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Evaluation Of The Human Error Probability In Cellular Manufacturing

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Abstract

Referring to Gutenberg there are three elementary production factors: material, equipment and human workforce. They all have a significant influence on the product quality. Nevertheless, in machining research they have been given differing attention, depending on the focused scope. This paper presents the results of an empirical study of the human error probability (HEP) in a Cellular Manufacturing environment. First, it is shown that the influence of human work on the resulting product quality in machining so far has only been given little attention. Therefore a content analysis according to MAYRING has been conducted on publications in the domains of production technology and ergonomics. Second, various schemes for the classification of human errors are presented and evaluated in terms of their applicability to human tasks in machining. Finally the design and results of an empirical study which has been conducted at the Cellular Manufacturing reference line, consisting of two lathes and four milling machines, in the Center for industrial Productivity (CiP) at TU Darmstadt are presented. Overall 2700 human-machine interactions have been observed and evaluated in terms of their influence on product quality. Results show that there is a significant influence of the human worker as three percent of these interactions incorporated a spurious action.

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Keywords: human error; cellular manufacturing; quality

1. Introduction

Cellular Manufacturing, as a concept for designing lean and efficient production processes, has proven to be an economic approach, even in high-wage countries [1]. In contrast to a done-in-one concept which tends to integrate all necessary manufacturing technologies in one machine, Cellular Manufacturing aims at reducing complexity and increasing flexibility by distributing the work content to several right-sized machines, using an operator for material handling and transport [2]. In consequence, the number of human-machine interactions is relatively high and human errors are more relevant regarding their influence on product quality.

The goal of the research presented in this paper is to identify the importance of human errors in Cellular Manufacturing environments and show that this topic has been neglected in discussing the influence factors on product quality so far. Therefore, the following assumptions are discussed:

- A1. In investigations that regard the product quality in machining, human workers are not considered an important cause factor.
- A2. Human errors are a relevant cause factor regarding product quality in Cellular Manufacturing.
- A3. The amount of human errors which affect a workpiece depends on the number of machines used for its machining.

In order to investigate these assumptions, first, a short summary of existing human error taxonomies and methods for Human Reliability Assessment (HRA) is given in section 2. The results of a content analysis regarding the importance of human error as an influence factor on product quality in machining research are presented in section 3 whereas section

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4 describes an experiment for quantifying the human error probability (HEP) in a Cellular Manufacturing reference line. The statistical tests used for the investigation of the assumptions A1-A3 in section 3 and 4 are based on the instructions of BAMBERG et al. [3] A final conclusion is given in section 5.

2. Human reliability

Human error and human reliability describe two complementary aspects of human action. In VDI 4006 human reliability is defined as the "capability of human beings to complete a task under given conditions within a defined period of time and within the acceptance limits", whereas an error is a "human action which exceeds the defined acceptance limits". Accordingly, the human error probability (HEP) and human reliability probability (HRP) are indicators for the relative occurrence of errors and respectively faultless actions and defined as [4]:

$$HEP = \frac{number\ of\ observed\ errors}{number\ of\ the\ possibilities\ for\ an\ error} = \frac{n}{N} \quad (1)$$

$$HRP = 1 - HEP \quad (2)$$

In order to evaluate the human error probability a classification of possible errors as well as an appropriate methodology is needed. The following paragraphs present an overview on taxonomies for the classification of human errors and existing HRA.

2.1. Taxonomies of human error

For the differentiation of certain types of human error taxonomies have been developed. These can either be cause oriented, occurrence oriented or a combination of both types. An overview on existing classification schemes for human error types can for example be found in [5].

NAKAJO and KUME present three categories to classify human errors and describe each one with several examples: The first category involves those errors that occur when the worker does not remember the finished or remaining steps of

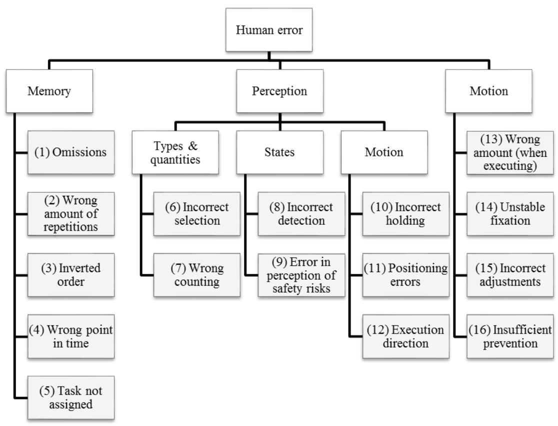

Fig. 1. Classification of human error (according to [6, 7])

a process. Errors of perception are further divided into perception of types and quantities, states as well as motions which all can be perceived incorrectly. Finally, errors of motion are errors which describe the situation when the execution of a task is false even though the task is memorized and the situation is perceived correctly. [6] SONDERMANN seizes the examples mentioned by NAKAJO and KUME and further subdivides their categorization into 16 types of errors (see fig. 1) [7].

2.2. Human Reliability Assessment

HRA techniques enable the quantitative or qualitative evaluation of human reliability. Their application is well-established in the design of control systems for nuclear power plants. Swain explains and evaluates 14 different HRA methods. The main criteria for his evaluation, which is based on an expert survey, are usefulness, acceptability and practicality. The methods which gain the best result in this evaluation are the Systematic Human Action Reliability Procedure (SHARP), the Accident Sequence Evaluation Program (ASEP) and the Technique for Human Error Rate Prediction (THERP). [8] Further summaries of various HRA methods can be found for example in [9–12]. Additionally, THERP is named as the most important HRA technique by several authors [10,11,13,14]. It estimates human errors and evaluates the related effects on the entire human-machine-system. As a basic tool a probability tree is used to model decision steps including wrong and correct choices. Additionally, a comprehensive set of tables links certain types of actions to a corresponding error probability.

One major issue with the quantitative evaluation of human error is the availability of reliable data. They can for example be determined via field study, experiment, statistics, estimation by experts or interviews [15]. Generally, data which has been derived from measurements should be preferred over subjective estimations [12].

3. Existing research of influences on the part quality in machining

In order to investigate the importance of human workers as influence factor on product quality in machining research a content analysis has been conducted. This research technique is a data acquisition procedure which can be used to analyze communication content in texts, pictures or films [16]. For the research presented in this paper the approach of MAYRING [17] has been used in order to facilitate the representation of the analysis material content in a category system.

The procedure to define convenient categories and assign papers to them is described in the following section. The goal has been to identify papers which present findings regarding the product quality in machining, classify these by the investigated cause factors and identify the main areas of research so far. As this topic includes two main elements, the influence of human error and the product quality in machining, two areas of research are found to be relevant: Production engineering and ergonomics.

Hence, the journals *“CIRP Annals – Manufacturing Technology”*, *“International Journal of Industrial Ergonomics”*, *“Procedia Manufacturing”* and *“Applied Ergonomics – Human Factors in Technology and Society”* have been included in the content analysis. The following paragraphs describe the selection of relevant scientific papers from these journals and their classification according to the investigated cause factors on product quality.

3.1. Relevant publications in production engineering research

In order to identify relevant publications in production engineering, papers published in the CIRP Annals have been filtered in three steps: first, pertinent CIRP Scientific and Technical Committees (STCs) have been chosen, 2nd, these papers have been narrowed down using specific key words and 3rd, remaining, quality related publications have been chosen.

The STCs are ten groups within the International Academy For Production Engineering (CIRP) that each focus on a specific research topic and organize the publication of findings in their fields. For the content analysis the papers of the STCs *“Life Cycle Engineering and Assembly”* (A), *“Electro-Physical and Chemical Processes”* (E), *“Forming”* (F) as well as *“Production Systems and Organization”* (O) have been excluded as they do not primarily deal with machining topics.

The key words, used to narrow down the amount of papers are split into two areas of interest. The first part (32 terms) is derived from DIN 8589 [18] which defines relevant terms for machining. The second part (25 terms) originates from the CIRP encyclopedia [19] which includes a large choice of term explanations from production engineering as well as logistics and have a relation to product quality in common. In order to find papers related to product quality the requirement for the selection of a paper has been to include at least one term of each of the both lists in the title or abstract.

Since the publications which have been identified in the first two steps do not necessarily deal with the investigation of influences on product quality the last step narrows down the selection of relevant papers by explicitly picking those that include the term *“quality”* in their title or abstract.

Fig. 2 shows the results of the single analysis steps for the production engineering as well as for the ergonomics area. Concerning the CIRP Annals 6.698 papers have been included in the investigation and reduced to 3.240 papers in the first step. The filtering via the two lists of key words reduced this to 1.150 papers. Finally, using the term *“quality”* 184 relevant papers have identified for the classification process.

3.2. Relevant publications in ergonomics research

The approach described in 3.1 does not deliver reasonable results for the selection of relevant papers in ergonomics research. In this field the procedure has been adapted for three reasons. First, ergonomics research focuses on the human being which renders the filtering for this factor unnecessary. Second, in contrast to the CIRP Annals these publications also discuss other parts of human life and not exclusively topics

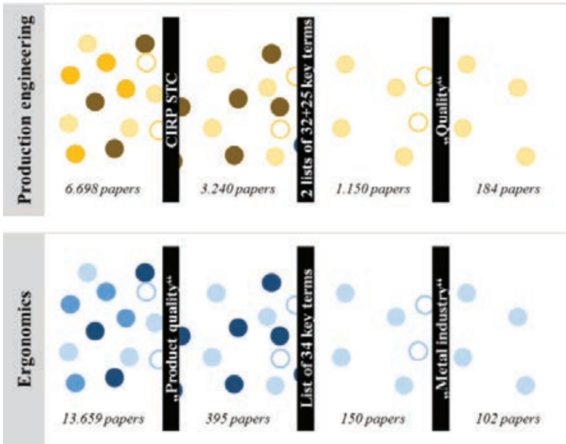

Fig. 2. Process of identifying relevant papers

from the production engineering domain. Third, concerning the lists of terms used for the analysis in 3.1, there are ambiguities regarding the use of these words in production engineering and ergonomics. For example, there is a high probability that the word *“turning”* has two different meanings, depending on the context of the regarded publication. The adapted filtering process also includes three steps:

1. Retrieving papers which include the term *“product quality”* in their abstract or title
2. Filtering papers using the list of terms from DIN 8589 expanded by *„worker“* and *„operator“*
3. Narrowing down to the publications which explicitly include the term *“metal industry”* in their title or abstract

As shown in fig. 2 overall 13.659 papers from the three journals of ergonomic research have been analyzed. Only 395 discuss a topic related to product quality. Out of these, 150 deal with a machining or an operator topic. Finally, 102 of the remaining publication concentrate on a question which has its seeds in the metal industry.

3.3. Publication classification

After having identified relevant papers which discuss the influence factors on product quality, their classification is described in this paragraph. The goal is to come to a conclusion concerning the relevance of human influence on the quality of machined products in research. The definition of appropriate categories is oriented to the separation of causes in the cause and effect diagram introduced by ISHIKAWA. He identifies five main causes which characterize a process: Material, machine, measurement, man and method. [20]

Furthermore, a vocabulary analysis has been conducted on selected publications to identify the most frequently used and thereby most relevant words. The presence of these terms in the title and abstract of a paper determines its categorization according to the following four rules which assign papers by

1. …the title of the paper
2. …the number of occurrences of a retrieval term
3. …the context in which the most frequently detected term is used
4. …an interpretation of the abstract

(1) In cases when a paper's title is already meaningful enough to allow a clear classification, the publication is assigned to the corresponding category. (2) If this is not the case the terms related to the different categories are counted. An occurrence of twice as many terms of one category compared to the other categories triggers the assignment to this type of influence. (3) Next, if the paper still cannot be allocated, a closer look is taken to the class incorporating the most occurrences of related terms. If these words are actually used in the context of this category the paper is accordingly assigned. (4) Last but not least, if all these rules do not apply the abstract is checked for an adequate classification of the paper. If this also is not possible it is excluded from the evaluation.

The resulting categories as well as the amount of papers assigned are shown in fig. 3. The class of papers which investigate the influence of human workers only incorporates eleven papers (6%). Out of these in fact only two consider a machining context. The others focus on quality management issues in general.

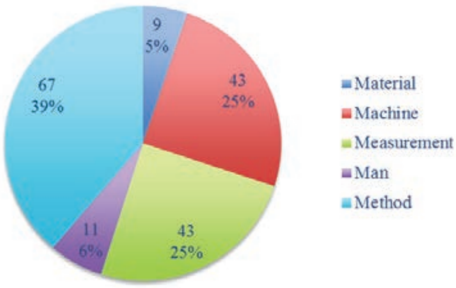

Fig. 3. Categorization of publications by the considered cause factor

An equal distribution of papers to the five categories would result in a share of 20% for each category. In order to evaluate assumption A1 (see section 1), a binomial test has been conducted, testing the hypothesis H_0 that the share of papers assigned to the category of the influence factor man is at least 20%. If this is the case human workers are considered to be an important cause factor in investigations regarding the product quality in machining. As level of significance α=0.01 has been defined. As shown in table 1, H_0 is rejected as the result of the test statistic v is an element of the rejection range B. This means that the influence of human workers on product quality in machining research has been neglected so far.

Table 1. Results of the binomial test for assumption A1 ($\alpha = 0.01$)

Assumption	Hypothesis	v	B	Decision	Test
A1	H_0: $p \geq 0.2$ H_1: $p < 0.2$	11	{0,…,22}	H_0 is rejected	binomial test

4. Evaluation of human error in Cellular Manufacturing

For the evaluation of the human error probability in Cellular Manufacturing an experiment has been conducted in the Cellular Manufacturing reference line at the Center for industrial Productivity (CiP) at TU Darmstadt. The following section describes the experiment design and presents the results.

4.1. Experimental environment

The CiP is a model factory on the campus of TU Darmstadt. It incorporates a value stream for eight variants of a pneumatic cylinder. In a machining cell a one-piece-flow system is established where the cylinder bottom is machined consecutively on four mills and the piston rod on two lathes. Material handling and transport within the cell as well as the operation of the machines is performed by an operator whose total work content aggregates to approximately 20 seconds per machine.

4.2. Selection of relevant human error types

The selection of relevant human error types for Cellular Manufacturing has been conducted in three steps with the results shown in table 2:

1. The taxonomy of SONDERMANN / NAKAJO and KUME has been chosen as a reference.
2. Error types of this reference have been checked for their relevance for Cellular Manufacturing.
3. The remaining types have been reviewed concerning their influence on product quality.

One advantage of SONDERMANN's classification scheme, which is based on the taxonomy of NAKAJO and KUME, is that it includes erroneous human actions as well as thinking processes. Furthermore, it is very detailed and focuses on human activities. As it has been developed for designing Poka Yoke solutions it also is well suited for production environments.

For the selection of relevant human error types the taxonomy has been conducted to the tasks identified in a MTM-analysis of the cell which has already been presented in [21]. The results show that the error types *"wrong amount of repetitions"* (2), *"task not assigned"* (5), *"wrong counting"* (7), *"incorrect detection"* (8), *"incorrect holding"* (10), *"wrong amount (when executing)"* (13) and *"insufficient prevention"* (16) are not relevant for human tasks performed in Cellular Manufacturing. The main reasons are that these types describe tasks which the operator is not responsible for. Also, they can be suspended as a one-piece-flow guarantees that the operator only has to deal with one piece of material in each manual task.

In the third step, the remaining error types are checked for their potential influence on the product quality which is defined as the "degree to which a set of inherent characteristics fulfills requirements" [22]. *"Omissions"* (1) can occur in each manual task but are particularly critical to product quality when unloading the machine, cleaning the workpiece and clamping device, clamping the workpiece and selecting the machining program. Forgetting to close the door or starting the machine can become relevant, when this is not recognized and an unmachined workpiece is transferred to the next machine. The *"incorrect selection"* (6) of parts, tools or documents is a relevant error type when the operator picks up the workpiece at the first mill or lathe where orders are triggered or when the machining program is selected. Significant degradation of the product quality can be caused by *"positioning errors"* (11) during the process of loading the machine. An *"erroneous execution direction"* (12) describes a situation where the material orientation is wrong or movements are accidently performed the wrong way for perception reasons. This can happen when the machine is loaded and the workpiece is clamped. An *"unstable fixation"* (14) is particularly critical when clamping the workpiece but can also become relevant when the part is not fixed properly in the hand of the operator and drops. Finally *"incorrect adjustments"* (15) are errors that can occur during workpiece positioning or when adjusting the clamping force.

The error types *"inverted order"* (3), *"wrong point in time"* (4) and *"errors in perception of safety risks"* (9) have not been assigned to a manual task in Cellular Manufacturing due to their lacking influence on the product quality when operating a machining cell.

Table 2. Human error types relevant for manual tasks in Cellular Manufacturing (adapted from [21])

Manual task	Error type					
	1	6	11	12	14	15
1. Picking up the workpiece from the storage next to the machine or from the previous machine		X			X	
2. Workpiece transport and depositing between machines					X	
3. Opening the machine door						
4. Unloading the machine	X				X	
5. Cleaning of the workpiece	X				X	
6. Cleaning of the clamping devices	X					
7. Loading the machine correctly			X	X	X	X
8. Clamping the workpiece in the machine	X			X	X	X
9. Selecting the correct machining program for the variant	X	X				
10. Closing the machine door	X					
11. Starting the machine	X					

4.3. Experiment design

The experiment has been set up as an observation where one test person has operated the machines of the cell and the experimenter has observed him using a structured form which has included a table with one row for each workpiece and the potential human errors represented as columns. Compared to section 4.2 some minor adjustments regarding the relevant error types have been made. The *"incorrect selection"* (6) has been further divided into an incorrect selection of a machining program and a variant of raw material. *"Positioning errors"* (11) and *"incorrect adjustments"* (15) are only identifiable with adequate measurement equipment and thereby cause a disproportional effort since obvious errors regarding the material orientation are defined as *"erroneous execution direction"* (12). Using the resulting tally sheet, human errors have been counted and linked to the specific operator, workpiece and machine during the experiment.

Overall, the production of 450 cylinder bottoms and 450 piston rods has been simulated using real parts, machines and machining programs. The only adjustment here has been to move the zero point in z-direction. Consequently, the workpieces have not been touched by the tool. This has been considered not to be necessary since a measuring of the workpiece will include all cause factors and not just human errors. Also, for the experiment the error probability has been of major interest and not the effects of an error. As there are six machines in the cell this adds up to 2.700 human-machine interactions and consequently 27.000 manual tasks to be performed, since there are 10 tasks per machine which may have an influence on product quality (table 2). The probands have been engineering students at the of age 22-25 years who have been trained prior to the experiment and have produced 150 workpieces each, which corresponds to five hours of overall production time per person. The order of the triggered variants has been random but the same for each person.

4.4. Results

Overall 82 human errors have been observed throughout the experiment which results in a HEP of 0.003. As shown in fig. 4, *"omissions"* (1) have been identified as the most important error type. Most frequently the cleaning of workpiece and clamping device have been neglected. In terms of product quality this is a crucial task since metal chips and further impurities can influence the clamping process. Furthermore the *"incorrect selection"* (6) of the machining program and the *"unstable fixation"* (14), which obviously have a negative impact on the product quality, have been registered 32 times in total. Due to the application of one-piece-flow in the cell the correct variant of raw material only has to be chosen at the first machine in line – not at every single station. Consequently, the amount of incorrect selections of the workpiece variant has been rather low compared to the overall criticality of the error type *"incorrect selection"* (6). Also, this error has only affected the piston rods. Due to their shape and number of variants they are a lot harder to distinguish from each other compared to cylinder bottoms.

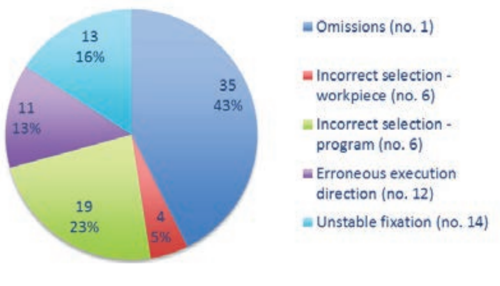

Fig. 4. Share of human error types

The work in the considered cell is rather monotonous since the worker's cycle time for unloading and loading one machine is only about 20 seconds. Nevertheless, an increase concerning the error rate has not been observed.

In order to evaluate assumption A2, the process capability index C_{pk}, which is a common tool for evaluating the quality of a manufacturing process [23], has been used as a reference. C_{pk}=1.00 means that a process variation of $\pm 3\sigma$ equals the tolerance of a product feature. This corresponds to a reject rate of 0.27%, assuming a normal distribution. Even though the human error types, introduced in section 2.1, can have a negative impact on product quality, an error does not necessarily have to cause a defect, except for the *"incorrect selection"* (6) of the machining program. Therefore only this error has been included in the binomial test for assumption A2 which results in the rejection of the null hypothesis H_0 that human errors do not endanger a C_{pk}=1.00 for the level of significance α=0.01 (see table 3).

Regarding assumption A3, the hypothesis H_0 is that the amount of human errors which effect a workpiece X and the number of machines used for its production Y are independent. For a level of significance α=0.01 it also is rejected using a χ^2 contingency test (see table 3).

Table 3. Results of the tests for the assumptions A2 and A3 ($\alpha = 0.01$)

Assumption	Hypothesis	v	B	Decision	Test
A2	H_0: $p \leq 0.0027$ H_1: $p > 0.0027$	11	{0,…,22}	H_0 is rejected	binomial test
A3	H_0: X and Y are independent H_1: X and Y are independent	321.36	(193.20; ∞)	H_0 is rejected	χ^2 contingency test

5. Conclusion and outlook

The presented paper has shown that the investigation of the human influence on product quality in machining has been of almost no importance so far. In production engineering research, quality factors are analyzed and discussed in a wide range but the focus is biased by a clearly technical perspective. On the other hand ergonomics research examines human reliability but not in a machining context. The presented experiment has shown that also in machining there is a significant influence of human workers on the quality of manufactured parts, at least for less trained workers. Especially omissions and the incorrect selection of variants or machining programs are of great importance. In Cellular Manufacturing with a low level of automation where multiple machines are operated by one worker and workpieces are clamped several times, human errors are crucial for product quality. Poka Yoke systems [24] and the principle of Autonomation [25] address this issue and help to identify and prevent human errors prior to the occurrence of a product defect. Their necessity so far usually is evaluated by a failure mode and effects analysis (FMEA) [26]. In doing so, error probability is rated in interdisciplinary teams using a points rationing scheme. A possibility to estimate the human error induced reject rate is valuable but missing.

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