Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 9 (2017) 33 – 40

Procedia MANUFACTURING

7th Conference on Learning Factories, CLF 2017

Demonstration of a Concept for Scalable Automation of Assembly Systems in a Learning Factory

Jens Buergin[a],*, Fabio Echsler Minguillon[a],
Fabian Wehrle[a], Benjamin Haefner[a], Gisela Lanza[a]

[a]*wbk Institute of Production Science, Karlsruhe Institute of Technology (KIT), Kaiserstrasse 12, 76131 Karlsruhe, GERMANY*

Abstract

Companies operating assembly systems in global production networks constantly have to deal with change drivers. For the design of adaptable assembly systems, change drivers can be considered as fluctuating KPIs, such as labor costs, as well as changing KPI targets, such as rising quality requirements.
In this paper, a concept for the design of changeable assembly lines with scalable automation is introduced and applied to the Learning Factory Global Production at KIT. The change of the automation level over time is based on an ex ante evaluation and ex post performance assessment of the impact of change drivers.

Keywords: Scalable Assembly Systems; Scalable Automation; Changeability; Learning Factory

---

1. Introduction

The conditions for manufacturing companies nowadays are changing drastically [1]. In the context of globalization, companies are facing several drivers of change that are hard to predict, including, for example, rising labor costs, changing quality requirements and fluctuating customer demands [1].

A further challenge consists in the increasing individualization of customer demands leading to an increasing number of product variants [2]. Thus, in order to maintain competitiveness, the production of companies has to be

---

* Corresponding author. Tel.: +49-721-608-44013; fax: +49-721-608-45005. *E-mail address:* Jens.Buergin@kit.edu

doi:10.1016/j.promfg.2017.04.026

adaptable to changing conditions, i.e. they have to be flexible and changeable [3]. The turbulences generated by change drivers can be mastered by designing and managing flexible and changeable assembly concepts [1].

In this paper, a concept for the design of changeable assembly lines with a scalable degree of automation to face change drivers is introduced. In addition to the assembly process, the logistics concept for material supply is also considered. The concept comprises the factory aspects technology (determined by the production equipment), space (influenced by the layout) and organization (with respect to the logistics and workforce concept) [2]. The impact of scaling the degree of an assembly line is to be quantified ex ante, i.e. before making changes, and ex post, i.e. after having made changes, by means of a performance assessment using key performance indicators (KPIs) such as investment costs, throughput times and quality requirements.

The structure of this paper is as follows: In section 2, a literature review with regard to different degrees of automation in assembly, relevant KPIs and the topics of flexibility and changeability is given. In section 3, an approach for the design of scalable assembly systems is presented. Technical aspects of scalable automation are discussed and a cost analysis for evaluation of different assembly system configurations is introduced. Section 4 includes an application of the approach in the Learning Factory Global Production at the wbk Institute of Production Science at the Karlsruhe Institute of Technology (KIT). The learning factory is composed of a U-shaped assembly line for the assembly of an electric motor. In order to illustrate the scalability of the degree of automation and thus the changeability of the assembly line, three different line configurations are introduced in consideration of exemplary change drivers. In addition, the didactic concept for the application of the approach in the Learning Factory Global Production is presented. In section 5, a summary of the essential aspects of this paper as well as an outlook are given.

2. Literature review

2.1. Degrees of automation

According to DIN 8593 and VDI 2860 the core tasks of assembly are classified into the categories joining, handling, testing and adjusting [4]. The degree of automation of an assembly system can be described as the ratio of the automated functions to the total number of all functions of the system [5]. Based on this definition, assembly systems can be classified into the following categories according to their degree of automation [4]:

- *Manual assembly systems:* All process steps of assembly are carried out by human beings in this concept [6].
- *Partially automated assembly systems:* Partially automated assembly systems are combining manual stations with automated stations [4]. For such a hybrid concept, manual assembly is taken as a basis for partially automated systems, adapting the degree of automation of an assembly process to the optimal level [4].
- *Fully automated assembly systems:* Automated assembly systems are designed to automate all process steps of assembly [6]. In case of numerous variants and the increasing demand for just-in-sequence delivery, the logistics concept is a challenge in a fully automated assembly line [4].

Besides these general categories for the classification of assembly systems according their degree of automation, assembly stations being part of assembly systems can be classified to provide a more detailed degree of automation [7]. Within each assembly station, the assembly process itself, feeding of parts and transportation of workpieces can be identified as largely independent modules, which can either be performed manually or automated [7].

2.2. Key Performance Indicators (KPIs) for the evaluation of assembly systems

The degree of automation of assembly systems has an impact on economic efficiency that can be evaluated by KPIs. For this reason, the most severely impacted KPIs are presented in the following, demonstrating their potential causality with the degree of automation (see Figure 1):

- *Costs:* Costs can be structured in investment costs for the capacities provided and operating costs that accrue when operating these capacities such as labor costs [8]. In the case of investment costs, there is usually a direct causality between the degree of automation and investment costs. While manual assembly systems have the lowest investment costs, fully automated assembly concepts afford the highest investments [4]. On the other hand, by

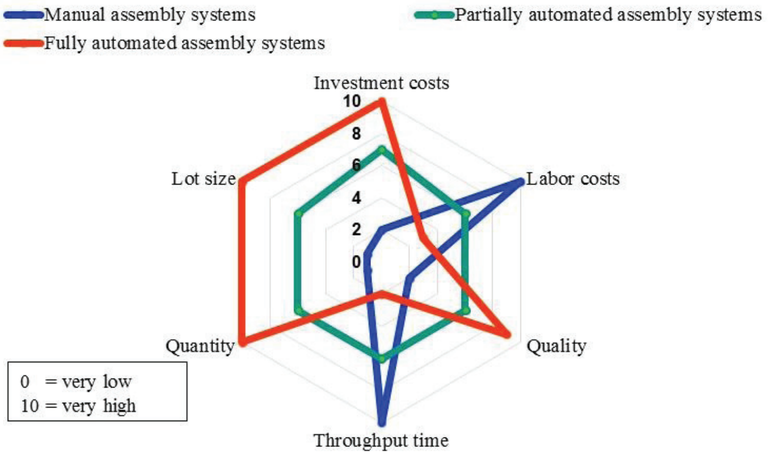

Figure 1: Potential causality between degree of automation and KPIs

increasing the degree of automation, labor costs can be reduced [9]. Thus, labor costs are inversely proportional to investment costs [10]. In order to minimize unit costs, a corresponding degree of automation must be selected considering investment costs as well as labor costs and the production rate depending on the location of an assembly system [11]. One method for cost evaluation is the net present value method considering the present values of the payments made due to an investment [12]. If only costs and no incoming payments are considered, the investment in the production equipment configuration with the highest net present value, i.e. the lowest costs, is the most favorable one [12].

- *Quality:* Quality requirements depend on customers, the strategy of a company's management as well as laws and standards [13]. The First Pass Yield and Final Yield can be used to measure the quality. The First Pass Yield measures the number of units that pass directly through the process without any quality problems, whereas the Final Yield measures how many units can be sold in the end, including possible rework [14]. Torque monitoring and other kinds of sensors can be used to ensure quality [15]. In a manual assembly system, the quality of the products depends very much on human performance, whereas in fully automated assembly systems a consistently high quality can be guaranteed [4, 13].
- *Throughput time*: The throughput time is composed of different individual times, such as setup times, process times and transport times [13]. The throughput time depends strongly on the synchronization of individual stations [11]. Short throughput times can be achieved by takting the transportation of workpieces [11]. According to Little's Law, the throughput time is directly related to the production rate, i.e. the quantity of units produced in a time interval [16, 17], which can therefore be increased by automation [18].
- *Quantity:* The quantity of products being produced by an assembly system, i.e. the output quantity, is usually higher in the case of fully automated assembly systems compared to manual ones [13]. This has to be the case in order to keep the costs per unit produced low in spite of high investment costs [13]. The unit costs depend on the utilization of the operating resources since the fixed costs per unit decrease with a higher utilization rate and thus a higher output quantity [10].
- *Lot size:* A production lot is defined as the quantity of a series of products of a product variant which is produced successively and without any additional set up or interruption of the production process [19]. A manual assembly system is characterized by simple changeover possibilities [4]. With regard to the optimal production lot size, this leads to lower set-up costs compared to a fully automated assembly line, which leads to a smaller optimum lot size overall [4]. Thus, the so-called one-piece flow principle can be applied better in manual assembly in the case of assembling multiple variants [4].

2.3. Adaptability of assembly systems in terms of flexibility and changeability

KPIs such as costs, e.g. labor costs, fluctuate over time. Additionally, KPI targets also change over time. For example, quality requirements sufficient in the past may increase for future products. Both cases, fluctuating KPIs as well as changing KPI targets, depict change drivers that need to be addressed by adapting assembly systems.

Flexibility describes the ability of a system to adapt to changes quickly and with minimal financial effort. For example, assembly systems may be flexible in terms of the output quantity and product variants to be assembled. A flexible system is defined by upper and lower limits of KPIs within which adaptations can be performed without changing the physical elements of a system. In contrast, the concept of changeability as an extension of flexibility refers to the ability of being able to carry out technical, organizational and spatial changes beyond the limits of flexibility, requiring additional time and investment costs to realize adaptations. [1, 20]

Time and investment costs to realize changes can be reduced by designing and installing changeable assembly systems. The characteristics compatibility, universality, mobility, modularity and scalability enable the changeability of assembly systems and are thus referred to as change enablers [1]. The degree of implementation of these change enablers in an assembly system can be evaluated by conducting a changeability potential value analysis [2].

Compatibility refers to the interchangeability of different elements, which is relevant in an assembly system, as information, material and energy have to be exchanged between its elements. Universality is the design of elements according to various requirements of the product or the technology to be applied, e.g. the technological capability of being able to produce different product variants. Mobility refers to the spatial mobility of elements, enabled e.g. by rollers allowing for easy changes of the layout. Modularity is the ability to easily exchange standardized, functional elements. For example, a docking interface of a robot can be designed such that the attached robot arm can be replaced by another arm for different assembly tasks. Scalability in the context of assembly systems is the technical, organizational and spatial expandability and reducibility. [1]

3. Approach for the design of scalable assembly systems

3.1. Concept of scalable automation

One way scalability can be applied to an assembly system as a change enabler is scalable automation, meaning the scalability of the degree of automation of individual stations. In particular, the degree of automation of a line can be gradually adjusted from manual to fully automatic through the exchange of standardized modules. In the following, the assembly steps workpiece transportation, material feeding and the assembly process itself are considered as modules of each assembly station. Although workpiece transportation is performed between two stations, it is assigned to the station to which the transportation is directed in order to prevent mixing stations with modules. Thus, an assembly system can be scaled by scaling the degree of automation of the modules of each station. Therefore, modularity as a change enabler can be regarded as a prerequisite of the change enabler scalability in the context of scalable automation.

Moreover, the other change enablers can be regarded as a prerequisite for modularity. Compatibility is required in order to have modules with a different degree of automation that are interchangeable. Universality means that identical modules can be applied at different stations to perform processes with different parameters. Mobility of modules means that they can be exchanged and moved easily, for example by means of rollers.

In summary, it can be said that the change enablers compatibility, universality and mobility can all be regarded as prerequisites for modularity, which in turn can be regarded as a prerequisite for scalability. In this context of scalable automation, the changeability of an assembly system is negatively correlated with the degree of automation because automated modules require interfaces for energy supply and software.

3.2. Technical potential for scalable automation and KPI analysis of different configurations

Scaling automation of the three modules transportation, feeding and process of each station, that can be executed in two different modes, either manually or automated, results in $2^3=8$ different degrees of automation per assembly station. As the amount of possible permutations grows exponentially with the number of assembly stations, it is not practical to consider all possible solutions. The main task therefore consists in identifying which of these combinations is potentially to be implemented from both a technical as well as an economical perspective.

From a technical perspective, it has to be clarified how difficult it is to automate a specific module and to which extent it makes sense to have the same degree of automation for modules that are closely related to each other. Some processes such as longitudinal pressing can be more easily automated than others (e.g., gluing) [4]. At the same time, the difficulty of automation increases with an increasing number of variants to be handled. For example, when using an industrial robot for automation, it is important to position multi-variant parts or workpieces in a defined position such that the robot can handle all variants. Moreover, an example for realizing the same degree of automation for all the modules transportation, feeding and process of a station is given in the following: If the assembly process can be carried out manually and the distance for both workpiece transportation and feeding is quite short, all tasks can be fulfilled by a worker. In this case, it makes sense to either maintain a fully manual station or to automate all of its modules. Since a worker is present anyway, it is not feasible to only automate some of the modules. However, this consideration may change when multiple stations are examined, since workers could work on more than one station and the number of required workers may drop in that case. Additionally, worker safety has to be considered when combining manual and automatic modules. For example, the Pilz Safety Eye, a camera system for 3D space monitoring, detecting the penetration of objects entering pre-defined areas, can be applied in such cases [21].

An increasing degree of automation does not only require a change in the dimension of technology, but also in space and organization such as logistics planning. In the case of automated material feeding, it may be necessary to feed parts in the required sequence using a magazine and thus to adapt the supply of parts to the station accordingly.

In order to design and install a changeable assembly system, the change enablers have to be considered in the design process as well as in later stages, when modules are changed. For example, compatibility can be considered by implementing uniform software interfaces enabling plug & produce [7]. Moreover, the availability of additional space in a factory is an important factor as the required space may also change with changing modules. In general, the consideration of changeability in the design and installation of assembly systems may require additional investment costs.

From an economical perspective, the impact of the degree of automation on the KPIs has to be anticipated for configuring an optimal assembly system. KPI requirements regarding short throughput times or high quality may require a high degree of automation if manual assembly cannot physically meet the required pace or is not accurate enough. Regarding costs, the trade-off between higher investment costs required for automated modules and higher labor costs required for manual modules has to be analyzed. In order to perform the economical evaluation, the net present value method may be applied. In this context, the difference between purchasing and leasing assembly modules is of major importance regarding changeability. The purchase of a module is likely to inhibit change since immediate resale may not be possible, leading to sunk costs. In the case of leased modules, immediate exchangeability can be assumed, resulting in a positive impact on changeability.

4. Application of the approach to the Learning Factory Global Production at KIT

4.1. Application of the approach using scenarios regarding change drivers

The Learning Factory Global Production consists of a U-shaped line with ten stations for the assembly and testing of ten variants of a small electric motor developed by Robert Bosch GmbH. First, magnets, clips and sockets are pressed into the housing and subsequently the magnets are magnetized. This is followed by the assembly of the rotor, the commutator, the gearbox, gear wheels and the cover of the gearbox. Finally, a function test of the produced electric motor is performed.

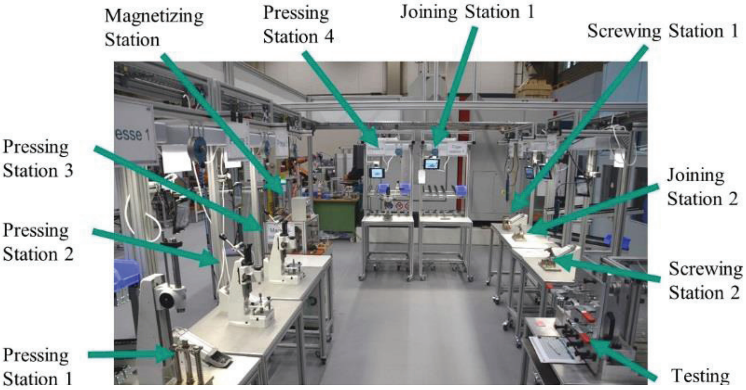

Figure 2: Manual assembly system

The learning factory allows an analysis of the impact of change drivers based on KPIs such as those introduced in section 2.2. In order to react to anticipated change drivers presented in different scenarios for demonstration purposes, the degree of automation of the assembly line can be scaled. Based on a forecast of change drivers, the KPIs can be evaluated ex ante. Regarding costs, a net present value analysis is conducted. Having made a decision on the required change of modules and having installed the changes, the performance of the changed assembly line can be assessed, so that the causality of the degree of automation and selected KPIs are analyzed ex post.

Starting with a manual assembly line (0% automation) with hand lever presses at the pressing stations 1 to 4, tables with fixtures at the joining stations 1 and 2 and screwdrivers at screwing stations 1 and 2 (see Figure 2), changes based on the following scenarios can be demonstrated in the learning factory:

- *Scenario 1- Rising quality requirements:* Quality requirements are rising as customers require the monitoring of the press capacity of all the pressing stations 1, 2 and 3 and the torque of the screwing stations 1 and 2. Therefore, the process modules of the stations concerned need to be automated. The additional automation of feeding and transportation is also technically possible, but not economically reasonable due to the elaborate separation and handling of many variants and small parts. Thus, the concerned stations have to be partially automated and the other stations have not to be changed. Due to increasing automation, software interfaces to the head control system are required for the pressing and screwing stations (e.g. for assembly line emergency stops), limiting the mobility and thus overall changeability of the assembly system.
- *Scenario 2 - Increasing labor costs:* Labor costs are rising and a net present value analysis reveals that it is optimal to fully automate pressing station 4 and joining station 1. From a technical perspective, both processes and feedings are quite simple and thus it is cost-effective to automate using an industrial robot since the universal picking positions of the parts allow for easy handling and joining of different variants. Since both stations are located directly next to one another, workpiece transportation can be realized using a conveyor belt. Additionally, safety measures are required to protect workers by installing either a housing for each station or the Pilz Safety Eye. A universally designed protection system such as the Pilz Safety Eye is more flexible than housings.
- *Scenario 3 – High worker fluctuation and further increasing labor costs:* Due to rising competition for labor, worker fluctuation is very high, while labor costs increase even more. At this point, a partially automated system with human-robot collaboration becomes cost-effective at screwing station 1. In addition to the process, transportation is now also being carried out automatically using a robot.

Figure 3 shows the assembly line with implemented changes from all three scenarios. The presented scenarios demonstrate how the degree of automation can be continuously adapted to change drivers such as increased quality requirements, increased labor costs and high worker fluctuation. Regarding the KPIs, the gradual increase in the degree of automation has the following effects: The quality and leasing costs have increased, while the labor costs have been reduced.

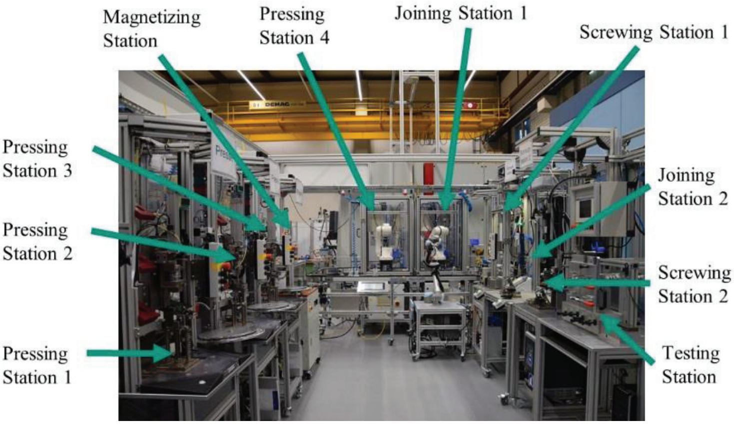

Figure 3: Partially automated assembly system

4.2. Didactic concept for the application of the approach

For training purposes in the Learning Factory Global Production, the respective didactic concept is described in the following. The learning targets of the training are for participants firstly to understand the causalities between the degree of automation and KPIs and secondly to be able to plan, evaluate and validate assembly systems in the context of change drivers. Therefore, participants first participate in an e-learning course in order to acquire the necessary theoretical background of scalable automation and the potential causalities between the degree of automation and KPIs. The subsequent on-site training in the learning factory covers the following four phases:

1. Analysis of change drivers
2. Analysis of technical potential of the assembly line for scalable automation
3. Net present value analysis for evaluating potential assembly line configurations
4. Assembly in line with optimal configuration and ex-post performance assessment of KPIs

According to the three scenarios being demonstrated in the Learning Factory Global Production, the introduced four planning phases are passed through in each scenario as illustrated in Figure 4. In phase 3, KPIs other than costs are included in the net present value analysis by monetarizing them or considering their target values as hard constraints. In the latter case, configurations neglecting those constraints are not considered feasible.

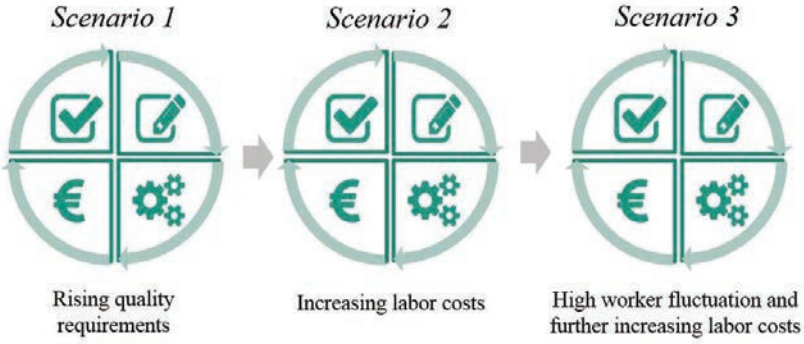

Figure 4: Planning phases of training

In phase 4, the participants take over the roles of the workers in the assembly line including the consignment of parts in the warehouse and their supply to the assembly line. Collecting data during assembly and assessing respective KPIs such as the Final Yield and throughput times provides the possibility to compare the realized KPI values to the expected ones. Thus, the planning of the assembly line configuration can be validated in a realistic setting.

5. Conclusion and Outlook

Based on a literature review in section 2 on the degree of automation in assembly systems, KPIs, flexibility and changeability, scalable automation was introduced in section 3 as a concept for adapting assembly systems depending on change drivers. It was noted that the change enablers compatibility, universality and mobility are prerequisites for modularity, which in turn is necessary for scalability in the context of automation. Subsequently, the technical implementation of scalability of individual workstations was addressed and the independent modules transportation, feeding and process were introduced, recognizing that from a technical perspective, only certain combinations are feasible. The introduced concept was applied in section 4 to the Learning Factory Global Production demonstrating its changeability in terms of automation with respect to KPIs based on three fictitious scenarios. Moreover, the didactic concept for the application of the approach in trainings conducted in the Learning Factory Global Production has been presented.

In the future, the concept of scalable automation can be further promoted by integrating Industrie 4.0 solutions for demonstration in the Learning Factory Global Production for both students at KIT and practitioners from the industry.

References

[1] Nyhuis, P., Reinhart, G., Abele, E., Editors, 2008. *Wandlungsfähige Produktionssysteme: Heute die Industrie von morgen gestalten.* 1st edn.: TEWISS.

[2] Heger, C.L., 2007. *Bewertung der Wandlungsfähigkeit von Fabrikobjekten*. Garbsen: PZH, Produktionstechn. Zentrum.

[3] Westkämper, E., Zahn, E., Editors, 2009. *Wandlungsfähige Produktionsunternehmen: Das Stuttgarter Unternehmensmodell*: Springer.

[4] Lotter, B., Wiendahl, H.-P., Editors, 2012. *Montage in der industriellen Produktion: Ein Handbuch für die Praxis.* 2nd edn.: Springer Berlin.

[5] Handrich, W., 2002. *Flexible, flurfreie Materialflusstechnik für dynamische Produktionsstrukturen*. München: Herbert Utz Verlag.

[6] Grote, K.-H., Feldhusen, J., Editors, 2007. *Dubbel Taschenbuch für den Maschinenbau.* 22nd edn.: Springer.

[7] Kluge, S., 2011. *Methodik zur fähigkeitsbasierten Planung modularer Montagesysteme*. Heimsheim: Jost-Jetter.

[8] Weber, J., 2005. *Gestaltung der Kostenrechnung: Notwendigkeit, Optionen und Konsequenzen.* 1st edn. Wiesbaden: Dt. Univ. Verl.

[9] Lauber, R., Editor, 1988. *Prozessrechensysteme: Automatisierungstechnik, Leittechnik, Informations- und Kommunikationstechnik*: Springer.

[10] Fichtmüller, N., 1996. *Rationalisierung durch flexible, hybride Montagesysteme*. Berlin, New York: Springer-Verlag.

[11] Hagedorn, J., Blanc, F.S.-L., Fleischer, J., 2016. *Handbuch der Wickeltechnik für hocheffiziente Spulen und Motoren: Ein Beitrag zur Energieeffizienz*: Springer Science and Business Media; Springer Vieweg.

[12] Carstensen, P., 2008. *Investitionsrechnung kompakt: Eine anwendungsorientierte Einführung*. Wiesbaden: Betriebswirtschaftlicher Verlag Gabler.

[13] Westkämper, E., 2006. *Einführung in die Organisation der Produktion.* 1st edn. Berlin: Springer.

[14] Toutenburg, H., Knöfel, P., 2009. *Six Sigma: Methoden und Statistik für die Praxis.* 2nd edn. Berlin, Heidelberg: Springer Berlin Heidelberg.

[15] van Basshuysen, R., Editor, 2012. *Handbuch Verbrennungsmotor: Grundlagen, Komponenten, Systeme, Perspektiven.* 6th edn.: Vieweg+Teubner.

[16] Schnurr, R. Littles Law - Six Sigma Black Belt. http://www.sixsigmablackbelt.de/littles-law-gesetz-von-little/. Accessed 5 May 2015.

[17] Schulte, H., 1964. *Kapitalfreisetzung durch rationelle Lagerhaltung in industriellen Unternehmen*: VS Verlag für Sozialwissenschaften.

[18] Kruse, J., Kunz, D., Uhlmann, L., 1968. *Wirtschaftliche Auswirkungen der Automatisierung*: Duncker & Humblot.

[19] Paul, J., 2011. *Praxisorientierte Einführung in die Allgemeine Betriebswirtschaftslehre: Mit Beispielen und Fallstudien.* 2nd edn. Wiesbaden: Gabler.

[20] Möller, N., 2008. *Bestimmung der Wirtschaftlichkeit wandlungsfähiger Produktionssysteme*. München: Utz.

[21] Shen, Y., 2015. *System für die Mensch-Roboter-Koexistenz in der Fließmontage*. München: Utz, Herbert.