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Development of a Concept for Real-Time Control of Manual Assembly Systems

Martin Sudhoff[1], Matthias Linsinger[1], Daniel Schulte[1], Bernd Kuhlenkötter[1]

[1] *Ruhr-Universität Bochum, Chair of Production Systems, Universitätsstr. 150, 44801 Bochum, Germany*

Abstract

In contrast to automated machines and installations, manual assembly still lacks real-time process monitoring and possibilities for short-term control and adaptation of assembly systems. This article describes an approach for a concept of real-time control of manual assembly systems. For this purpose, KPIs that can be determined predictively are considered. These indicators enable a standardized and objective process data acquisition and a local process optimization for a higher flexibility and adaptability. In addition to the key figures developed, an approach for the automated acquisition of appropriate process data in manual assembly is described. The further usage of the KPIs and the validation within a real production environment is finally presented.

Keywords

Production Planning; Manual Assembly; Process Control; Key Performance Indicator; Standards

1. Introduction

Shorter product life cycles and smaller batch sizes impact increasingly on industrial production. In addition, there is a diversification of the product range and increasing cost pressure. Corresponding to these conditions, future innovations are more and more subject to the targets of adaptability and flexibility [1]. One way to ensure this flexibility in assembly systems is to continuously monitor process parameters and adjust the configuration of the system. This is already frequently used in automated assembly. In manual assembly, however, this process monitoring and control is missing [2]. The reason for this is the absence of process data acquisition. The integration of sensors and specific evaluation is rarely used in manual assembly [3]. Due to the non-existent objective data acquisition, the current state in manual assembly does not enable real-time process monitoring and thus also no short-term production control. Furthermore, there is no standard concerning KPIs (Key Performance Indicators) for real time control in manual assembly.

In order to implement real-time process monitoring in manual assembly systems, KPIs commonly used in other fields of production are first analysed. For the development of the KPIs existing systems of predetermined times (e.g. Work Factor or MTM (Methods-Time Measurement)) on the one hand and already existing KPIs used for automated machine monitoring (such as Overall Equipment Effectiveness (OEE)) on the other hand are purposefully derived. After that, the application of the developed indicators within an industrial environment at the LPS is described and a concept is presented which allows real-time data acquisition with Message Queuing Telemetry Transport (MQTT) within manual assembly systems.

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2. State of the art

2.1 KPIs for production systems

Key Performance Indicators are indicators that enable organisations to measure progress or the degree to which key objectives have been met. A business key figure serves as a basis for making decisions, for control (target vs. actual) as well as for the documentation and coordination of important processes. [4] The standard VDMA 66412-1 summarizes common KPIs in industry. Based on the classification of the standard for use in Manufacturing Execution Systems (MES), an application focus of KPI for processing machines, operating personnel and other automated processes can be identified [4]. This is also reflected in the KPIs mentioned in the standard, such as "Overall Equipment Effectiveness" (OEE) to describe the efficiency of machines and systems, or "availability" as an indicator of machine utilization.

It can be concluded that many KPIs have been developed in particular for automated production processes and cannot be applied to predominantly manual and hybrid assembly without additional adaptation. However, some of the indicators described in the mentioned VDMA-standard, such as lead time, idle time or employee productivity, are of equal importance for manual and hybrid assembly systems.

2.2 Value stream analysis

Within value stream analysis, key figures such as lead time, waiting time, stocks or processing times are recorded in order to obtain an indication of the degree of flow of a process. As a result, the process behaviour can be displayed via cycle time diagrams and the bottleneck of a process can be determined very quickly. At this point, no distinction is made between manual and automated processes. [5,6] Hence, the value stream method uses some process analysis tools which are suitable to measure manual or hybrid assembly processes.

2.3 Assembly process planning

There are numerous methods for medium to long-term assembly process planning. The purpose of assembly planning is to minimize the costs per unit. It contains the methods for designing the work content of an assembly system [7]. A distinction is made between assembly system planning and assembly process planning. REFA presents a general planning procedure for production systems in six stages, which can be applied for the planning of assembly systems [8]. Another example is an approach by Lotter. He has developed a planning system specially designed for assembly systems. It consists of 11 steps that can be adapted to the assembly requirements depending on the characteristics and complexity of the product [9]. For process planning, the MTM procedure can be mentioned as a system of predetermined times for manual assembly [10]. To describe an assembly process in terms of sequence and restrictions, a precedence graph or assembly priority chart can be used. It shows the individual assembly steps in a technically and organizationally predefined sequence. In addition, processing times and required resources are documented. [11,12,7] Line balancing is a key factor in assembly process planning. The more balanced a process, the shorter the idle times and waiting times and the better the utilization of personnel and assembly technology [11,13]. One key figure used to determine line balancing, for example, is the flow rate [5]. Both, assembly system planning and assembly process planning methods are always applied before the implementation and execution of an assembly process. Consequently, they are not suitable for monitoring an ongoing assembly process.

In the short-term planning horizon, assembly control deals with the activities necessary for the fulfilment of assembly orders on the basis of the results of assembly planning. This includes the definition of the workload, the provision of materials, the provision of information, personnel deployment planning as well as the monitoring of the assembly progress and reaction to malfunctions. [14,15] However, there are no methods found in literature that measure KPIs in real time within a manual or hybrid assembly process and use them for systematic in-process assembly control such as situational line balancing for instance.

As a summary of the state of the art, it can be stated that for manual and hybrid assembly processes no KPIs are measured in real time and used for process control. Thus, there is a specific need for action in the definition of suitable KPIs for manual and hybrid assembly processes as well as their technical real-time elevation in an ongoing assembly process in order to be able to take suitable control measures at short notice.

3. Indicators for manual assembly systems

As a first step of the presented approach, suitable KPIs for assembly process monitoring have been identified. A crucial criterion is that KPIs can be determined predictively in order to be able to make short term forecasts for imminent assembly processes. For a first pilot application, the following KPIs have been identified for process prediction and monitoring:

- lead time,
- throughput,
- process ratio and
- cycle time deviation.

The calculation of the **lead time** is usually described as the sum of all processing times, waiting times and transport times (see [5]). These are summarized under the process time (PT). In order to determine the lead time of an entire lot in an assembly system with several workstations, the bottleneck process with PT_{max} must also be taken into account. For this purpose, Linsinger and Stecken et al. have presented a formula (1) [16]:

$$L_{Lot} = \sum_{1}^{n} PT_i + PT_{max} \cdot (\mathrm{m} - 1) \tag{1}$$

Formula (1) shows that the lead time of an entire lot L_{lot} over several process steps results from two summands: The first addend describes the lead time of the first part, which can run through the work steps of an empty system without waiting times as there are no other parts within the assembly system. Its lead time results from the sum of all process times PT_n. The second addend determines the lead time of all following parts of the lot. The first part that has already been determined with the first addend must be subtracted from lot size m. Since these parts always have a preceding part in the process, they can only move through the process depending on the longest work step PT_{max} as PT_{max} represents the achievable cycle time of the current process.

The **throughput** specifies the product quantity that can be produced in a time unit. It is calculated by dividing the lot size by the lead time.

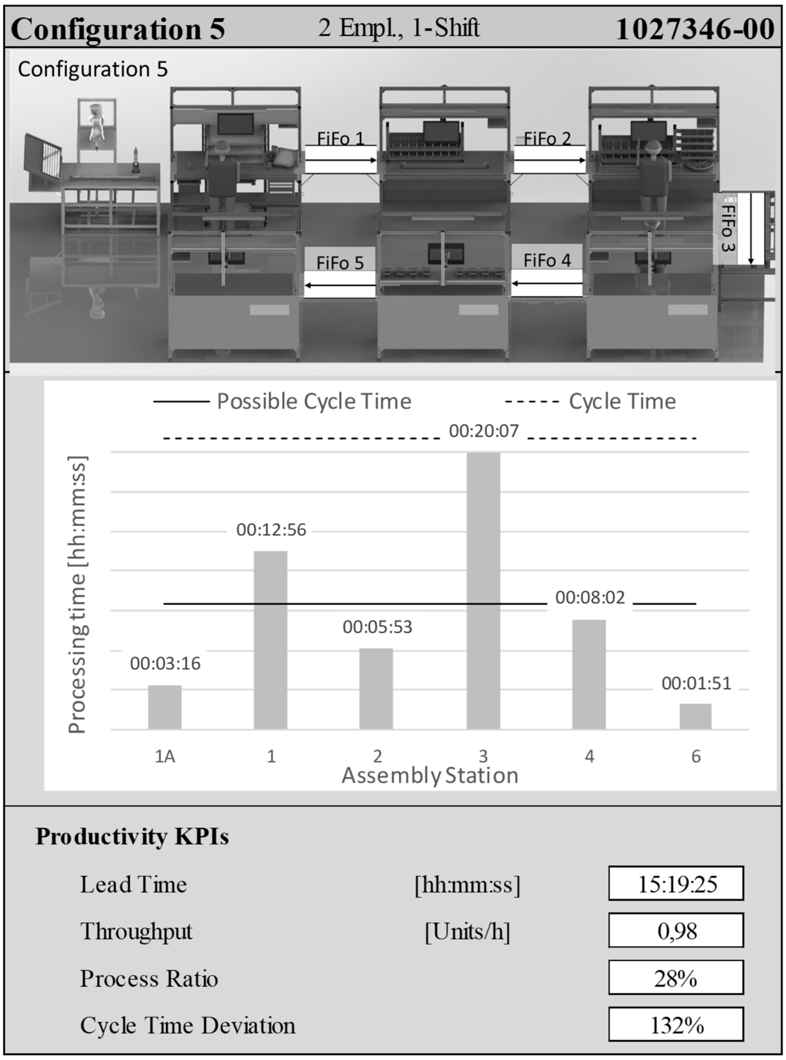
The **process ratio** gives an indication about the so called process density. The higher the ratio, the more efficient is the process. It is calculated by dividing the value adding process steps (in time unit) by the lead time.

The **cycle time deviation** compares the highest process time PT_{max} within an assembly station (this gives the actual possible cycle time) with the average ideal cycle time T for an optimized balanced assembly system. It is calculated according to formula (2):

$$D_T = \frac{PT_{max} - T}{T} \cdot 100\ [\%] \tag{2}$$

4. Industrial Application

The suitability of the identified and adapted KPIs for assembly process monitoring has been demonstrated using the assembly line for terminal strips at the LPS learning factory. The motivation to operate assembly line production for industrial customers at LPS in cooperation with Phoenix Contact GmbH & Co. KG. is the development and testing of new assembly processes and technologies under industrial conditions. The u-shaped assembly line consists of six stations. After cutting the strips, terminals are mounted onto the strip at station 1. Then the labelling takes place at station 2. Based on this, circuit bridges and other additional components are assembled at station 3 before the quality with regard to deviations is checked at station 4. Finally, pre-cabling (Station 5) and packaging for shipping the terminal strip is carried out (Station 6). [17] In order to support the employee, a mobile robot is either used for terminal (Station 1A) or circuit bridge assembly (Station 3A). [16]



Configuration 5 2 Empl., 1-Shift **1027346-00**

Productivity KPIs

Lead Time	[hh:mm:ss]	15:19:25
Throughput	[Units/h]	0,98
Process Ratio		28%
Cycle Time Deviation		132%

Figure 1: KPI-Cockpit with station configuration layout, cycle time diagram and KPIs

We developed a software tool, which uses planned process values based on MTM in order to calculate the KPIs. Based on the input of the current customer order, the program displays the predicted lead time with the current configuration of the assembly system by means of a KPI cockpit. In addition to the presented KPIs, a cycle time diagram of the assembly process is given. It displays the processing time of each assembly station. The KPI cockpit is shown in Figure 1 by means of an exemplary real customer order of 15 terminal strips.

Using the given configuration of the assembly system, a cycle time of more than 15 working hours is predicted for two employees. With a process time of approximately 20 minutes the cycle time diagram visualizes a bottle neck at station 3 where the processing time is almost two times as high as at the remaining station. Therefore, the cycle time diagram immediately provides an explanation for the low process ratio of only 28 % and the high cycle time deviation of 132 %.

Based on the information of the cockpit, the need of an immediate countermeasure to reduce processing time at station 3 can be derived. An organisational measure could be to double station three (reduced lead time by 36 %). Another possibility is moving the mobile robot from the first to the third station (reduced lead time by 25 %). The example shows the importance of monitoring assembly processes. Using MTM planning values, KPIs can be calculated to optimize the process for a given order. However, in order to conduct an in-process monitoring for manual and hybrid assembly processes, technical solutions have to be implemented and methods as well as countermeasures for situational process adaptation have to be developed.

5. Objective data acquisition for real time monitoring

It has been demonstrated that individually developed KPIs on the basis of planning values are enabling efficient monitoring in manual assembly. In order to further improve this process prognosis, the static basic data must be supplemented with dynamic process data. These have to be collected and processed automatically. A concept for automatically capturing and processing this data is presented in the following. In our assembly system the relevant data are both process data and customer order data. The relevant customer order data consists of the product identification number, the ordered lot size and the required delivery date. The dynamic process data to be collected includes the processing times, waiting times and transport times (see chapter 3). In addition, the throughput must be measured.

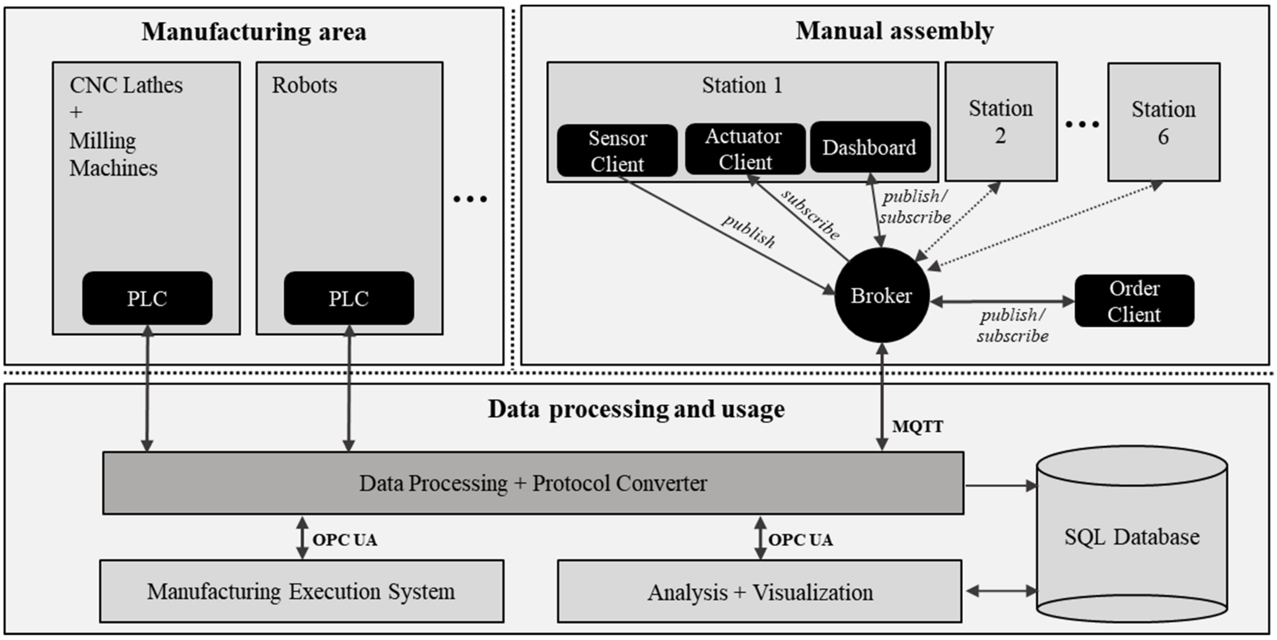


Figure 2: Data infrastructure of the assembly line at the LPS

In order to collect these data, the terminal strips are provided with an individual QR-code so that they can be located within the assembly system. Furthermore, as a first step, each assembly station will be equipped with a scanner integrated into the workpiece fixture, so that an automatic detection can take place without causing additional work for the employee. The scanner is connected to a microcontroller and integrated in a network using MQTT. [18] This protocol is designed to connect embedded devices with applications and middleware and is therefore an optimal protocol for machine to machine communication. [19,20] Hence, the sensors act together with the microcontroller as publishers and send the information to the broker (Figure 2). In addition, the Order Client receives and processes the customer order data for publishing it. The broker provides this data to various subscribers like the actuators and dashboards within the assembly system on the one hand. On the other hand, an OPC-Router acts as a subscriber and protocol gateway for providing the data in OPC UA protocol for the integration into the already existing IT infrastructure in the learning factory. Thus, the data from the manual assembly as well as the data from the manufacturing area are transferred to the SQL database where they can be further analyzed and evaluated.

This implementation for data acquisition and processing enables real-time calculation of process and waiting times. In addition, the stocks between the stations and the throughput can be determined. This makes the prediction, which was previously based on static data, real-time-capable and allows flexible reaction to unforeseen changes like rework or technical faults.

6. Summary and Outlook

The article introduces a concept implementing a real-time control of manual assembly systems. For this purpose, existing KPIs are analysed and adapted to manual assembly. These indicators were afterwards tested in a real production environment and it is shown that an increase in productivity is possible with process control. In order to further improve this process prognosis, real-time data will be included. For this reason, an approach for real-time process data acquisition and analysis is presented. This concept will be integrated into the existing IT infrastructure of the LPS in 2020. The KPIs, validated with static data to date, will be validated and enhanced on the basis of real-time data taken from the manual assembly system. Furthermore, the sensitive use of personal data will be considered within this application. The following tests will show to what extent process control can be improved with the help of real-time data.

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Biography

Martin Sudhoff (*1991) is a member of the Lehrstuhl für Produktionssysteme (LPS) at the Ruhr-University of Bochum since 2017. He earned a bachelor's and master's degree in mechanical engineering at the Ruhr-University of Bochum. His primary research topics are the digitalization and automation of assembly systems.

Matthias Linsinger (*1979) is a member of the Lehrstuhl für Produktionssysteme (LPS) at the Ruhr-University of Bochum since 2016. He earned a diploma in industrial engineering at the Cooperative State University Stuttgart and a master's degree in manufacturing engineering at the University of Nottingham. His primary research topics are hybrid assembly systems and human-robot interaction in assembly.

Daniel Schulte (*1990) is a member of the Lehrstuhl für Produktionssysteme (LPS) at the Ruhr-University of Bochum since 2018. He earned a bachelor's degree in electrical engineering and master's in industrial informatics at the Hochschule Emden/Leer. His primary research topics are the industrial communication and digitalization of manufacturing facilities.

Till 2009 **Bernd Kuhlenkoetter** was responsible for product management and technology at ABB Robotics Germany. In 2009 Bernd Kuhlenkötter took over the Professorship for "Industrial Robotics and Production Automation" at the Technical University of Dortmund. Since 2015 he holds the professorship of "Production Systems" at the Ruhr-University of Bochum.