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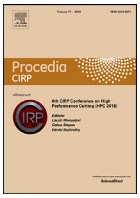

Fluid Automation – A Definition and an Application in Remanufacturing Production Systems

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ABSTRACT

Production systems must be able to quickly adapt to changing requirements. Especially in the field of remanufacturing, the uncertainty in the state of the incoming products is very high. Several adaptation mechanisms can be applied leading to agile and changeable production systems. Among these, adapting the degree of automation with respect to changeover times and high investment costs is one of the most challenging mechanisms. However, not only long-term changes, but also short-term adaptations can lead to enormous potentials, e.g. when night shifts can be supported by robots and thus higher labor costs and unfavorable working conditions at night can be avoided. These changes in the degree of automation on an operational level are referred to as fluid automation, which will be defined in this paper. The mechanisms of fluid automation are presented together with a case study showing its application on a disassembly station for electrical drives.

1. Introduction

The trends of mass customization and fluctuating demand requires production systems to be capable of adapting quickly to these changing requirements. For planning production systems, the degree of automation (DoA) is a key property. The DoA is generally defined as the ratio between the processes in a system that are automated and the total number of processes (DIN IEC 60050-351:2014-09 2014). On the one hand, automation typically enables to increase the productivity by reducing the process times, ensures higher quality standards or relieves human workers from repetitive and tedious tasks. On the other hand, automated production equipment usually comes with higher investment costs and leads to production systems that are more rigid than their manual counterparts when it comes to the ability to adapt to varying products. Since the requirements and the optimal design changes with its products and their life-cycles, production systems have to be reconfigured within their own life-cycle.

Under the aforementioned circumstances conventional production systems are not capable of adapting appropriate and fast enough in ever shorter time periods. Therefore scalable and changeable production systems gaining on importance (Stähr et al., 2018). They are designed to be reconfigured when requirements coming from different products change over their lifecycle. However such scalable production systems usually offer a limited amount of configurations. An optimal adaption to continuously changing conditions is not possible. Fig. 1 displays how waste arises in the absence of enough reconfigurations and inappropriately dimensioned (conventional) production systems. This waste can be characterized as under-utilized equipment or inventory on the one hand or demand that could not be satisfied on the other hand. In remanufacturing, where products are subject to a great amount of insecurity in terms of their condition, identity and availability, changeability is a key property for production systems.

In this paper the concept of fluid automation is introduced. It proposes a framework and rules for the design of quickly adaptable assembly systems with DoAs which are as continuous as possible.

First, the current state of the art for the design of flexible and changeable production systems is pointed out. Then the general concept of fluid automation and a related framework are introduced. Afterwards an implementation of the concept of fluid automation for a use-case of remanufacturing, which consists of disassembly processes, is illustrated. The paper finishes with a short evaluation and conclusion.

2. State of the art

Flexibility and changeability are important properties of a production system to determine its ability to adapt to changing

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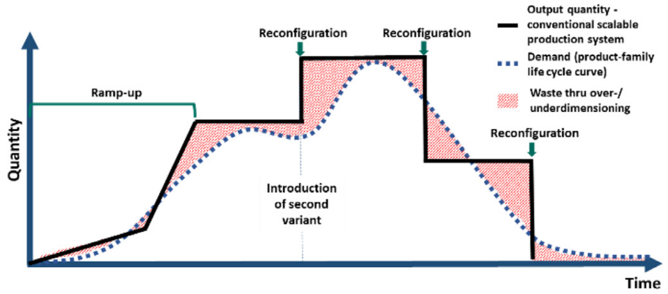

Fig. 1. Lack of adaptability of conventional production systems.

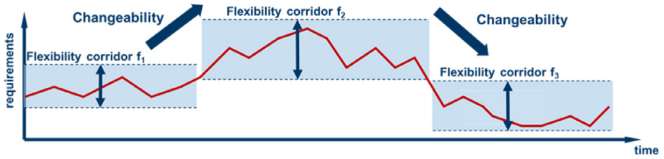

Fig. 2. Comparison of flexibility and changeability, adapted from Wiendahl et al. (2014).

product types and production volumes. Modern manufacturing and assembly lines require both in order to adapt appropriately to rapid changes. According to Wiendahl et al. the ability of a production system to adapt without an additional investment within a certain range is called flexibility (Wiendahl et al., 2014). Changeability on the other hand is the ability to adapt within a maintained range. This range called changeability corridor is bigger than the flexibility corridor but requires further investment and a reconfiguration of the system. Fig. 2 shows in a schematic way how flexibility and changeability are linked to each other.

In the scope of planning changeable factories, Heger and Hernandez Morales make an important contribution by identifying the most important change drivers as well as change enablers (Hernández Morales, 2002; Heger, 2007). In today's consensus, there are five change enablers to be mentioned: modularity, universality, mobility, compatibility and scalability.

Loferer presents an approach for computer based planning of assembly components. He achieves changeability by using modular assembly stations (Loferer, 2002). Kluge focuses on modular assembly systems as well (Kluge, 2011). He extends the approach of Loferer by taking into account future change drivers.

Weyand proposes an approach, which aims at reusability of the resources of assembly systems. He assumes that an increase in the degree of automation always cuts down the processing time and raises the production output (Weyand, 2010).

Pachow-Frauenhofer assumes that there is an optimal degree of flexibility and changeability for an assembly system. She proposes a method to plan such a system. For this, she transfers the methods of Heger and Hernandez to system level, using a control cycle logic (Pachow-Frauenhofer, 2012).

Landherr aims at minimizing the investment when reconfiguring an assembly system. He tries to achieve this by an integrated view on product and assembly configurations (Landherr, 2014).

Neumann focusses on short-term adaptability of production systems, with a time frame between four weeks down to one shift (Neumann, 2015). His two step method can be divided into the identification of change drivers and the selection of appropriate change measures. He focuses on the second step, the situative adaptability. Both, Neumann and Landherr use a digital model of assembly systems in order to support appropriate adaptability.

Eilers proposes a reference model for assembly systems. His goal is to simplify to plan them with the focus on finding not as much as possible, but just the right degree of scalability and reconfigurability. He defines a mechanism, so that an appropriate response to occurring change drivers is possible. One of these mechanisms is the adaption of the degree of automation (Eilers, 2015).

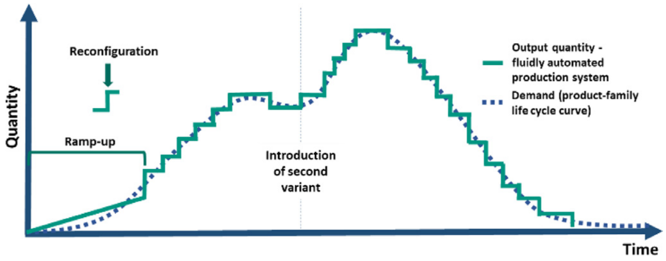

Fig. 3. Adaptability of fluidly automated production systems.

Another method to select an appropriate degree of automation is proposed by Salmi et al. Based on product data, different configurations of an assembly line with a differing DoA are designed. Then the best option is selected based on unit costs (Salmi et al., 2016).

Burggräf et al. propose an approach to calculate a target DoA. An equipment database is build and used to design the assembly system according to the selected target DoA (Burggräf et al., 2019).

In conclusion, existing approaches mainly focus on thinking ahead potential changes and enabling production systems to adapt appropriately. However, most of them do not consider its capability for quick and incremental adjustments. Furthermore, there is a lack for an integrated design guideline for flexible and changeable production systems, which include both, physical and information technological aspects. Moreover, an application of flexibility or changeability has not been considered in production systems for remanufacturing yet. This is where the concept of fluid automation can deliver an important contribution.

3. Concept of fluid automation

The vision of the concept of fluid automation relates to production systems that are able to instantly adjust their degree of automation continuously in minimal increments. This also implies an effortless reconfiguration of the production system, like moving portions of a fluid from one container to another. Because of that, such production systems are able to adapt dependent on fast-changing varying product types and production volumes and pro a target configuration accurately. In the following, the proposed new type of production system is called fluidly automated production system. The idea of the concept especially the capability of such production systems to adapt closely to varying demand is illustrated in Fig. 3. In industrial practice, of course, infinitesimal small increments of the DoA are neither feasible nor economically reasonable, as enabling a fluid DoA for a production system is useless in practice, if the effort for reconfiguration is too high. Thus, practically the concept of fluid automation aims on decreasing the DoA increments on economically optimal levels between two subsequent configurations.

In order to design such a fluidly automated production system for practical applicability, a crucial aspect is the reduction of the effort of reconfiguration aiming at a plug & produce capability. For this, all potential measures of flexibility and changeability are to be taken into account. A higher level of flexibility usually comes with an additional investment up front. Indeed, fluidly automated production systems require a higher investment than their specialized counterparts but have the ability to adapt to fluctuating quantities in a series production and integrate multiple product generations and product families.

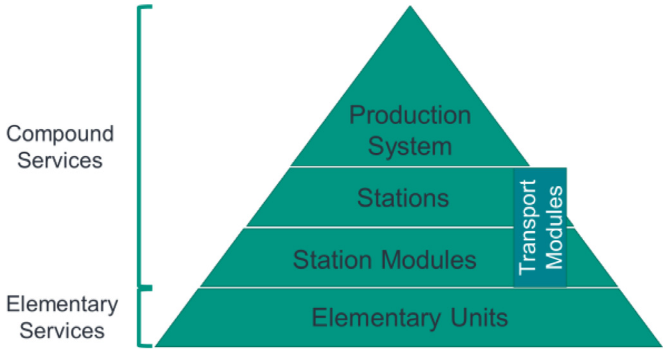

Fig. 4. Modular-hierarchic structure of fluidly automated production systems.

In order to effectively make use of the various potential flexibility and changeability measures and consistently integrate them, the key characteristics of the concept of fluid automation are standardization, modularity and a service-oriented architecture, both in its physical and digital representation. In the following, a general framework to design the physical and virtual representation of a fluidly automated production system are introduced.

3.1. Physical representation of fluidly automated production systems

The general idea of the physical representation of the fluidly automated production system is structuring it based on standardized components like LEGO bricks.

In more detail, for the following modular and hierarchical structure is proposed for a fluidly automated production system. Its structured modules are nested over four layers. This layer model is displayed in Fig. 4.

The top layer represents the entire production system itself. The second layer is the station layer, which consists of clustered station modules from layer three. These station modules are spatially combined and coupled. The fourth and lowest layer consists of elementary units. Elementary units (EU) constitute the smallest standardized elements in a fluidly automated production system that are intended to be changed during the life-cycle of the production system. They fulfill one specific function and offer a specific service. EU are classified by the service they offer. Basically six classes of EU can be distinguished:

- Process units
- Handling units
- Quality units
- Transfer units
- Storage units
- Customized units

This division of the EU leans on and modifies the terminology of the VDI 2860 (The Association of German Engineers 1990). The guideline is extended by transfer units, storage units and customized units. Quality units substitute the inspection class. Process units take over the actual production process and, therefore, provide the actual value-adding. Thus, they are the most important units and characterize the overall function of a station. For instance, a screwer, a press, or a robot with a tool can constitute a process unit. Handling units take care of the product handling within a station such as positioning and orientating them for the process units. A handling unit can be a robot with a gripper for example. Quality units conduct quality inspections within or in between processes. A universally applicable quality unit could e.g. be a robot equipped with a camera. The transfer unit is a handling unit, specifically designed for the transfer of workpieces or other components between stations and transport modules. Entities of a system that are currently not used can be buffered or stored in a storage unit. A storage unit can store products or production resources such as tools that are frequently used and have to be available at all times. Therefore, a storage unit can be a tool magazine or just a common storage surface. Notwithstanding the function, these EU have a standardized size with standardized interconnects to the platform units of the station modules. All elementary units have standardized dimensions and interfaces to each other. Exceptions in terms of geometry can be made for EU in order to fulfill special functions, which cannot be realized within the given design restrictions. However, their size should be a multiple of an elementary unit. Since reusability is a priority, the number of customized units should be kept low. Human workers supporting in the actual value-adding process play a supplementary role within the concept. A workplace for a human worker constitute an example for a customized EU. A EU and its services should be universally applicable. This can be achieved by deploying standard equipment like robots. Specific services for products can be supplied by combining EU on base units of modules. In the following, they are called elementary services - analogue to the definition of elementary functions in mathematics - and compound services. The service-oriented architecture corresponds to the architecture of the physical system.

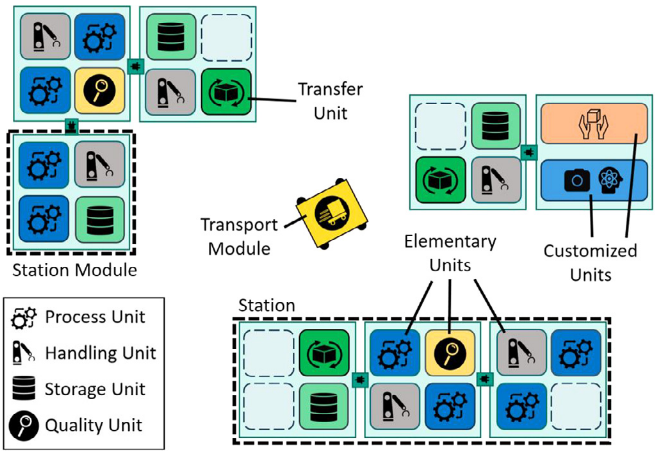

Fig. 5. Modular set-up of a fluidly automated production system.

A station module consists of a standardized physical platform as well as its mounted and plugged EU. The size of the platform and its interface to the EU is unified. All base platforms are identical. Any EU can be installed, if its interface corresponds to the standard. The functions of EU can be combined by mounting them on one platform in order to offer required compound services. These compound services offered by combined EU, can be easily changed by recombining summarized EU. If the required space on one platform is not sufficient, additional station modules can be joined to add more EU. All station modules are coupled and spatially combined in a station.

Fig. 5 displays the makeup and structure of a fluidly automated production system, including all important types of units and modules.

A fluidly automated production system consists of multiple stations that offer different services. The stations are interconnected by appropriate transport modules. A factory structure that enables very flexible material flows is the matrix layout. Matrix-structured production systems are vividly discussed recently (Greschke et al., 2014; Greschke, 2016; Echsler Minguillon and Lanza, 2017). Such production systems are characterized by the elimination of equal cycle times. Additional freedom in the material flow increases flexibility. Production errors on single stations cannot cripple the whole system as in rigid flow production. The production can adapt easily to changing requirements. New stations can be added to offer new services, unnecessary stations can be removed. Bottlenecks can be circumvented by duplicating stations at full capacity. This makes such production systems easily scalable and brings a further boost for the changeability of a fluidly automated production system.

A matrix structure can, but does not have to necessary be deployed for a fluidly automated production system. Either way transport modules have to be provided to cater for the material flow within the fluidly automated production system. For conventional layouts with a rigid material flow, the transport modules can consist of common conveyor belts. For the loose linkage of the stations in a matrix layout, autonomous guided vehicles (AGVs) pose a possible solution. In this case as shown in Fig. 5, each AGV can be seen as an elementary unit in the system themselves.

A standardized rapid clamping system enables an effortless exchange of EU. This plug & produce capability is important for the flexibility and changeability of the production system. The service a station offers can be changed quickly by changing the combination of the EU.

A control system recognizes plugged EU and their offered services immediately.

3.2. Virtual representation of fluidly automated production systems

While the physical representation depicts just the basis for a fluidly automated production system, proper information management is mandatory to utilize its full potential. The subsystems and components of a fluidly automated production system merely do not have to be connected but have to know each other and understand mutual functions. To achieve this, providing a digital twin the virtual architecture of the fluidly automated production system builds on the Reference Architecture Model Industrie 4.0 (RAMI4.0) (International Electrotechnical Commission (Ginebra) 2017) and the concept of the asset administration shell (Federal Ministry for Economic Affairs 2018) developed by the Plattform Industrie 4.0. RAMI4.0 is a general service-oriented architecture for a holistic standardized description of components in a production system over three dimensions. Its purpose is to enable and simplify the interaction between the physical components. Each physical component in a system, is described as an asset, whose properties and functions are described machine-readably by means of the asset administration shell. In combination, the asset and the asset administration shell build a so called Industry 4.0 component. An illustration of the concept of the asset administration shell, which is adapted from German Electrical and Electronic Manufacturers' Association (2020) is displayed in Fig. 6.

In the concept of fluid automation, the EU are the smallest elements considered in the system. Their data streams are channeled via a standardized interface. They are the smallest undividable assets and have their functions and properties described within their own asset administration shell. Besides that, stations build a thematic unit, a combined asset and have a common asset administration shell. The architecture of the asset administration shell corresponds to the physical and the service architecture. Thus, a harmonized integration of the physical and digital representation in fluidly automated production systems can be realized that enables flexibility and changeability.

4. Application of fluid automation in an agile production system for remanufacturing

An exemplary realization of the approach is shown within the AgiProbot research project. The aim of the project is the development of an agile production system, which is especially capable of reacting autonomously to uncertain product specifications. The system to be developed has to be able to deal with uncertain component states with regard to wear, geometry, degree of contamination, etc. and to develop agile solutions to cope with the tasks in production. Within the scope of the project, the focus is on assembly systems.

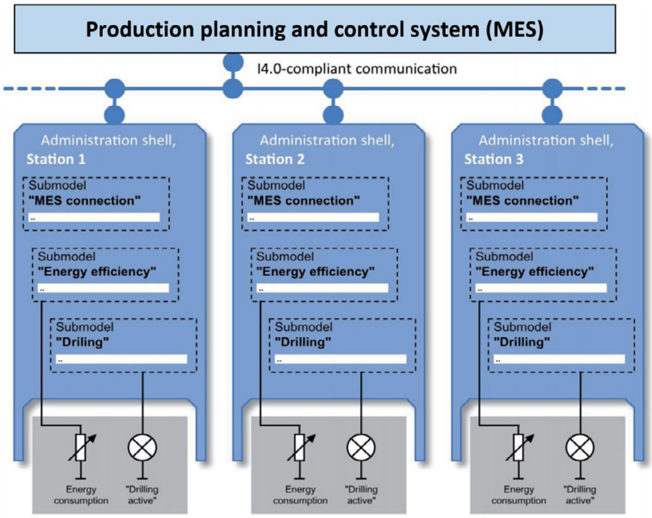

Fig. 6. Concept of the asset administration shell, adapted from German Electrical and Electronic Manufacturers' Association (2020).

In order to demonstrate a real-world implementation of the developed methods, an agile production system is implemented on the basis of a challenging industrial application example, in which a particularly large variance and uncertainty of the components to be processed is to be mastered, taking into account high quality and efficiency requirements. Such an exemplary application case is the so-called remanufacturing of electrical drives of an automotive supplier, whereby old products are recovered, disassembled and selected components are returned to serial production. Due to the increasing scarcity of central materials (e.g. rare earth metals), this approach is increasingly coming to the focus of important sectors such as the automotive industry (e.g. for batteries and electric motors in the context of electric mobility).

4.1. Fluidly automated production system with service-oriented architecture

The implemented hardware infrastructure of the fluidly automated production system for the remanufacturing of the electrical drives is based on a service-oriented plant architecture with a basic control module, which takes over the central functionality of a line control as well as of individual production modules. These are individual station modules with autonomous control and intelligence, which can be operated independently as stand-alone or combined with each other as station. A production station module consists of a combination of services provided by elementary units and offered to the production system. In order to design an agile and fluid production system, it is realized to reconfigure the individual elementary units on the production base platforms, e.g. screwing units. Since the classical programming of a line control does not allow reconfigurability of the control code, the programmable logic controller (PLC) of the individual platforms is moved to a modular web application. This allows the use of object-oriented programming languages, interactive user interfaces and thus a better usability. This approach is supplemented by predefined libraries and knowledge sources so that the required information can be provided and processed efficiently.

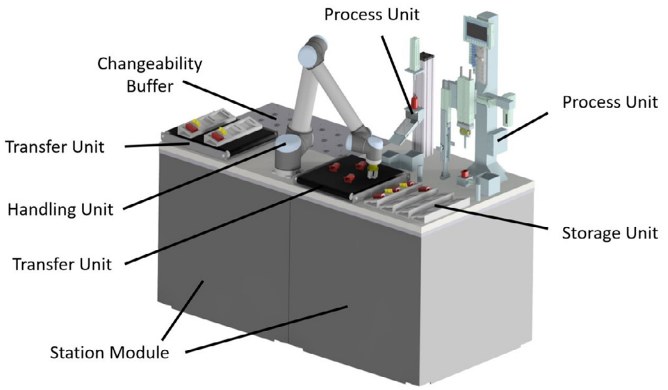

Fig. 7. Exemplary model of a station in the AgiProbot factory consisting of two process units, two transfer units, a storage unit and a handling unit, built up on two coupled station modules.

To manage the complexity of the overall control, the functions of the individual elementary units are encapsulated in services of a service-oriented architecture. The individual elementary units offer the execution of services in the control architecture. To call a service of an elementary unit only the relevant parameters are transferred to the server of the station modules. This enables a fast implementation of additional functions in a production system. The process chain for dismantling old products is thus a sequential composition of the offered elementary unit offering services, such as screw driving processes or ejection modules, They can be executed cyclically or event-oriented. The services are defined individually based on the respective functions of the elementary units and can, therefore, vary both in granularity and performance.

The available services of the function modules can be designed with different levels of intelligence. A service can be a combination of parametric elementary units that interpret the transferred values and execute them on the controller of the station module. Another possibility for an available service is the autonomous creation of the sequence of the functions. Based on the server client principle of the OPC UA control protocol, the service-oriented control architecture is designed. Each station module is equipped with an OPC UA server. The elementary units are designed as clients.

4.2. Hardware realization of the fluidly automated production system

The basic station modules on which the elementary units are docked are designed from a continuous cast aluminum profile. An aluminum base plate with the dimensions 1000 mm × 1000 mm is mounted on this frame. The base platforms of the station modules are mounted on rollers so that they can be moved with high flexibility. They are fixed and aligned using adjustable feet. Each base platform is equipped with a PLC and also provides the necessary electrical supply and compressed air for the elementary units. In addition to safety functions, each platform of a station module has standardized interfaces, which are also used for communication via data ports. This means that all basic functions for operating the elementary units can be provided. Individual station modules can be connected to each other via centering elements with very high precision. This allows an individual layout to be implemented. The communication between the station modules takes place via the standardized interfaces. In the realization of the AgiProbot remanufacturing factory, up to four elementary units can be installed on a base platform of a station module. An area of 500 mm × 500 mm is provided for each elementary unit. In order to enable a quick exchange of the elementary units, zero-point clamping systems with power and data coupling on the base plate are provided. The elementary units are identified by means of RFID. This provides the station modules with information about which elementary services are provided by the elementary units.

The realized functions in the AgiProbot factory of the elementary unit are manifold. All types of the defined types of EU are implemented such as a transport unit, a screwing unit, a pressing unit, various quality units or standardized handling units consisting of a Universal Robot UR 10e. Fig. 7 displays a station in the AgiProbot factory that is configured for pole housing disassembly.

In the future, DC motors, among other products, will be disassembled in the AgiProbot factory. The simple reconfigurability of the stations can be illustrated by the example of a station for motor armature disassembly, where the ring magnets and worm wheels are to be removed (cf. Fig. 8). For a variant A of the armature, both the ring magnet and the worm wheel are pressed onto the armature shaft. The station is equipped with two process units for the pressing operations (6, 7) two robots for handling (4, 5), a quality unit (2), where the worm wheel is inspected for damage, a transfer module (1) and a buffer unit (3). One slot for an EU on the platform of the second station module is empty and serves as a changeability buffer. Now another variant B is also to be disassembled, whose worm wheel was not pressed onto the shaft but screwed onto it. To be able to disassemble both variants at the station, a reconfiguration is conducted. For this purpose the existing station is extended by an additional process unit (8), catering for the unscrewing of the worm gear of variant B. Due to the modular and service-oriented design, this process unit can be easily docked and the station can be adjusted to the additional variant in a relatively short time.

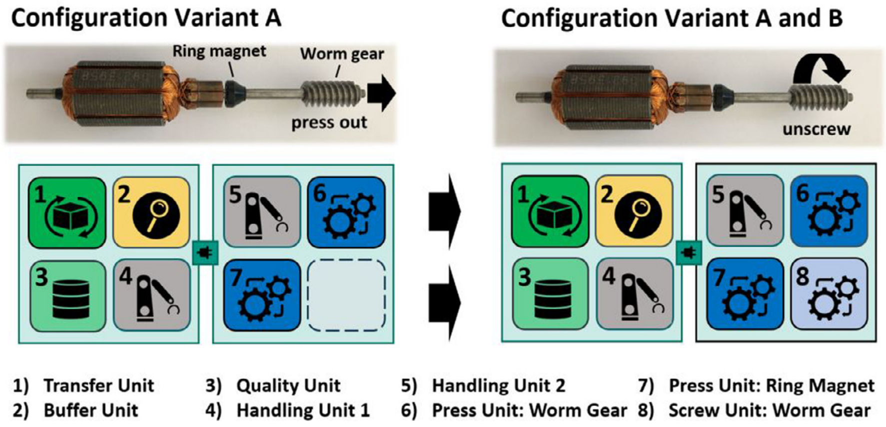

Fig. 8. Reconfiguration of a fluidly automated station in order to integrate an additional variant to be disassembled (left: before, right: after).

5. Conclusion and outlook

In the present paper, the concept of fluid automation was introduced. A vision was illustrated, a framework and design guidelines were defined, and the current state of a practical application of the concept was shown. The framework consists of a multilayer structure with four modularly built hardware layers (elementary units, stations modules, stations and production system) as well as a modular service-oriented software architecture. The holistic design guidelines have a higher degree of modularity than current approaches. In combination with consonant hardware and software a fluidly automated production system will have lower reconfiguration barriers. Modularity on station module level decreases the DoA increment. Bearing this in mind, the concept will boost flexibility and changeability to a higher level.

The framework will help to concretize software and hardware components for the AgiProbot factory. Its production system for remanufacturing in turn will provide a suitable and realistic use case to conduct tests and evaluate and explore the potential of the concept.

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