based on each other: error analysis, reliability analysis and comparison of alternatives. The following figure illustrates the substantial elements of the developed assembly planning method and gives an overview of both needed inputs as well as outcomes resulting from method application.

Figure 1: Elements of the MTQM method



Source: Own elaboration

2.1 Error Analysis

According to EN ISO 9000:2015, human errors are defined as failure to fulfil a requirement (ISO 9000:2015). 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. So, to serve a basis for the determination of error risks, within the error analysis it must be determined which handling errors can occur by the contained movements and assembly components that need to be done for carrying out the considered work task. A good starting point for the analysis of potential errors of action is the established fault classification by Swain and Guttmann that subdivides human errors inter alia in sequence errors, omission errors, executions errors and addition errors (c.f. (Swain, 1983).

For an entirely capturing of error happening, in context of the MTQM method, additionally error classifications extended by assembly-specific error categories (e.g. mental errors, handling errors), failure mode and effect analyses (cf. (Jochem, 2012)), expert interviews with representatives from industry and Ishikawa-diagrams are used.

2.2 Reliability Analysis – Forecast of error risks

The reliability prediction, which occurs on the basis of a modified application of Expert System for Task Taxonomy (ESAT) (cf. (Brauser, 1990)), represents the central element of the MTQM method. In this connection, it is to indicate that the ESAT procedure depicts an HRA (human reliability analysis) method that originally was developed for nuclear industry and aerospace industry. In recent past, the method has also been successfully used in alternative application fields like picking tasks and preparing tasks and therefore on principle is suitable to evaluate the human reliability of any work task that could be carried out in a man-machine-system.

The ESAT method itself can be divided into four different process steps. The starting point of the procedure is always a detailed description of the considered task. This task description must be a clear instruction to fulfil the task (phase one of the ESAT procedure). For this purpose the considered task must be constructed out of standardized terms derived from the ESAT database. Therefore, the ESAT database contains about 200 standard terms that are structured to main categories. By using these standard terms, the user is able to describe all actions, mental operations and tools which are necessary to fulfil the considered task (cf. (Brauser, 1990); (Kern, 2014)).

Furthermore, the ESAT database also contains elemental times which are necessary to fulfil the different steps of the considered task and pre-weightings with a score between zero and ten collected by empirical research studies. By evaluating these data (elemental times and pre-weightings), the user is able to carry out a first estimation of the risk potential of the considered task (phase two of the ESAT-procedure).

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 (phase three of the ESAT-procedure, cf. (Brauser, 1990); (Hamrol, 2008); (Kern, 2016)).

When analyzing manual assembly tasks, for an entirely consideration of all performance-influencing factors it is necessary to involve several general environmental factors (e.g. lights, noise and climate) as well as a range of further workplace specific factors (e.g. ergonomic conditions, arrangement of material flow, suitability of used instruments and auxiliary tools). To ensure this, based on the analysis of performance-influencing factors established in several HRA (human reliability analysis) methods (THERP (cf. Swain, 1983), CAHR (cf. Sträter, 1997), SLIM (cf. Embrey, 1983)) and predetermined motion time systems (MTM (cf. Britzke, 2013), WF (cf. WF-C, 2015), etc.), an assembly-specific stress vector has been generated which in total is composed of 40 single components (cf. Figure 2).

Figure 2: Assembly-specific stress vector (extract)

PSF 1: time references	PSF 2: task-relating factors	PSF 3: system factors	PSF 4: tiredness factors
- perception - detection - …	- corrigibility/ error correction - check intensity - …	- man-machine interface - time pressure - …	- physical tiredness potential - psychological tiredness potential
PSF 10: buffering factors	**Assembly-specific stress vector**		**PSF 5: environmental factors**
- precision of task settings - precision of task methods - …			- noise: volume, duration, etc. - spatial texture - …
PSF 9: task characteristics	**PSF 8: personal factors**	**PSF 7: motivation**	**PSF 6: work protection**
- complexity - difficulty - …	- experience/ practice - reaction rate - …	- motivational influence on performance - …	- labelling/ marking - personal protective equipment - …

Source: Own elaboration

The modelling of the stress vector takes place 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. After determining all groups of performance shaping factors the calculation of the stress vector G takes place by adding its components.

$$G = \sum PSF\ 1 + \ldots + \sum PSF\ 10 \qquad (1)$$

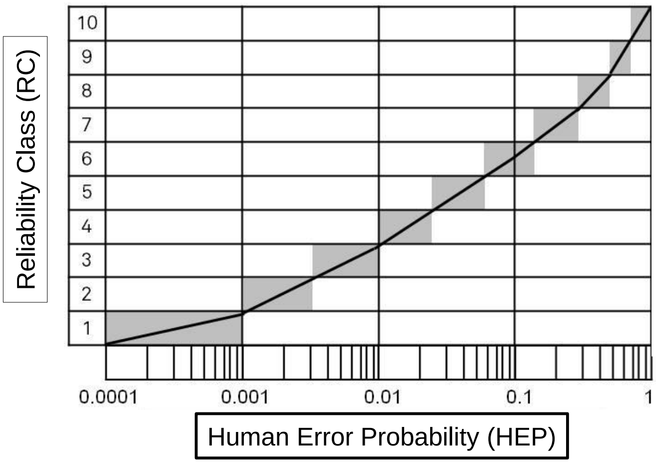
The last step of the ESAT procedure deals with calculating the reliability class and the human error probability of the considered assembly operation by using the following calculation formulas (phase 4 of the ESAT procedure):

$$\text{Reliability Class (RC)} = \text{Integer}\ (1.2 * 0.035\ G * \log 0.035\ G) + \sum PSF\ 1 \qquad (2)$$

$$HEP = \text{Fract}\ (RC) * D\ (RC) + HEP_{min}\ (RC) \qquad (3)$$

Here, the scale shown in figure 3 represents the basis for the classification of human error probabilities in ten intervals (Brauser, 1992).

Figure 3: Subdivision of reliability range in ten reliability classes



HEPmin (ZK)	HEPmax (ZK)	D (ZK)
0.7	1.0	0.3
0.45	0.7	0.25
0.26	0.45	0.19
0.133	0.26	0.127
0.062	0.133	0.071
0.026	0.062	0.036
0.0096	0.026	0.0164
0.0033	0.0096	0.0063
0.001	0.0033	0.0023
<0.0001	0.001	0.001

Source: Own elaboration

Reliability class one signifies very small error probabilities and reliability class ten portrays very high error probabilities. In this context, the following rules for classifying reliability classes can be derived (Lolling, 2003):

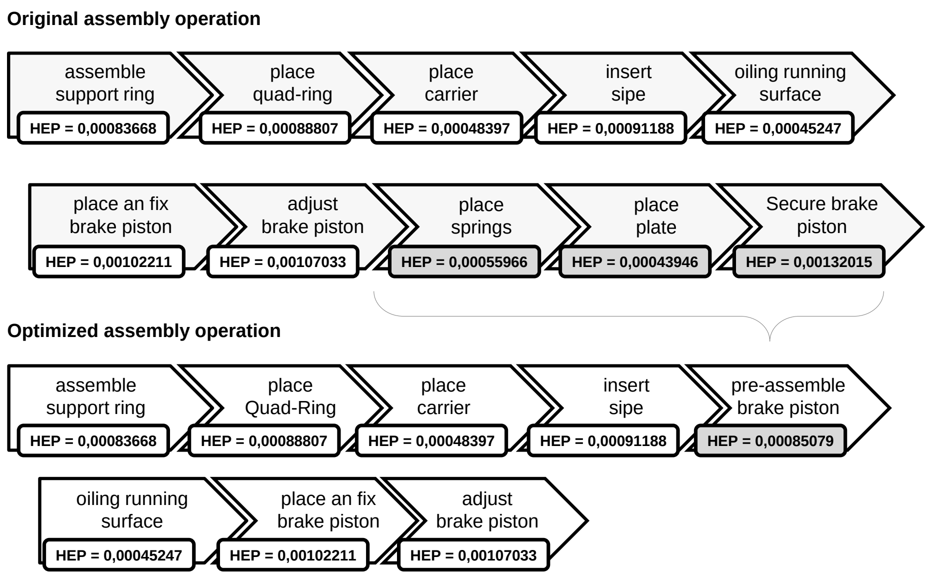
- The internal performance-influencing components of the stress vector resulting from the task description (cf. task characteristics in figure 2) dominate the lower part of the scale of reliability classes (reliability class one to reliability class four).
- The external performance-influencing components of the stress vector (conditions of operation – e.g. personal and environmental factors in figure 2) can lead to a further decrease of human reliability and thus effect a classification of the considered assembly task into reliability class five to ten.

2.3 Comparison of alternatives

A comparison between different variations of carrying out assembly operations requires a trade-off between the proceeds realised by a lower error risk and the expenditure that is necessary to realize the alternative design of the assembly system. By rating planning alternatives with the MTQM method the assembly planner can predetermine the effectiveness of process changes within the assembly system at an early stage of the planning process.

In the context of illustrating the prospective assessment of planning alternatives, at first an ESAT-based reliability analysis of the manual assembly profile "assemble a brake piston" has been carried out by using the MTQM procedure. Figure 4 shows the calculated human error probabilities for the ten task items of the considered assembly operation resulting from the methods application.

Figure 4: Manual assembly of a brake piston - comparison of alternatives



Source: Own elaboration

Considering the assembly operation "assemble a brake piston", the analysis showed that the motion sequence "secure brake piston" with a human error probability of 0.00132015 represents the most error-prone work step. A further root cause analysis showed that the high error rate of this work step is substantially caused by a high number of movements that must be carried out in parallel. For this reason, the assembly operation "assemble a brake piston" was reengineered in order to reduce its risk potential significantly.

The optimized assembly process shows an alternative process flow. Thus, by reducing the necessity of parallel movements and by changing the order of single assembly steps it was possible to increase the accessibility of components and thereby to reduce the risk of injury to employees associated with the task execution significantly. As a result, the risk potential of the total task could be reduced by about 15 % (c.f. figure 4).

2.4 Validation of MTQM

The testing and validation of the MTQM method took place on the basis of numerous case studies at several business partners from automobile industry, heaters technology as well as drive and control technology. Here, always those manual assembly operations were analysed for which already entirely gathered, retrospective error data exist. Furthermore, when selecting the case studies it was ensured that the considered assembly operations clearly differ from each other in its work content, its execution time and its task complexity.

As a result, the developed procedure was applied for the prediction of human error probabilities for assembly profiles of different volume that consist of ten to hundred task items.

The evaluation of the analysis results showed that although the predicted HEP values in absolute height deviated from actual error rates (depending of the input data's level of detail and the analysis scope, two to thirty times too high prediction values resulted) the order of assembly stations' forecast error susceptibility however in all cases tallied with companies' practices. With it, the established reliability values enable an unambiguous prioritization for the development of process optimization measurements. By prospective determining of human reliability in the assembly process, the production planner is able to both recognize and transfer necessary system adaptions already before putting the assembly system into service, so that cost-intensive rearrangements in the ongoing process can be reduced.

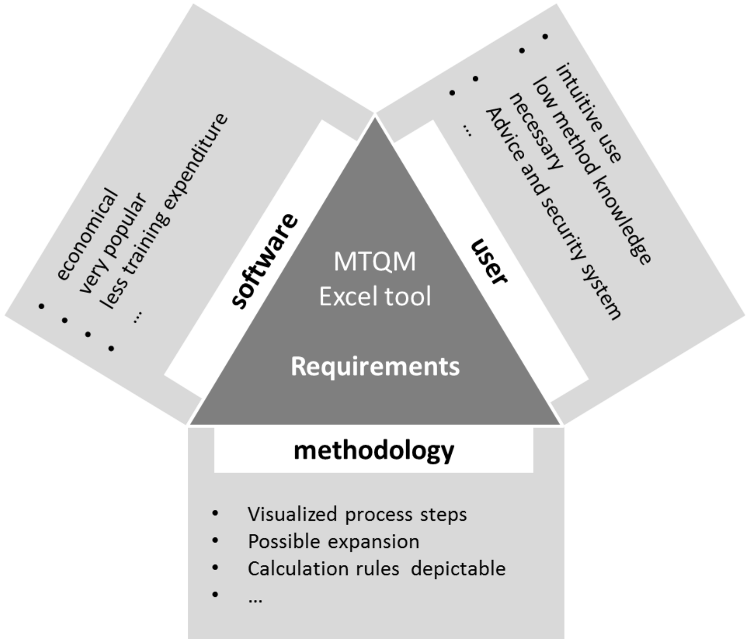
3. Conception of an Excel-based MTQM software tool

As mentioned before, applying the MTQM method until now requires an in-depth knowledge of predetermined motion time systems and established procedures of human reliability analysis. This affected, that companies having heretofore no experience in dealing with both predetermined motion time systems and procedures of human reliability analyses had difficulties in applying the MTQM method. For enabling also those companies to analyse manual assembly operations under time and risk aspects, in the following chapter the conception of an Excel-based software tool is presented, that allows to evaluate different assembly operations, to describe them standardized and to automatically determine target times and pre-weightings that are necessary for the following risk analysis (cf. chapter 2).

3.1 Major requirements for the MTQM software tool

The demands on the computer-aided analysis tool on the one hand result from the methodology of the developed procedure for the assessment of human failure in manual assembly (cf. chapter 2), and on the other hand are determined by the planned application field of the analysis tool. The presented requirements which can be subdivided into the categories "software", "user" and "methodology" are illustrated in figure 5.

Figure 5: Requirements for the MTQM software tool (extract)



Source: Own elaboration

The analysis tool is primarily designed for the assembly planning in small and medium sized enterprises (SME), which are frequently restricted in financial resources and method knowledge. For prospectively carrying out risk analyses even in SME, it is necessary to choose a favourably software for developing the analysis tool. This software should potentially be widespread in the regarding companies, so that expensive investments and laborious trainings can be dropped. Furthermore, this increases the necessary acceptance of testing the developed software tool in the industrial practice.

In order to make the software tool useful for as many employees as possible and also for those having only little method knowledge in HRA and predetermined motion time systems, an intuitive and safe menu navigation along necessary process steps had to be implemented. With it, the user should be gradually leaded through the analysis procedure and at wrong or incorrect inputs be directly pointed to the operating error. Hence, this inherent note and control system prevents the analysis from being useless.

The method for determining human error probabilities in manual assembly is steadily further developed and also expanded as well as improved by data from previous risk analyses. Therefore, the developed analysis tool is prohibited to be designed as a closed system, but has to be rather open for expansions, e.g. modified computational regulations. Hence, the fields for later users and the fields for potential expansions by an administrator have to be clearly separated and protected from unauthorized access.

3.2 Implementation concept

For generating an economic analysis tool usable with low training expense, the analysis tool is based on the globally spread software Microsoft Excel. This inter alia offers the considerable advantage that simple arithmetic operations can be directly reproduced in Excel. Additional operations and analysis modules being infeasible in Microsoft Excel can be replenished on little effort by macros programmed with Visual Basic (Walkenbach, 2013). Furthermore, the basic structure of Excel offers the following advantages:

- The system environment is already familiar for the user (single work sheets, tabular structure, familiar symbolism etc.). This plainly lowers the inhibition level for using a new program.
- Since known application patterns were picked up, the usage of the analysis tool will ensure rapid learning effects.
- The Excel tool is designed open and can be easily linked to other systems. Because of the known system environment, company-specific adjustments can be simply made by system administrators.
- The use of Microsoft Excel as basis facilitates the acquirement of industry partners for validating the Excel tool, since of the known system surrounding safety concerns only exist in exceptional cases.

3.3 Development and structuring of the database

The structure of the developed Excel tool is based on the proceedings of both the Expert System for Task Taxonomy (cf. (Brauser, 1990)) and the MTQM method (cf. chapter 2 and (Kern, 2013); (Kern, 2015)). For the implementation of the computer-aided Excel tool, the creation of a database was required which currently contains about 30 assembly-specific analysis modules. The direct access to this database was protected by password block to secure that only authorized users (e.g. administrator) can make modifications or replenishments.

Purpose of the standardized analysis modules stored in the database 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 human error probabilities.

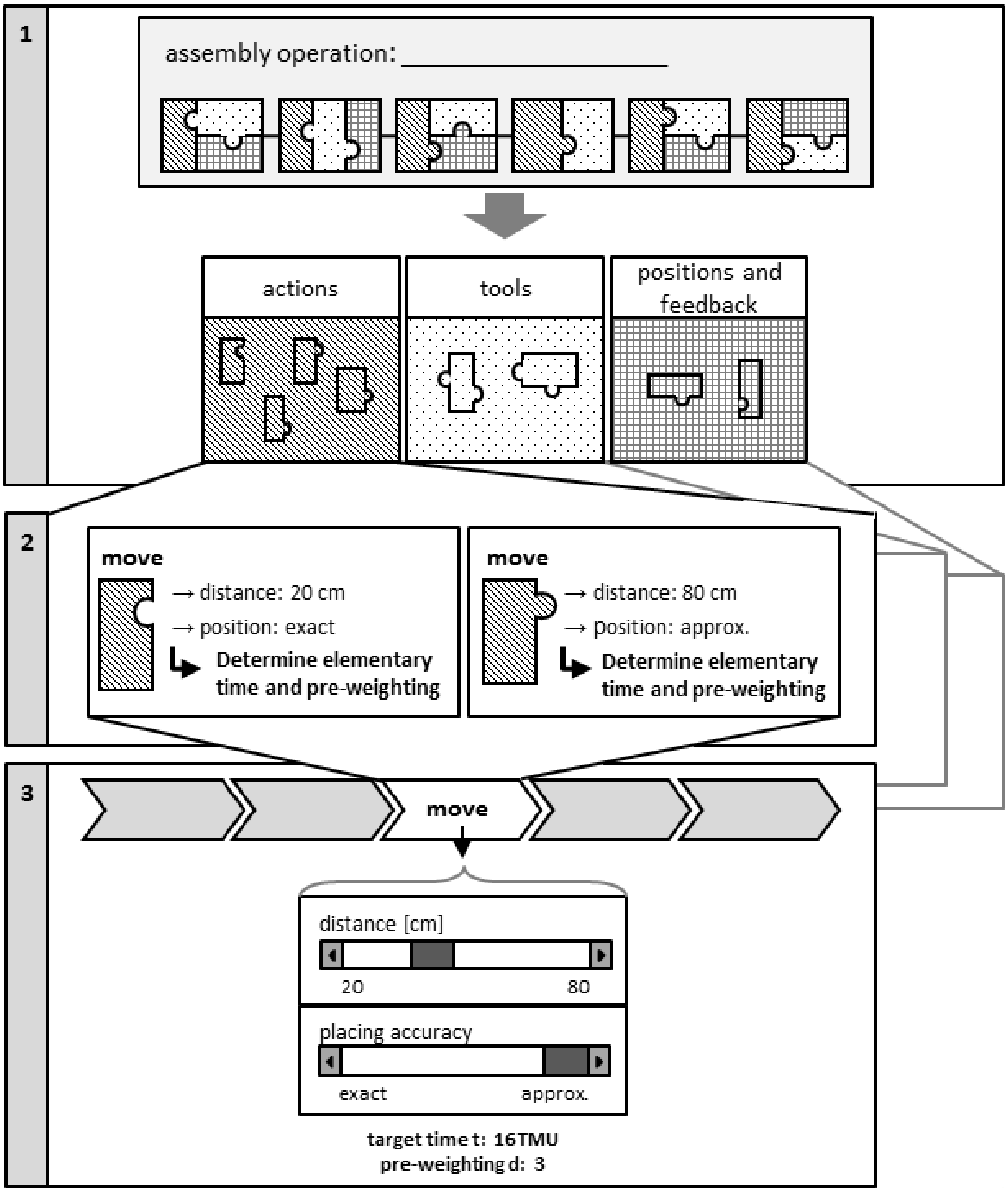
Under recourse to the results of all risk analyses that were already carried out in the course of developing the MTQM method, to create the addressed analysis modules a three-stage approach has been chosen.

According to figure 6, the first step of crating standardized analysis modules is to decompose all task items of the already manually carried out risk analyses in single modules and afterwards allocate those generated modules to the categories “actions“ , “tools“ and “positions and feedback“ (cf. figure 6, step 1).

Based on this, in the next step within the single categories, modules having the same content are selected and then their dedicated parameters (time values, pre-weightings, difficulty) are analysed concerning their value ranges of the factors involved (distances, weights, placing accuracy, etc.)(cf. figure 6, step 2).

In the last step, universally applicable standardized analysis modules arise by spanning assembly-specific value ranges of factors involved (e.g. distance 20 cm, distance 50 cm and distance 80 cm). From those standardized analysis modules thereupon a multitude of manual assembly operations can be composed (cf. figure 6, step 3). In result, by generating this database and the containing analysis modules, the majority of frequently occuring manual assembly operations can be described and analysed under time and risk aspects. As the MTQM method is steadily further developed and regularly expanded by data of already carried out risk analyses, the software is moreover open-designed so that authorized administrators can expand it by additional analysis modules at any time.

Figure 6: Procedure for determining standardized analysis modules



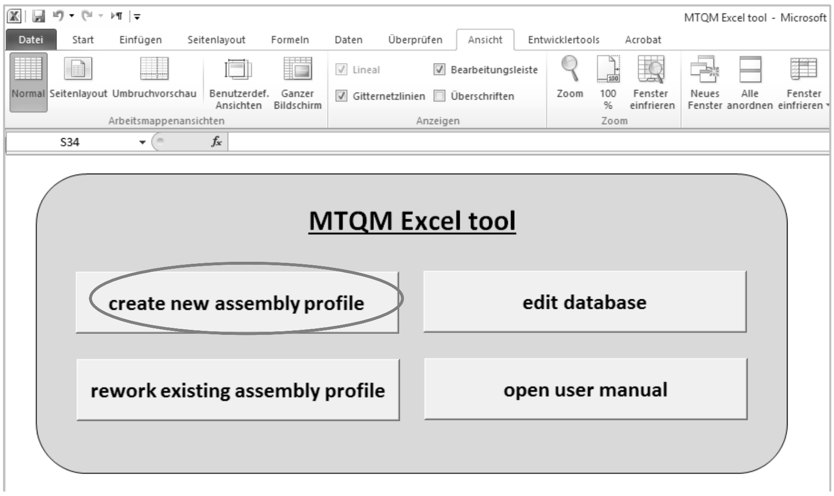
Source: Own elaboration

3.4 Modules of the software tool

In the following sectors, the structure and several different analysis options of the developed Excel tool should be presented in excerpts.

The MTQM-based risk analysis starts with a home screen, which is linked to all considerable areas of the software. In detail, these are the analysis modules "create a new assembly profile", "rework an existing assembly profile", "edit database" and "open user manual" (cf. Figure 7).

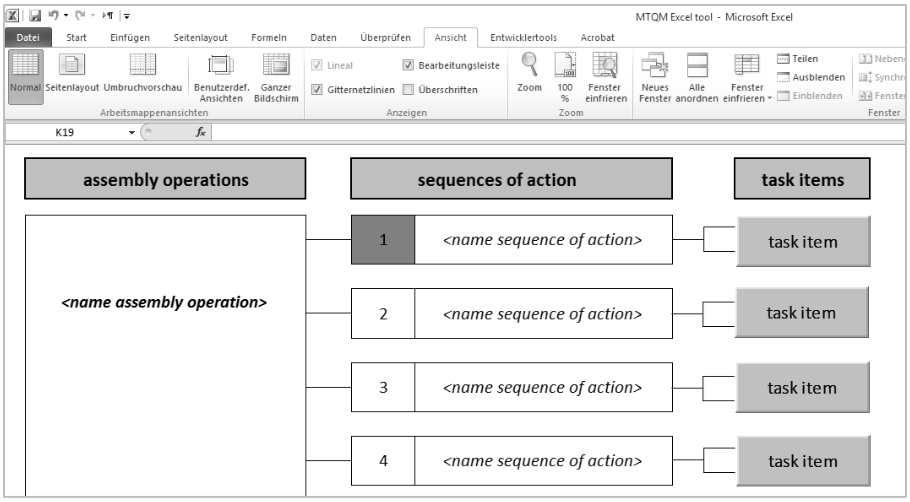
Figure 7: Home screen of the software tool



Source: Own elaboration

Usually, the starting point of the analysis is choosing the program section “create a new assembly profile”. In the next step, the assembly operation has to be named and subdivided into single sequences of actions and task items. For this purpose, the user interface of the software tool is configured in that way that the user is lead through the analysis along a predetermined hierarchic structure from the left to the right (cf. figure 8).

Figure 8: Subdivision of the considered assembly operation (extract)



Source: Own elaboration

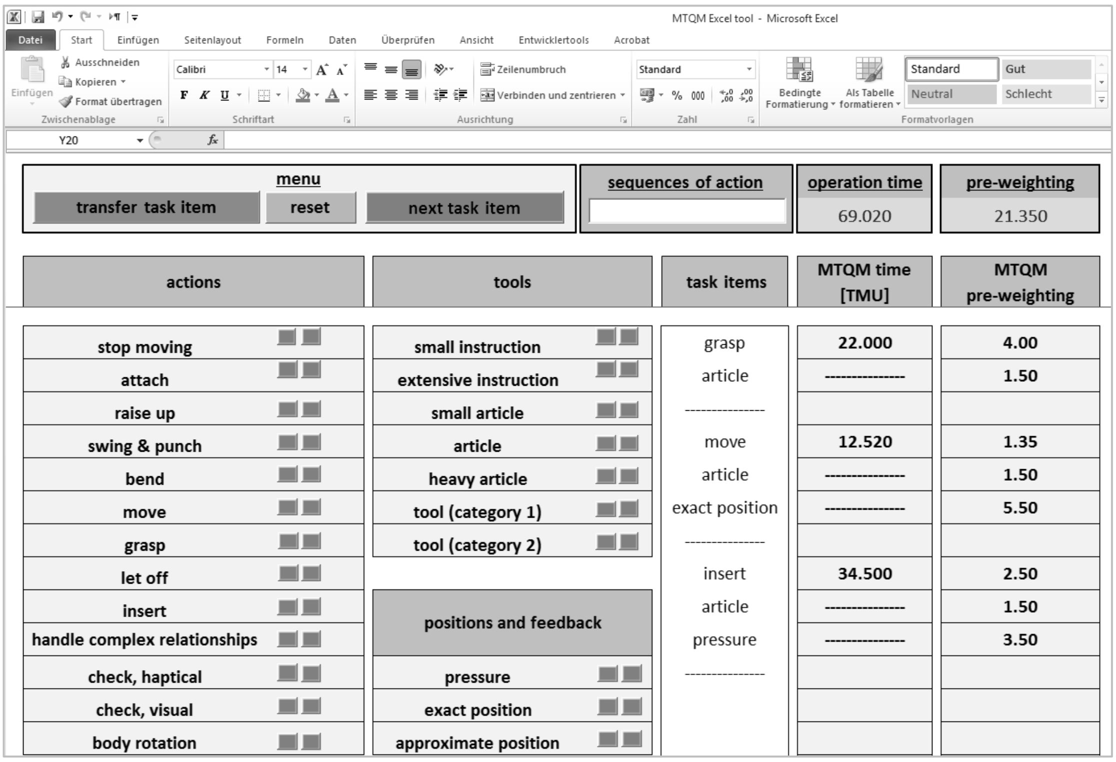
After compiling the assembly operation to be analysed via input field “name assembly task”, in the next step via input field “name sequence of action” the user has to subdivide the assembly operation into single process steps, the so-called sequences of action. In the later analysis course, this subdivision enables a consideration of single sequences of action isolated from the total task, so that already in the planning phase time- and risk-critical sequences of action can be detected. Afterwards, those quality-critical work steps can be proactively improved in an iterative planning process.

Next along the hierarchic structure, the created sequences of action must be further subdivided into single task items, to which the analysis modules deposited in the database (cf.

chapter 3.3) are later allocated. For proactively avoiding incorrect operations, a feedback function has been integrated into the Excel tool, which recognizes faulty inputs and automatically gives the user suggestions for improvement. If, for instance, the user draws up a task item which - against the guidelines of the based methodology for risk analysis - contains more than one module of category "actions", the system interface gives a warning which ensures the error correction and with it the functionality of the analysis.

In order to assign analysis modules to specific elements of the task description, a click on the colour-highlighted button "task items" (cf. figure 8) diverts to the next level of the Excel-based analysis software. Here, 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 items of the considered assembly task and, based on this, the user can task-specifically determine the range of influence factors (distances, weights, placing accuracy, etc.) being linked to the analysis modules. With it, in the left column of the analysis the user initially chooses an analysis module (e.g. move, turn, press, article, exact position, etc.) and subsequently assigns it to the correlating element of the task description by pressing the left button (cf. figure 9).

Figure 9: Assignment of analysis modules to task items of the considered assembly operation (extract)

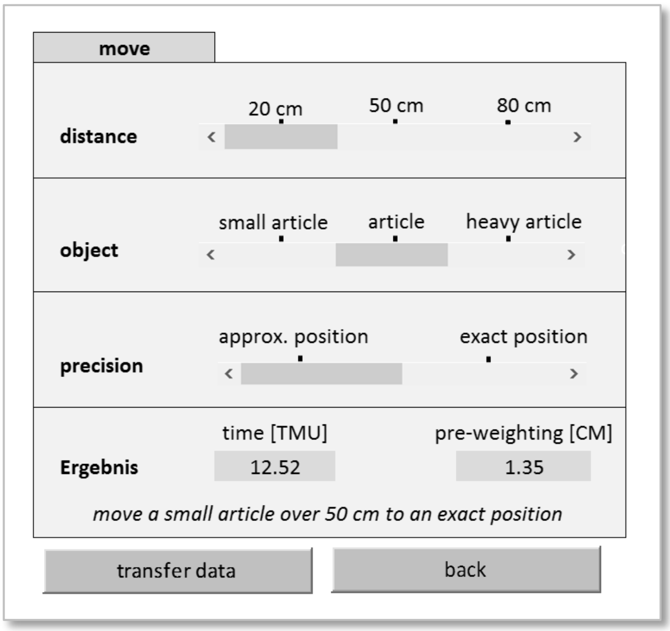


Source: Own elaboration

Here, the allocation on analysis modules occurs with automatic recourse to the previously created database, in which the assigned time values, pre-weightings and performance shaping factors are deposited. When the analysis module is by clicking transferred to the column "task item", the corresponding time values and pre-weightings are automatically transmitted to the provided columns in the right part of the analysis section (cf. figure 9). Hence, a completely systematic illustration of the task description of the considered assembly task is created. For correcting usage faults, via clicking the right button any analysis module being inadvertently allocated to the task description can be deleted.

In some cases, the time values and pre-weightings stored for single analysis modules are variable and determined by valuable markedness of analytically based influence factors. The corresponding analysis modules in figure 9 are marked by an orange-coloured selection button. For also enabling those users having less method knowledge in carrying out a MTQM analysis, within the system development for all relevant influence factors of manual assembly (distances, weights, placing accuracy, etc.) typical values have been identified, which can be allocated to the appropriate analysis module with the help of an especially developed selection tool reached by clicking the orange-coloured button (cf. figure 10).

Figure 10: Selection tool for influencing factors on the example of the analysis module "move"



Source: Own elaboration

The example of the analysis module "move" shown in figure 10 has got the three influence factors "distance", "object" and "precision" and describes the task item "move a small article over 50 cm to an exact position".

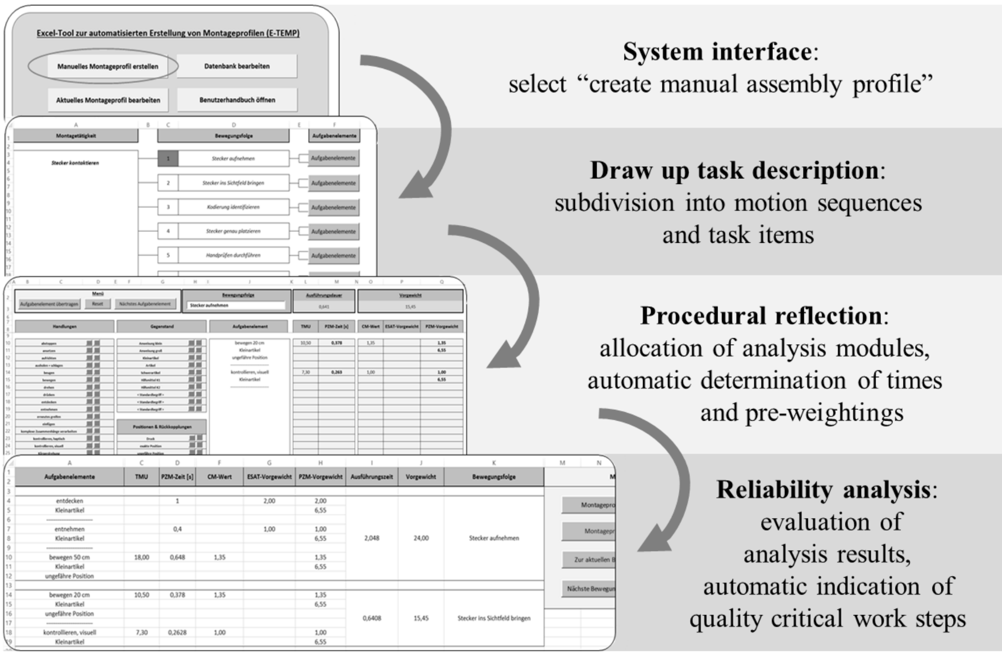
The user establishes the value range of the influence factors by scroll bar and with it receives the time in typical MTM time unit TMU (time measurement unit) and the correlating pre-weightings in CM value (Cue Motion) in result. By an immediate update of time and pre-weightings, the user here directly receives an advice about potentially time- or risk-critical influence factors of the investigated task items. By clicking the button "transfer data", the results created by the selection tool are subsequently integrated into the analysis section of the Excel tool and afterwards can be automatically evaluated under time and risk aspects appropriately to the MTQM procedure.

4. Summary

Based on the presentation of the assembly planning method MTQM (Methods Time and Quality Measurement), this paper showed how the MTQM method including the necessary method knowledge can be transferred into a computer-aided methodology, which enables an automatically conducting and evaluating of time and risk analyses for manual assembly tasks.

Figure 11 shows the conception results of the Excel-based MTQM software tool and once again describes the essential elements of the developed software tool in summary.

Figure 11: Components of the software tool to simplify complex risk analysis



Source: Own elaboration, cf. (Kern, 2015)

By program modules based on each other (e.g. task description, procedural reflection, reliability analysis, time and risk prediction), the integrated method knowledge and the visualization of work operations, the user is conducted through the analysis step by step. By using the analysis modules stored in the software`s database the user is able to evaluate not only complete work tasks but also single process steps of a manual assembly operation under time and risk aspects on less expenditure.

As a result, by visualizing the MTQM method inclusive required method knowledge risk analyses for evaluating human failure in manual assembly will be carried out automatically and can also be conducted in companies having limited method knowledge, restricted financial devices and small workforce.

5. Acknowledgement

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