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The role of equipment flexibility in Overall Equipment Effectiveness (OEE)-driven process improvement

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Abstract

In manufacturing and assembly operations, Overall Equipment Effectiveness (OEE) is a frequently used quantitative metric for measuring the overall productivity of a single machine, cell or an integrated manufacturing system. However, it does neglect and typically even penalizes flexibility capabilities. Today's customer needs for highly customized products put these productivity-based measurements more and more under pressure. Frequent product changes on assembly workstations typically result in lower availability through more set-up, more performance losses due to slower cycles and the learning-forgetting effect of operators, and start-up defects resulting in more frequent quality issues. A contradiction arises: in modern production and assembly this flexibility becomes more and more important as an enabler for the mass customization paradigm, but is difficult to incorporate in (or put in relation to) an OEE figure or trend and conflicts with the OEE-driven process improvement strategies. Consequently, it can be argued that flexibility capabilities should be embedded in the equipment effectiveness calculation. Modern manufacturing and assembly cells should have a high equipment effectiveness through a high product mobility with a stable and uniform productivity across the complete range of products. This paper first highlights the importance of flexibility in the measurement of equipment effectiveness to facilitate the mass customization paradigm and to try to continuously improve towards a resilient manufacturing system. Next, the heuristic measurement framework for the Flexibility-included Overall Equipment Effectiveness (OEE_{Flex}) metric is introduced, based on three core indicators: mobility, uniformity and range. The three factors are introduced and described. Links to current OEE measurement frameworks are made. The approach towards the new metric starts from a long list of losses and variables and possible calculation methods for the indicator values. Future research describes illustrative simulation scenarios to filter towards a short list of relevant and valuable calculation options for the overall metric. Followed by an expert based approach towards final selection of the metric and a case based in-company validation of the result.

Keywords: Resilient Manufacturing Systems; Equipment Effectiveness; Manufacturing Flexibility; Assembly Workstation Flexibility; Process Improvement; Mass Customization

1. Introduction

In today's diverse, uncertain and competitive environments, manufacturing facilities have to improve and adapt their processes constantly [10]. The ability to produce customized products that meet each consumer's requirements nearly at the cost of mass production is the ultimate goal of the current mass customization trend. Especially for assembly, flexibility is crucial because final assembly operations are frequently targeted to embed flexibility and compensate for the increased manufacturing uncertainties and mass customization needs [3]. It seems logical that these new challenges should result in new evaluation methodologies. It is already long known that the economic viability of a system should not be evaluated based on only one aspect such as productivity. It does not help in identifying specific areas, such as the need for flexibility, that need management's attention [9]. Nevertheless, companies still take decisions on how to manage their production systems more effectively and efficiently mainly based on productivity evaluations [7]. For example the Overall Equipment Effectiveness (OEE), which is based on three factors (availability, performance and quality), is seen as one of the most important Key Performance Indicators (KPIs) for production control [6]. It in fact represents the unused optimization potential and losses of a machine or workstation [10]. But, notwithstanding the high added value of OEE-improvement cycles to limit waste, OEE sometimes comes into conflict with today's flexibility needs and even penalizes these capabilities. Frequent product changes typically result in lower availability through more set-up, more perfor-

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mance losses due to slower cycles and the learning-forgetting effect of operators, and start-up defects resulting in more frequent quality issues, and thus a lower overall OEE. Because on one hand high and stable productivity remains important to safeguard profits and on the other hand flexibility is not something that is bought, plugged in, and forgotten, they should both be carefully justified, planned and managed [2]. Therefore an operational measurement framework combining both productivity and flexibility could aid in justifying the proper investments and optimizations in multi-product environments [25]. This paper further highlights the importance of equipment flexibility in OEE-driven process improvements and suggests a different heuristic methodology towards equipment effectiveness evaluation. Section 2 describes the current state-of-the-art on equipment effectiveness measurements in modern production and today's needs for manufacturing flexibility. Section 3 describes the fundaments of the here-introduced Flexibility-included Overall Equipment Effectiveness (OEE_{Flex}) measurement framework. The three subcomponents are discussed in depth. Next, section 4 outlines the two-step approach of selection and validation towards the final metric. Conclusions and further research directions are found in section 5.

2. State-of-art

Today, manufacturing and assembly operations in modern production companies should be both operationally excellent and flexible. Both are consequences of the gradual shift from mass production to mass customization. The study of the effectiveness of industrial systems, their processes and machines has already a long tradition and remains important in recent research [18, 14, 20]. Also a lot of research has been done on the flexibility of equipment in manufacturing and the interplay towards their combined manufacturing flexibility. Work is focused on defining the concepts, operationalization, measurement frameworks etc. [21, 29]. Section 2.1 concerns operational excellence and more specifically the work done on equipment effectiveness. Section 2.2 further elaborates on manufacturing flexibility.

2.1. Operational Excellence and Equipment Effectiveness

Continuous improvement cycles are key to achieve operational excellence [24]. Today, in a lot of manufacturing companies, machines do not deliver their full potential. There is a difference between the actual achieved and the maximum theoretical productivity [18]. To be competitive, actual productivity should be brought to the utmost possible, therefore it is important to have measures reflecting the productivity. In its most basic form, productivity of a machine is the ratio of achieved work during the whole process divided by the time used for this process [19]. This is translated for assembly to the time it takes to achieve a predefined amount of assembly output. It is recognised that productivity can be improved by increasing the equipment effectiveness [11]. In general, effectiveness compares actual to targeted output. Peter Drucker summarizes the difference with efficiency as 'efficiency is doing things right; effectiveness is doing the right things' [4]. One of the most important and widely adopted effectiveness indicators, and starting point of the here developed metric, is the Overall Equipment Effectiveness (OEE). It merges information of equipment usage, process yield and product quality [6]. OEE fits into the concept of lean production and was first introduced in the light of Total Productive Maintenance (TPM). It is a tool usable as an operational measure to monitor production productivity, but it can also be used as an indicator for process improvement activities in a production context [1, 26]. OEE is defined in equation 1 as a number of complementary components: availability (A), performance (P) and quality (Q) [17]. Availability is herein defined as the actual production time T_A over the scheduled production time T_S. Performance puts the actual produced output per time unit $O_{A|T}$ in relation with the expected output per time unit $O_{E|T}$. Quality finally compares the non defective output O_{ND} to the total output O_T. Together they form the overall OEE. Each component links to typical losses present on the shop floor, the so called six big losses [30]. Availability is firstly related to unplanned stops linked to equipment failure and breakdown losses and secondly planned stops required for set-up and adjustments. Performance focuses on small stops and idle times, but also slow cycles due to reduced speed. Quality identifies the losses related to start-up, defects and rework. For each of these losses various causes are identified (Figure 1).

$$OEE = A \cdot P \cdot Q = \frac{T_A}{T_S} \cdot \frac{O_{A|T}}{O_{E|T}} \cdot \frac{O_{ND}}{O_T} \qquad (1)$$

The ability to integrate several factors of productivity within a global and single measure, which eases understanding and comparison, makes OEE a popular metric [7]. It also transcends the workstation or production line level evaluated because it embeds workstation-independent information as lack of input items (e.g. no parts, wrong parts delivered etc.) [23]. Next to output, time plays the most essential role as a parameter, as it reflects most of the losses. Despite all the advantages, the OEE framework has also some drawbacks. The calculation is frequently not transparent in companies, due to the heterogeneous data sources and manual inputs. Furthermore, there are different guidelines to calculate the OEE which makes it difficult to compare figures [6]. Next to this, it does not always incorporate all relevant factors and does not consider variations [19]. The latter is a problem in the context of today's need for highly customized products in low batch sizes. It results in a growing negative OEE trend because a strongly varying order structure or lot size decreases the achievable OEE significantly [15]. Different attempts were made to expand and/or adapt the scope of OEE to counter drawbacks. The scope can for example be broadened through the inclusion of more elements of productivity and effectiveness to the formula than just availability, performance and quality. Other productivity aspects could be included such as the effective use of raw materials and the production environment in which the equipment or process operates resulting in an overall resource effectiveness (ORE) metric [7]. Another option is to complete OEE with the production pace and production part cost to create a better productivity improvement driver [1]. Various other adaptations can be identified in literature [20, 7, 14]. It can also be argued that not all factors of OEE are equally important in all cases. Therefore the Production Equipment Effectiveness (PEE) was introduced which adds different weights to the factors and orientates OEE to specific situations [22]. After all, the environment in which equipment operates can also affect productivity [7]. Some adaptations specifically try to improve the measurement accuracy to promote their application in modern factories. For example, OEE in it's original form cannot be efficiently applied into the multi-product production system because of its changeable character and complex operations [14]. Variability is an 'enemy' of OEE in complex high-end plants [19]. Therefore the multiproduct production system effectiveness (MPSE) was introduced to improve the measurement accuracy of equipment effectiveness in a multi-product production system [14]. It brought the OEE principles to the product-level and allowed for a more in depth analysis. Notwithstanding the fact that various researchers identify the need to optimize OEE according to the environment its used in, there remains a need for studies on measurements and improvements specifically for multi-product production systems [7, 14]. We, on the same track, add and further identify the added-value of an equipment effectiveness measurement framework which does not penalize the strongly needed flexibility capabilities.

2.2. Manufacturing Flexibility

A lot of effort has been done to define flexibility and to examine its determinants. It is recognised that flexibility should be a key objective of modern manufacturing and assembly systems [21]. A widely accepted definition of manufacturing flexibility is provided by Upton [27]. Manufacturing flexibility is defined as 'the ability to change or react with little penalty in time, effort, cost or performance'. On the highest level it is identified that there are three distinct ways of being flexible for the dimension of change and time period considered: range, mobility and uniformity. Each domain of manufacturing flexibility is also composed of these elements which keeps it broad and opens up generalizable measures [13]. We explain them briefly [27, 28]. First, range affects the ability to produce large variation on key product characteristics. Mobility concerns the agility within this range, the lower the transition penalties, the more flexible. Lastly, uniformity further couples productivity to flexibility, it concerns the consistency of productivity within the range. Productivity should be high and vary as little as possible within the range. Manufacturing flexibility is seen as the collective term for a long list of subtypes. Due to the multidimensional nature of manufacturing flexibility and multitude of determining drivers, many different types, called dimensions, of manufacturing flexibility can be identified: process flexibility, volume flexibility, machine flexibility, labor flexibility and many more [29]. There is still a lack of consensus on the conceptualization, a problem which has limited its homogeneous operationalization and, consequently, the development of a common and coherent framework [21]. Most research is on base flexibility dimensions directly coupled with resources and equipment (labor flexibility, machine flexibility, material handling flexibility etc.). The impact of the flexibility of equipment on overall flexibility capabilities should not be neglected, definitely as the introduction of new Industry 4.0 technologies such as cobots and assistive technologies offer the opportunity to create new, more flexible configurations [3]. Individual capabilities are combined into an overall sytem and thus impact higher levels of flexibility (process flexibility, new product flexibility etc.). Today less research is concerned with higher level flexibility dimensions and their combined capability to cope with the dynamic market changes [16]. The issue of achieving the required level of manufacturing flexibility is an increasingly urgent matter in a never more rapidly changing environment. It is identified that a comprehensive and widely accepted empirical study to measure manufacturing flexibility is yet to be done [16]. Moreover, despite the fact that the definition of manufacturing flexibility suggests to couple productivity to flexibility, there is still lack of research that investigates the relation between flexibility dimensions and operational productivity metrics [5]. It is however beyond dispute that there is an interplay. It goes without saying that in industry, flexibility will never be implemented at all cost, only the required level will be implemented in accordance with the uncertainty faced [2]. Furthermore, the flexibility dimensions that enhance specific productivity metrics might not enhance another metric, which shows the dualities even within the different subtypes of manufacturing flexibility [5]. Therefore manufacturing flexibility and its determinants should be carefully monitored and planned on the highest level.

3. Flexibility-included Equipment Effectiveness

From both literature described in section 2.1 and 2.2, similar conclusions can be drawn. Flexibility implications are difficult to isolate because they impact the equipment effectiveness, and isolated effectiveness evaluations are not always suitable for modern production environments because they penalize the flexibility capabilities. The research question to tackle is how to embed and add the context of flexibility into operational productivity measures, here more specific for equipment effectiveness driven process improvements. As already stated above, the three distinct ways of being flexible (mobility, uniformity and range) integrate several factors of productivity with the context of flexibility and therefore seem suitable to embed in the measurement of flexibility-included equipment effectiveness. Therefore it is the intention to combine these three subcomponents, with respective weighing factors α, β and γ, in the $\mathrm{OEE}_{\mathrm{Flex}}$ metric as highlighted in equation 2. Mobility (M) and uniformity (U) mainly define the effectiveness of equipment (section 3.1), while range (R) heuristically reflects the extent of the capability to adapt (section 3.2).

$$OEE_{Flex} = \alpha M \cdot \beta U \cdot \gamma R \tag{2}$$

3.1. Effective Equipment

The $\mathrm{OEE}_{\mathrm{Flex}}$ metric has the goal to be an indicator for process improvements aiding to bring the actual productivity to the

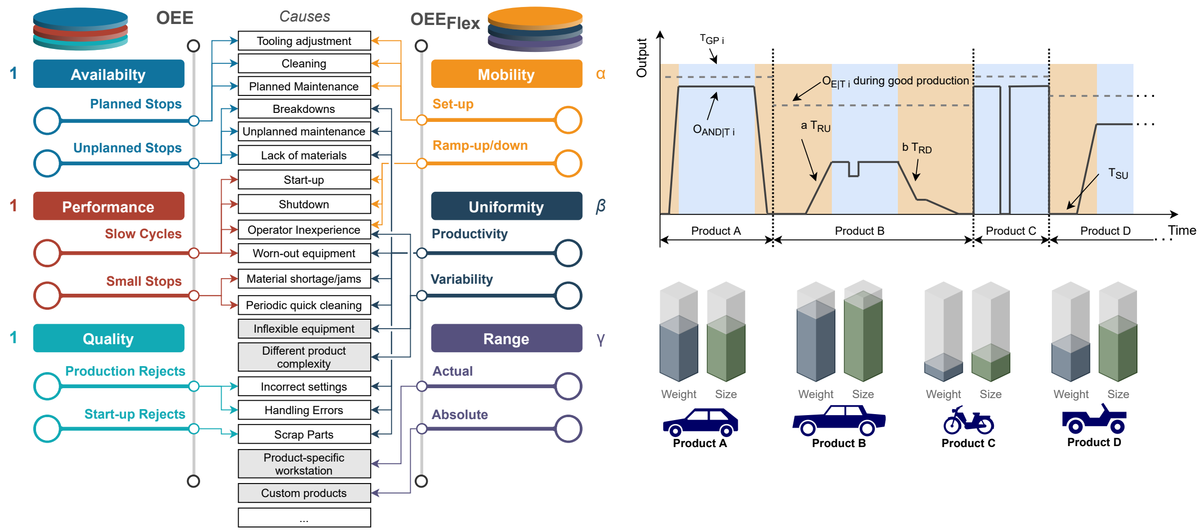

Fig. 1. Interconnection of OEE and OEE_{Flex} in a fictitious multi-product environment

utmost possible through more effective equipment. Therefore it is important to embed also the losses identified by OEE as described in section 2.1. Figure 1 shows various causes of losses and shows the connection between regular OEE and OEE_{Flex} through these causes. The figure further shows the impact of these causes on the output to time in a fictitious production cycle of a multi-product environment. It can be seen that most losses of OEE are linked to mobility and uniformity. From the explanation of mobility in section 2.2 it can be concluded that mobility in fact directly relates to changeover in its broad form. Flexible systems are those in which the transition penalties for moving within the range are small and frequent changes do not compromise productivity. A good mobility thus implicates less losses during changes. Changeover time is defined as the total elapsed time from the last unit of good production at normal speed and efficiency of the preceding run to the first unit of good production of the succeeding run at normal speed and efficiency [8]. Emphasis is placed on 'good production' which means normal speed and efficiency. Mobility can thus consist of a set-up period without any production and a start-up or shutdown period at lower efficiency. Set-up directly relates to losses of planned stops caused by cleaning, adjustments of tooling, planned maintenance etc. The ramp-up/down component partly incorporates the causes of slow cycles, specifically during the start-up and shutdown period. Also scrap during start-up result in a less effective ramp-up period. The main question for OEE_{Flex} remains however how mobility should be quantified and which components of changeover seem most relevant. The most obvious calculation method for mobility is shown in equation 3 where the impact of a changeover factor C is set against the scheduled production time T_S. A possible calculation method for the changeover factor C is displayed in equation 4 where the ramp-up time T_{RU}, ramp-down time T_{RD} and set-up time T_{SU} are coupled. Various other calculations methods are available and multiple questions remain: what is the weight of the ramp-up/down time and its relation to the actual non-defective output? More in general: in relation to other losses, how important is the loss during set-up and changeover in general? Therefore it is chosen to set-up a list of various calculation methods going further than the given examples and validate them through simulations as described in section 4.

$$M = 1 - \frac{C}{T_S} \tag{3}$$

$$C = a\,T_{RU} + T_{SU} + b\,T_{RD} \tag{4}$$

As mobility embeds every loss during changeover, the losses during good production should be monitored too. Uniformity concerns the consistency of productivity within the range, but also the absolute value of productivity during good production. A consistent low productivity for all products in the range, should of course result in a low uniformity. The productivity losses during good production are directly linked to slow cycles due to worn-out equipment, operator inexperience etc. Small stops result in less actual output. Also production rejects reduce productivity and should be accounted for in uniformity. A possible calculation strategy for this productivity component of uniformity is easily distinguished from the output to time in figure 1. Productivity P is given in equation 5 as the average of actual non-defective output per product $O_{AND|T_i}$ over the expected output per product $O_{E|T_i}$ weighted according to production time T_{GP_i} during 'good production'. By specifying 'actual output' as all actual and non-defective output, all production rejects are also embedded.

$$P = \frac{\sum_{i=1}^{n} T_{GP_i} \cdot \frac{O_{AND|T_i}}{O_{E|T_i}}}{\sum_{i=1}^{n} T_{GP_i}} \tag{5}$$

Mobility as a whole and the productivity during good production embedded in uniformity are most closely related to OEE and combine most of the losses identified by traditional OEE frameworks. The variability component of uniformity should reflect the consistency of productivity across the range of products and in fact brings the principles of OEE to the product level. What is the difference in losses between various products produced on the same workstation? The variability can be caused by for example the difference in complexity between products, but also by the inflexibility of some equipment. The causes listed in figure 1 are not limitative. In an ideal situation, each product has the same actual and expected output. This way the workstation is perfectly capable of producing the given product set at optimal productivity. A possible calculation method for the variability V could be as in equation 6 where the range between the actual output per product $O_{AND|T_i}$ over the expected output per product $O_{E|T_i}$ is calculated.

$$V = Max(\frac{O_{AND|T_i}}{O_{E|T_i}}) - Min(\frac{O_{AND|T_i}}{O_{E|T_i}}) \tag{6}$$

The difference in overall productivity between the outliers is covered, but no info is provided on the products in between. Not to mention, that the variability and productivity also should be combined in uniformity. This again shows that the selection of the calculation should be based on results from various situations simulated (Section 4).

3.2. Capable to Adapt

The workstation can be highly effective and the variability can be low, however the extent of the capability to adapt remains unaccounted for. This means that it remains unclear what the imposed flexibility requirements are and how effective the equipment is in terms of flexibility. It cannot be the intention to reduce the number of product variants produced (and thus flexibility) on a workstation to improve mobility and uniformity. Therefore, range is also an indispensable component of OEE_{Flex}. It shows the spectrum of what is possible to produce. This is key to interpret mobility and uniformity and allows for comparison. What is the size range, weight range etc.? It is the least straight forward factor as it should define context: 'Why is it difficult to improve the mobility? Because of the exceptionally broad range of produced product variants.' Range can be seen on two levels: actual range versus absolute range. We explain this by an example assuming that range is expressed by the number of product variants that are or need to be produced. The workstation considered as in figure 1 is able to produce four product variants but within the portfolio of that product category, the manufacturer offers eight products on the market. This means that in the evaluation, it should be embedded that the mobility and uniformity are calculated based on data from four product variants. Nevertheless, there is room for improvement because in the most flexible set-up the workstation could be able to produce eight product variants. Actual range is part of the calculation to make mobility and uniformity more interpretable. It can be seen as a normalization component. First it is important to achieve an as high as possible OEE_{Flex} within the actual range, which in fact relates to traditional OEE-driven process improvements where losses are reduced as much as possible. Absolute range reflects the flexibility benchmark to be met. The absolute range aids for the process improvements towards the company strategy on flexibility to e.g. produce more product variants on the same workstation. Again, various possibilities are available to embed range, but also the calculation of range itself can be based on various aspects: e.g. sizes, weights, complexity, number of parts, required skills related to skill-based modelling etc. Calculations that incorporate solely the number of products produced may capture some complexity effects, but will not capture essential differences in the capabilities of workstations [28]. The primary challenges of range measurement is thus determining which dimensions of 'difference' are most important in distinguishing one product from the next and thus providing some metric of those characteristics based on the data gathered from simulations as described in section 4.

4. Next Steps

Figure 2 shows the approach to be followed for the next steps in the OEE_{Flex} metric development. Simulations in a virtual environment will allow selection of the best possible calculation methods from a long list of combinations for both mobility, uniformity, range and their combination into OEE_{Flex}. Computer simulations are mainly used to analyze a process, activity or complex operation in order to improve its productivity with as main advantage the possibility for the comparison of variants and the selection of the best considerations [12]. Here, computer simulations will be used to select the most promising calculation methods for the OEE_{Flex}. The data of virtual manufacturing set-ups can be used to see how the metrics react in different predefined situations and how they compare to current OEE measurement frameworks. Simulations will consist of both inflexible and flexible set-ups to reflect various ranges. The interplay between and combinations of the subterms is also important. The complementarity of mobility and uniformity should be visible. Various tools exist for the simulation of processes as FlexSim, Plant Simulation and many more. One of the main strengths of OEE is that it integrates several aspects of productivity within a global and single measure. The calculation strategies should be theoretically justified, but should also be as usable as possible for process improvements in today's flexible environments. Therefore, in a later phase, a draft of the overall metric will be validated and further improved by a panel of manufacturing experts acquainted with equipment effectiveness improvement cycles. Lastly, the metric will be implemented and tested on an in-company use case to validate all results.

5. Conclusion and Outlook

In todays fierce competition, manufacturing companies are forced to become more resilient and meet customization needs at near mass production cost, the so called mass customization trend. New Industry 4.0 technologies are available to meet these needs, but operational KPIs should follow. Frequently, the flexibility requirements result in a negative impact on OEE. Therefore equipment flexibility cannot be decoupled from equipment effectiveness and vice versa. The OEE_{Flex} metric is outlined based on mobility, uniformity and range. Mobility and uniformity embed the traditional losses from OEE frameworks and

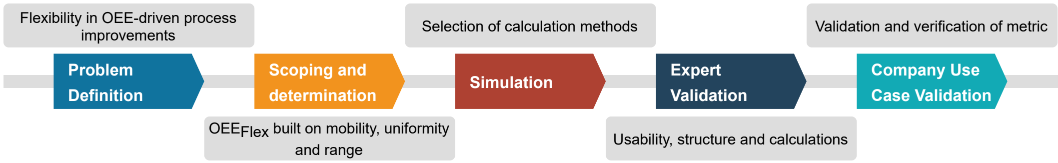

Fig. 2. Approach towards a Flexibility-included Overall Equipment Effectiveness (OEE_{Flex}) metric

bring them to the product level, while range extends the context of the multi-product environment. The process towards the overall metric is described and the limitations are set. Nevertheless, various challenges lay ahead. The described simulations will give insight on the best calculation strategies and the input of experts will improve the usability. Furthermore, to operationalize the metric, data captation will become important and a Standard Operating Procedure (SOP) will be indispensable for uniform implementations.

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