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# Evaluation of Work Measurement Concepts for a Cellular Manufacturing Reference Line to enable Low Cost Automation for Lean Machining

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**Abstract**

Cellular Manufacturing has been proven to be an economic, efficient and lean approach bringing flexibility into machining areas. Corresponding solutions use several basic machines that are adapted to the machining task in a right-sized equipment approach. However, the use of basic, low cost machinery providing just necessary functions results in a relatively high manual operation effort. The preferred approach in order to reduce manual work in production is automation. Traditional automation of man-machine systems – especially in western countries – tends to be comprehensive and thus often complex and expensive. A low cost, lean automation intelligently being adapted to the individual task, as well as a decision method for choosing the tasks worth being automated, is required.

The first step on the road towards a scientifically sound low cost automation method for a Cellular Manufacturing line is identifying and quantifying the different manual tasks which could potentially be automated. Therefore, this paper starts with investigating existing analytical methods for measuring work. The different measuring concepts have been applied to the Cellular Manufacturing reference line at the Process Learning Factory CiP at TU Darmstadt. An adequate evaluation system considering reality, detail, variation and effort levels has been defined in order to assess the results' suitability for evaluating manual work in a Cellular Manufacturing line, pointing out potentials and limits of the individual approaches. As the final outcome, a ranking of different work measurement concepts for the Cellular Manufacturing reference line is presented, verifying the applicability of the general approach and serving as a basis for further evaluation of other lines.


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*Keywords:* Low Cost Automation; Cellular Manufacturing; Work Measurement; Lean Machining

## 1. Introduction

State-of-the-art Lean Production systems aim to increase efficiency and flexibility in order to meet today's challenges in manufacturing. [1,2] The desired method for discovering inefficiencies and inflexibilities is the introduction of flow production with limited work-in-process inventory levels. [3,4,5] While these concepts are widely spread in assembly, flow production paradigms are rarely applied to technology driven machining areas.

By transferring the ideas of distributed, sequentially processed work content being adjusted to operator and tact time from assembly to machining, METTERNICH et al. [6] introduce Cellular Manufacturing as a lean approach bringing flow and flexibility into machining. Their proposed solution uses several basic machines that are adapted to the machining task in a right-sized equipment approach. Following METTERNICH et al.'s initial discussion on the economic viability of the Cellular Manufacturing concept, BECHTLOFF [7] further investigates economic boundaries for the application and proves the concept to be an efficient and economic alternative for machining.

The use of low cost machines with only basic functions results in a relatively high manual effort for operational tasks.


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Generally, manual work is being reduced by the introduction of automated solutions. However, classic automation in production – especially in the western world – is often set up as full-automation and thus tends to be complex and expensive. Frequently, certain functions are "overengineered" by the automatic solution, while other important ones are neglected. [8,9] This is contradictory to the low cost and right-sized equipment approach [10] immanent to Cellular Manufacturing. A low cost automation intelligently being adapted to the individual task as well as a precise, strategic decision method for choosing the tasks worth being automated in this environment of tight costs is required. Research in this area builds upon the work of TAKEDA [11], who first applied the concept at Toyota, using simple, self-made equipment.

The first step on the road towards a scientifically sound low cost automation method for a Cellular Manufacturing line is identifying the different manual tasks which could potentially be automated and quantifying the benefit they contain. Figure 1 gives an overview on the proceeding of the method and the structure of this paper.

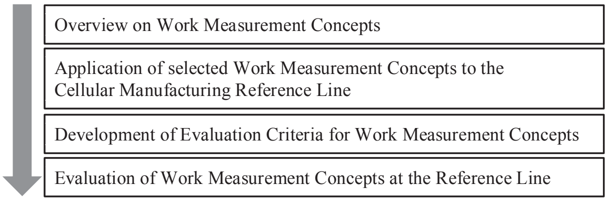


Fig. 1. Method of work measurement evaluation for Cellular Manufacturing described in this paper.

## 2. Work Measurement Concepts

Different analytical methods for quantifying manual work have been developed over the years. Across all methods, there is mutual agreement on "time" as a common unit of measure. [12,13] On an operational level three different approaches need to be distinguished (see figure 2). The first approach bases on the presence of a real observation environment, whereas the second approach determines planned times via calculated analytical methods. A third category collects methods that combine different aspects of the two other ones. [14]

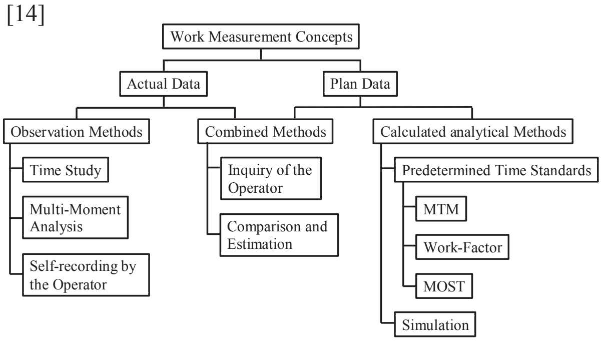


Fig. 2. Structure of different analytical methods for work measurement (adapted from [14,15,16]).

Time studies and systems of predetermined time standards as the two most relevant practical methods for the detailed work measurement of industrial processes that can be influenced by the operator [14,15] will be focused on in the following chapters.

### 2.1. Time Study

Essential prerequisite for the application of time measurement via time studies is an analysis of the entire working system including all variables with an effect on working time. [17] In a second step, all individual work processes are described in detail. Thus, the level of detail for the study can be defined by the analyst, depending on the individual goal of the analysis. The observed and recorded times are only valid for the specific work process observed. [13,15] Any change in the work process results in necessary adaptations of the recorded data. Leveraging time-recording equipment, trained analysts observe and measure the work being executed. Preferably, a number of different operators in various repeating cycles are part of the study. [12,13]

### 2.2. Systems of predetermined time standards

Systems of predetermined time standards belong to the category of calculated analytical methods. The major difference to time study approaches is their ability to calculate manual work times already during the planning phase of a work system via predefined time building blocks for standardized motion elements. With the use of analytically created matrices, target times are assigned to single motion elements. [14,18] In terms of practical relevance, systems of predetermined time standards can be further distinguished into Methods-Time Measurement (MTM), Work-Factor-Systems (WF) and Maynard Operations Sequence Technique (MOST), which is based on MTM. [14]

The original MTM system, also known as MTM-1, defines 19 separate basic movements, shown in figure 3, and is therefore quite a detailed and time consuming analytical instrument. All movements are linked with individual "Time Measurement Units" (TMU), in which one hour equals 100,000 TMU. In order to accelerate the application, various modified systems have been developed from MTM-1 over the years through a reduction of the detail level and an accumulated abstraction of tasks. [12,19,20]

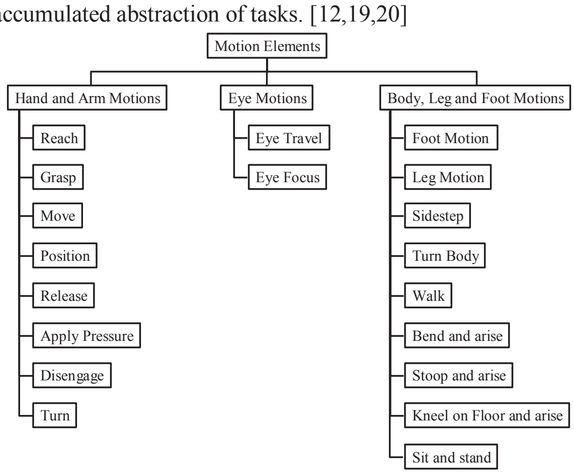


Fig. 3. Overview on basic movements of MTM-1 [19].

The WF standards differ from MTM mainly due to the fact, that only quantitative parameters are used to further describe motion elements. [15] The WF basic system uses eight elementary movements. These are further detailed, resulting in a relatively complex system. For simplification reasons, a reduced WF standard has been developed. [21,22]

While MTM and WF focus on composing basic motion elements, MOST works with predefined standard sequences of activities, originally built from MTM-1. Depending on the cycle time of the repeating processes to be analyzed, MOST systems are divided into BasicMOST, MiniMOST and MaxiMOST. [23]

## 3. Application of Work Measurement Methods to the Cellular Manufacturing Reference Line and Results

After the initial description of different methods for work measurement in chapter 2, this chapter focuses on the application of these methods to the Cellular Manufacturing reference line at the Process Learning Factory CiP at TU Darmstadt. Figure 4 gives an overview on the process and the products of the reference line, involving four milling machines (M) and two lathes (L).

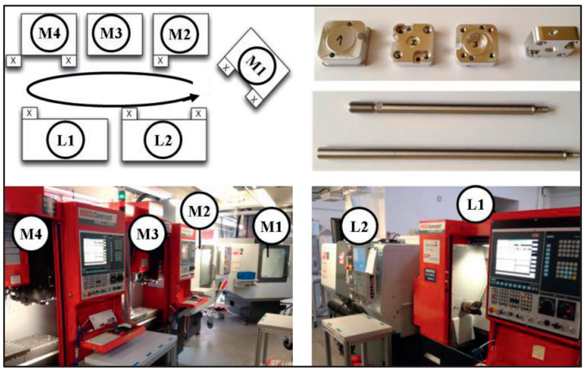


Fig. 4. Cellular Manufacturing line used for the investigation.

Following the right-sized equipment approach, the machinery can be classified as basic low cost with standard CNC-automation. All functions for operation beyond machining tasks are manually executed by an operator. The manual operations are listed in Table 1.

Table 1. Manual operations in the Cellular Manufacturing reference line.

| Nr. | Sequential Operations for each Machine |
|---|---|
| 1 | Picking up the workpiece from the storage next to the machine or from the previous machine |
| 2 | Transport and depositioning of the workpiece between machines |
| 3 | Opening the machine door |
| 4 | Unloading the machine |
| 5 | Cleaning of the clamping devices |
| 6 | Loading the machine correctly |
| 7 | Clamping the workpiece in the machine |
| 8 | Selecting the correct machining program for the variant |
| 9 | Closing the machine door |
| 10 | Starting the machine |
| 11 | Cleaning of the workpiece |

Seven different work measurement methods discussed in section 2 and recommended for this environment were applied to the reference line, including optional variant changes. Methods explicitly not recommended for the present conditions or without practical relevance were not considered. The methods and results are discussed in the next paragraphs.

### 3.1. Time Study

Due to the fact that the Cellular Manufacturing reference line exists and is already in operation, a time study could be conducted. Following prevailing guidelines [12,15] a total of 15 cycles has been analyzed in order to reduce effects of individual variation. The aggregated results of the time study can be extracted from figure 5. These results are especially important as they serve as reference regarding closeness to reality in the later evaluation of the different work measurement concepts. The time study focuses on total cycles, but could also be executed with an increased level of detail and concentrating on specific sub-operations.

### 3.2. MTM-1, MTM-2 and MTM-UAS

For the investigations with systems of predetermined time standards, the different manual processes for operating each single machine were first split up into independent movement building blocks and then further into single standard movements according to the basic definitions of each system.

Using MTM-1, all different basic movements were detected in the Cellular Manufacturing reference line. In the analysis, a dedicated hand (“L”/”R”) and an attribute for the distance, if applicable, were assigned to each single movement, as well as an identifying code. TMU times according to the standard time table were allocated. In case of parallel actions, the shorter one was left out. On average, 39.5 different movements were detected per machine (237 movements on six machines).

MTM-2 follows the same general approach as MTM-1. However, the number of basic movements is significantly reduced. [19] Attributes are clustered into wider ranges and are therefore less precise, making the application of the system easier and faster (171 movement lines).

MTM-UAS (Universal Analyzing System) is widely used for industrial assembly. [24] Contrary to the previously described methods, MTM-UAS utilizes basic processes (sequential basic movement chains) instead of single basic movements and is therefore rather a work content analysis. [19] The application to the reference line showed a tremendously reduced level of detail resulting in 90 lines.

Other MTM-systems have not been considered, either due to their similarity to the previous ones or due to non-fulfilled prerequisites (e.g. lot size).

### 3.3. MOST: BasicMOST and MiniMOST

For MOST, analyses with BasicMOST and MiniMOST were conducted. MaxiMOST is intended for processes with long cycle times and has not been taken into account for this study. As mentioned, MOST uses more abstract sequence models for determining manual work. With this approach, the manual work in the reference line could be described in an even more condensed form using MaxiMOST, resulting in 69 sequences for all operations. The reduced level of abstraction is also enabled through the option of partial frequencies and repetitions of single sequences inherent to the system.

The analysis with MiniMOST is more detailed, as some abstract sequence models are replaced by basic movements. 108 lines were identified in the Cellular Manufacturing reference line.

### *3.4. Work-Factor: Work-Factor Basic System*

The Work-Factor basic system is in its structure and application closely related to MTM-1. The analysis of the Cellular Manufacturing system was therefore detailed and resulted in 231 different operating movements.

## 4. Development of Evaluation Criteria

In order to compare the application and the results of the seven different work measurement approaches conducted, criteria for their evaluation have to be developed. Two guiding principles are predominant (see also [16,19]):

1. The data quality needs to match with the intended purpose of the analysis regarding actuality, preciseness, etc., and
2. the analytical effort – in terms of time and expenditures – needs to be kept to a minimum.

In case of a trade-off, the more important the pursued goals of the study are for the applicant, the more importance gains the first criterion over the second. [16] The criteria are further operationalized in:

1.a) Reality level / Closeness to reality
1.b) Level of detail
1.c) Influence level of the analyst / operator
2.a) Preparational effort
2.b) Effort for analysis and evaluation

The criteria “reproducibility” and “transparency” are purposely neglected, as they are immanent to all methods applied. “Qualification for the method” is seen as a one-time effort for the analyst and is therefore considered as minor. Table 2 gives an overview on all the evaluation criteria, measures and limits chosen. Their development is described in detail in the following paragraphs. The distribution between upper and lower limits for each criterion is linear.

Table 2. Evaluation criteria, measures and limits.

| Criterion | Measure | Fulfilled | Not fulfilled |
|---|---|---|---|
| 1.a) Reality Level | Relative deviation value to time study result [%] | 0% | 15% |
| 1.b) Level of Detail | Number of individual movements identified [#] | Max. # of lines | Min. # of lines |
| 1.c) Analyst’s influence | Time change in results with 5 cm deviation in distances / time measure [%] | 0% change | Max. % change |
| 2. Effort | Time for preparation work, analysis and evaluation [h] | 0h | Max. h |

The *reality level* is the criterion most important for any model. Especially in the present case, in which the manual effort of a low cost man-machine-system is intended to be quantified for further automation decisions, the reality level, largely determining the economic viability of the automation, must be the dominant factor defining the success of the study at hand. The times recorded during the time study in the Cellular Manufacturing line serve as reality reference. The average of the relative deviation value of each method for each machine is used as quantifier. The desired 0% deviation is set as a lower limit for the criterion. Regarding the upper limit, each increase in deviation also increases the probability for a wrong decision for or against automation. This calls for a preferably low limit. However, previous experience for MTM-1 for example shows a system-immanent deviation of standard times of up to 10%. [18] In order to keep the criterion at an operational level, 15% deviation is set as an upper limit, above which the results are too inaccurate to support a later automation decision.

The *level of detail* describes the extent to which movements are specified. The number of lines with individual movements can be regarded as an adequate, clearly quantifiable auxiliary variable, with a higher number of lines meaning more detail. For the time study method, the level of detail can be defined as an input variable by the analyst. This leads to an infinite number of possible results and makes the method hardly comparable with the other methods. Therefore, the time study method will be excluded from the analysis for the moment being the focus of further research.

In general, the more detailed a method is the better it is for quantifying manual work for later on automation. If the level of detail is too low, the results of the analysis are useless. For all methods applied to the Cellular Manufacturing reference line, there is a good level of detail. Therefore, the limits for the evaluation are set between the maximum and the minimum number of lines.

*Influence levels* need to be reduced to a minimum, as individual, subjective influences on the study’s objective results are not desired. In the systems of predetermined time standards, the analyst is the only source of influence. Presuming good scientific practices, which include sufficient training and qualification, intentional influences are left out. Unintentional influences cannot be excluded. For the analyst, three potential mistakes are present:

- Assigning the wrong basic movement element and time to the actual movement,
- overlooking/neglecting single basic movements, or
- measuring distances incorrectly.

The first two sources of influence and their effects are considered equally likely for all methods and are therefore of less interest. The last source is both different for individual methods and very likely, as it is nearly impossible to measure a distance in free space correctly. For quantifying this effect, a minor deviation of five centimeters, a length that can easily be measured incorrectly, is simulated for any distances used in the different methods and changes to the result are recorded as percentage. Thus, the sensitivity of each method is evaluated. The limit for tolerated variation was set to the maximum variation observed with 0% being the ideal goal.

Preparational *effort* considers all activities, that are necessary before a time or motion study can be conducted, including gathering all weights, distances, etc. Monetary effort can be neglected, leaving "time" as the unit of measure. The same is valid for analytical and evaluation effort. Again, the analyst's time is the predominant factor. In general, the more detailed a method is, the more time it takes for analysis and evaluation. [12] Due to the similarity of the two effort subcategories and in order to simplify the later on evaluation, both will be combined to the category "effort". The span for the effort spreads from 0 hours to the maximum hours of all methods analyzed.

Leveraging the benefits of pairwise comparison [25] and the Analytic Hierarchy Process (AHP) [26], the different criteria identified are weighted with a calculation of the eigenvector of the preference matrix as shown in table 3. After an initial pairwise comparison of the individual factors, assigning degrees of preference from 1 (equal importance) to 9 (extreme preference), the eigenvector is approximated leveraging the averages of normalized column values (in italics). As described above, the reality level is more important than any other criteria. The level of detail shows minor preferences over influence, as the unintentional influences coming from the analyst are expected to be minimal. However, an analysis with minimal influences at a poor detail level is of little use. High effort going along with a high level of detail and the other way around is acceptable. Effort being very high is equally undesirable as a low level of detail, resulting in identical importance. A high increase in effort for less analyst's influence is not preferable, assigning effort as more important than influence. The AHP consistency ratio for all preferences has been calculated to 0.059, staying well below the target of 0.1 and proving consistency.

Table 3. Development of weighting criteria using AHP.

| | 1.a) Reality Level | 1.b) Level of Detail | 1.c) Analyst's influence | 2. Effort | **Weight Factor / Principal Eigenvector** |
|---|---|---|---|---|---|
| 1.a) Reality Level | 1<br>*0.65* | 5<br>*0.68* | 7<br>*0.44* | 5<br>*0.69* | ***61.5*** |
| 1.b) Level of Detail | 0.2<br>*0.13* | 1<br>*0.14* | 3<br>*0.19* | 1<br>*0.14* | ***14.8*** |
| 1.c) Analyst's influence | 0.14<br>*0.09* | 0.33<br>*0.05* | 1<br>*0.06* | 0.2<br>*0.03* | ***5.7*** |
| 2. Effort | 0.2<br>*0.13* | 1<br>*0.14* | 5<br>*0.31* | 1<br>*0.14* | ***17.9*** |

## 5. Evaluation of Work Measurement Methods and Results

After the application of the different work measurement methods and the development of evaluation criteria in the previous sections, this chapter is intended to execute the evaluation and depict the results.

Regarding the reality level, figure 5 illustrates the outcomes of the various work measurement methods applied to the machines of the Cellular Manufacturing reference line. Quite a spread of the individual results around the actual time study results can be observed. For each machine, BasicMOST gives by far the highest absolute times, Work-Factor results on the other hand are the ones with the lowest times. Both deviate significantly from the actual time study. Projected to a full eight-hour shift, an operator could perform 161 or 295 operating cycles, depending on the use of either one of these two methods. One reason why BasicMOST results are deviating strongly is the fact that this method distinguishes distances only in two categories: more and less than 5 cms. MTM-2 and MTM-1 show the most realistic results for the Cellular Manufacturing environment.

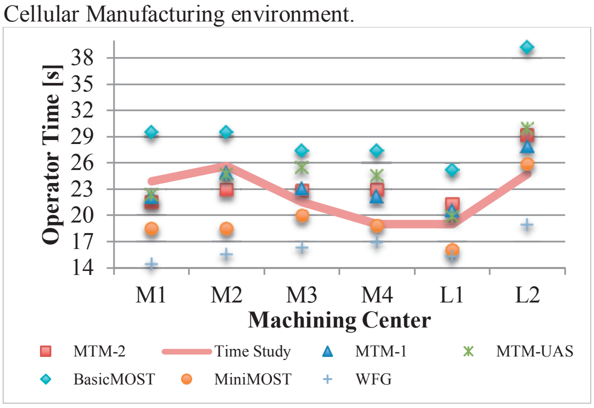


Fig. 5. Results of different work measurement methods vs. actual time study.

The level of detail is one of the main distinguishing characteristics for the different work measurement methods. It is highest with the MTM-1 method and lowest with MaxiMOST. The data for the different methods have already been mentioned above and are presented again in table 4.

Regarding the influence level of the analyst, no change will occur in the results for BasicMOST with a simulated variation of the distances within 5 cms. For all the other methods, the sensitivity change resulted in variations from 1.5% to 6.3%. Up to 145 individual basic movements influenced by distance levels have been adjusted per method.

There is a clear link between preparational and analytical/ evaluation work and the level of detail of each method. MTM-1 and WF, the two methods with the highest number of single basic movement lines, show the highest time effort. For preparation, a comparably large number of distances and details need to be taken into account. For WF for example, distances are recorded to an accuracy of 2.5 cms. Also for analysis and evaluation, both methods are the ones requiring the highest intensity, even if TMUs can relatively conveniently be read from the standard time tables. These methods are followed in descending order by MTM-2, MTM-UAS, MiniMOST and BasicMOST, again related to the descending level of detail. The time effort for BasicMOST with only two different distances for movements is significantly lower than the others. The findings are also supported by SAKAMOTO [27], SCHLAICH [22] and ZANDIN [23]: With an effort of one hour, a trained analyst creates a total of 300 to 500 TMU with MTM-1, about 1000 TMU with MTM-2, roughly 4000 using MiniMOST and 12000 TMU with BasicMOST.

Table 4 gives an overview on the results for the different criteria per method considered. Table 5 translates the values into weighted factors and overall ranks. The evaluation shows that MTM-1 has clear advantages for measuring work in the Cellular Manufacturing reference line. This is due to the fact that it has the highest reality level and the highest level of detail of all methods compared. However, the effort for this method is also considerably high. The second best option in the present evaluation is MTM-2, closely followed by MTM-UAS and MiniMOST, convincing with average results in all categories.

Table 4. Evaluation.of different work measurement systems applied to the Cellular Manufacturing reference line

| Criterion | MTM-1 | MTM-2 | MTM-UAS | Basic MOST | Mini MOST | Work-Factor |
|---|---|---|---|---|---|---|
| 1.a) Reality Level | 9.3% | 13.6% | 13.5% | 33.2% | 13.3% | 24.8% |
| 1.b) Level of Detail | 237 lines | 171 lines | 90 lines | 69 lines | 108 lines | 231 lines |
| 1.c) Analyst's influence | 5.0% | 2.1% | 1.5% | 0% | 6.3% | 4.2% |
| 2. Effort | 13.8 h | 5.8 h | 2.0 h | 0.5 h | 0.9 h | 15.2 h |

Table 5. Translated and weighted values for the evaluation results

| Criterion | MTM-1 | MTM-2 | MTM-UAS | Basic MOST | Mini MOST | Work Factor |
|---|---|---|---|---|---|---|
| 1.a) Reality Level | 23.5 | 6.0 | 6.2 | 0.0 | 7.1 | 0.0 |
| 1.b) Level of Detail | 14.8 | 9.0 | 1.9 | 0.0 | 3.4 | 14.3 |
| 1.c) Analyst's influence | 1.2 | 3.8 | 4.3 | 5.7 | 0.0 | 1.9 |
| 2. Effort | 1.7 | 11.1 | 15.6 | 17.3 | 16.9 | 0.0 |
| Sum | 41.1 | 29.8 | 28.0 | 23.1 | 27.4 | 16.2 |
| Rank | 1 | 2 | 3 | 5 | 4 | 6 |

A sensitivity analysis conducted via variation of the weighting factors of the different evaluation criteria showed stable results. MTM-1 was ranked in the lead up to a change in weightings (as percentage of the values set in table 3) of -64% in the reality level, -100% in the level of detail, +408% in the influence category and +95% in effort.

## 6. Conclusion and Outlook

With the results of the study, the basic foundation for a scientifically sound method for automating a Cellular Manufacturing line on a low cost basis is laid. By leveraging the various methods for work measurement in the Cellular Manufacturing reference line in the Process Learning Factory CiP at TU Darmstadt, the different manual tasks showing yielding potential to be automated for Cellular Manufacturing have been identified allowing the quantification of contained benefits. Executing work measurement using MTM-1 has proven to give the best results when considering the trade-off of reality, detail, influence and effort at the reference line. The approach presented has been proved viable and serves as a basis for further application and verification on other Cellular Manufacturing lines.

However, for cases where an actually existing operating system can be used as reference, time study approaches with the same level of detail need to be further evaluated and compared with the same evaluation criteria in a next step. They might present a good alternative for these environments. Besides, the analysis showed that the basic movements for operating the different machines in a Cellular Manufacturing line are pretty similar, except for additional positioning work in some special cases.

## References

[1] Abele E, Reinhart, G. Zukunft der Produktion (The Future of Production). Munich: Carl Hanser; 2011.
[2] Abele E, Meyer T, Näher U, Strube G, Skyes R. Global Production. A Handbook for Strategy and Innovation. Berlin: Springer; 2005.
[3] Liker J, Meier D. The Toyota Field Book. New York: McGraw-Hill; 2006.
[4] Womack JP, Jones DT, Roos D. The machine that changed the world. New York: Free Press; 1990.
[5] Ohno T. Toyota Production System. Beyond large scale production. Portland: Productivity Press; 1988.
[6] Metternich J, Bechtloff S, Seifermann S. Efficiency and Economic Evaluation of Cellular Manufacturing to enable Lean Machining. Procedia CIRP 2013; 7: 592-7.
[7] Bechtloff S. Identifikation wirtschaftlicher Einsatzgebiete der Sequenzfertigung in der Bohr- und Fräsbearbeitung von Kleinserien (Identification of economic Applications for Cellular Manufacturing in Drilling and Milling of small Batch Series). Aachen: Shaker; 2014. In Preparation.
[8] Lay G, Schirrmeister E. Sackgasse Hochautomatisierung? (Dead End High Automation?). FhG -ISI 2001; 22: 1-12.
[9] Weck M, Brecher C. Werkzeugmaschinen. Maschinenarten und Anwendungsbereiche (Machine Tools. Machine Types and Areas of Application). Springer: Berlin; 2005.
[10] Zelinski P. Why Boeing is big on right-size Machine Tools. Modern Machine Shop 2006; 78: 72-9.
[11] Takeda H. LCIA – Low Cost Intelligent Automation. Landsberg am Lech: mi-Fachverlag; 2006.
[12] Matias A. Work Measurement: Principles and Techniques. In: Salvendy G, editor. Handbook of Industrial Engineering. Technology and Operations Management. New York: Wiley; 2007. p. 1409-1462.
[13] Barnes R. Motion and Time Study. New York: John Wiley & Sons; 1949.
[14] Schlick C, Bruder R, Luczak H. Arbeitswissenschaft (Ergonomics). Heidelberg: Springer; 2010.
[15] Poppelreuter W. Zeitstudie und Betriebsüberwachung im Arbeitsschaubild (Time Study and operational Monitoring in the Working Diagram). Munich: Oldenbourg; 1929.
[16] REFA. Methodenlehre des Arbeitsstudiums. Datenermittlung (Methodology of Work Study. Data Acquisition). Munich: Carl Hanser; 1992.
[17] Steffy W. Uses of Predetermined Time Standards. In: Maynard H, editor. Industrial Engineering Handbook. New York: McGraw-Hill; 1971. p. 5-3 - 5-19
[18] Bokranz R, Landau K. Produktivitätsmanagement von Arbeitssystemen. MTM-Handbuch (Productivity Management of Work Systems. MTM-Handbook). Stuttgart: Schäffer-Poeschel; 2006.
[19] Maynard H, Stegemerten G, Schwab J. Methods-Time Measurement. New York: McGraw-Hill; 1948.
[20] Quick J, Duncan J, Malcolm J. Work-Factor Time Standards. Measurement of Manual and Mental Works. New York: McGraw-Hill; 1962.
[21] Schlaich K. Vergleich von beobachteten und vorbestimmten Elementarzeiten manueller Willkürbewegungen bei Montagearbeiten (Comparison of observed and predetermined Basic Times of manual arbitrary Movements in Assembly). Berlin: Beuth; 1967.
[22] Zandin K. MOST Work Measurement Systems. New York: Dekker; 1990.
[23] REFA. Den Erfolg vereinbaren (Agreeing on Success). Munich: Carl Hanser; 1995.
[24] Lotter B. Die Primär-Sekundär-Analyse (Primary-Secondary Analysis). In: Lotter B, Wiendahl H, editors. Montage in der industriellen Produktion (Assembly in industrial Production). Berlin: Springer; 2006. p. 59-93.
[25] David HA. The Method of paired Comparisons. London: Charles Griffin & Company; 1963.
[26] Saaty TL. The Analytic Hierarchy Process. Planning, Priority Setting, Resource Allocation. New York: McGraw-Hill; 1980.
[27] Sakamoto S. Beyond World-Class Productivity. Industrial Engineering Theory and Practice. London: Springer; 2010.