Determination of Cognitive Assistance Functions for Manual Assembly Systems

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Abstract. Since a growing number of variants increase complexity in today's production systems, higher flexibility is needed. However, automated production systems are often not economical in high-variant production scenarios. Therefore, human flexibility plays an important role, especially for assembly tasks. In order to increase human flexibility in manual assembly a variety of assistance systems providing cognitive support for individual workers has been developed in recent years. Cognitive assistance systems can support assembly workers by providing, processing or collecting information. This paper presents an approach to determine cognitive assistance functions in manual assembly. The need for different assistance functions is investigated in order to make a needs-based selection. The results can then be matched with suitable technologies to design an assistance system. An application of this approach is shown for a manual assembly system in the learning factory for cyber-physical production systems in Augsburg, Germany.

Keywords: Cognitive assistance · Manual assembly
Technology management · Industry 4.0 · Human factors

1 Introduction

In order to be successful in saturated markets, more companies are offering customer-individual products [1]. Besides production in lot size one, volatile demand [2] increases complexity in production. Furthermore, a rising product complexity [3] and shorter product lifecycles [4] are challenges producing companies face today. Rising complexity in production not only increases quality costs [3] but also requires a broad qualification of employees [2]. In order to master rising complexity, production systems need to become more flexible.

Depending on the industrial sector, assembly is responsible for up to 70% [5] of total production costs. Since manual work is the most flexible factor of production [6], flexibility in production is especially enabled by manual assembly. Manual assembly workers can be supported by assistance systems in perceiving assembly tasks, making

T. Z. Ahram (Ed.): AHFE 2018, AISC 795, pp. 198–207, 2019.
https://doi.org/10.1007/978-3-319-94619-1_19

decisions and executing assembly tasks [1]. Physical assistance systems can be applied to improve ergonomics in handling heavy components. Cognitive assistance systems can support manual assembly workers by providing, processing or collecting information. Due to rising complexity in manual assembly, the importance of correct and relevant information in manual assembly is rising [7]. Therefore, cognitive assistance systems play an important role to increase flexibility in manual assembly systems. Furthermore, the use of cognitive assistance systems can result in higher efficiency and error-free assembly [8].

2 Complexity Evaluation in Manual Assembly

In order to design a needs-based cognitive assistance system in manual assembly, it is necessary to analyze the required assembly tasks. Several models have already been developed for measuring complexity in assembly. Samy et al. [9] are using detailed geometrical information to measure product assembly complexity. Zeltzer et al. [10] identified 11 complexity drivers in assembly to quantify complexity for mixed-model assembly workstations. These complexity drivers cover several technical aspects from the analyzed assembly operations. These models can be used to reduce complexity during the design-phase of a product.

In order to develop a needs-based assistance system for a given product, worker-specific information has to be considered as well. Zäh et al. [11] are using a temporal, a cognitive and a knowledge-based factor in order to measure complexity of manual assembly operations. Besides product complexity Claeys et al. [12] are also considering operational complexity of the workstation as well as operator-specific information. Hold et al. [13] are using MTM to structure assembly tasks and also consider human error probability for each task group.

Several existing models allow a very detailed analysis and quantification of assembly operations. Since product life-cycles are shortening [4] and the investment of cognitive assistance system has to be amortized, the lifecycle of a cognitive assistance system is often longer than product lifecycles. Therefore, it is necessary to consider product changes during the lifecycle of the assistance system. Furthermore, several models for measuring assembly complexity focus on detailed technical aspects and don't consider legal aspects, such as documentation tasks.

3 Determination of Cognitive Assistance Functions

This section introduces a method for needs-based determination of cognitive assistance functions for a given manual assembly process. It can be applied for workshop assembly scenarios which are not equipped with cognitive assistance systems. In this method the complexity of an assembly task is evaluated in order to select suitable assistance functions. In order to include all relevant aspects all stakeholders (e.g. industrial engineering, assembly workers, production IT) should be involved in the evaluation process.

3.1 Assembly Process Analysis and Complexity Evaluation

In order to design an application-specific assistance system, the assembly process shall be analyzed from worker-centric perspective. Assembly processes is therefore divided into different tasks, which are defined in the work plan. For each assembly task an assembly worker has to perceive information [11], execute the assembly task and document the performed assembly. In order to introduce a needs-based assistance system the complexity of an assembly task needs to be evaluated in different dimensions. The goal of this method is to develop an applicable assessment of manual assembly that focusses on key aspects in order to limit the evaluation effort.

Therefore, for each assembly task three dimensions of complexity shall be analyzed:

- *Perception Complexity (PC)* aims to evaluate the cognitive workload an assembly worker before the physical assembly execution.
- *Execution Complexity (EC)* aims to evaluate the risk of an assembly error during the assembly.
- *Documentation Complexity (DC)* aims to evaluate the necessity and effort of documentation during the assembly task.

3.1.1 Perception Complexity

During several workshops with production engineers from different industrial sectors three main complexity drivers were identified that increase the cognitive workload during the perception of an assembly task. They include worker-specific information [12], variant-specific information [10] as well as influences from product changes. In order to evaluate the Perception Complexity of an assembly task, the following three components are introduced:

- The *Employee Qualification Factor (EQF)* describes if assembly workers have the necessary qualification for the performed assembly task.
- The *Customization Level (CL)* describes the influence of product customization on the analyzed assembly task.
- The *Change Frequency (CF)* describes the time intervals the assembly task changes during product changes or the introduction of new products.

In order to achieve a compromise between accuracy and practicability, the three components are evaluated with integer values on a scale from 1 to 10. The three complexity components are multiplied and weighted equally to quantify the Perception Complexity:

$$\mathrm{PC} = \mathrm{EQF} \cdot \mathrm{CL} \cdot \mathrm{CF}. \tag{1}$$

Table 1 shows typical scenarios for the lowest and highest value for the three Perception Complexity components. To assess the complexity for a given assembly task, an intermediate value within the given limits has to be chosen.

Table 1. Perception complexity components with lowest and highest value.

Perception Complexity component	Lower limit: 1	Upper limit: 10
Employee qualification factor	All employees are trained for the assembly task	The assembly task is regularly performed with new employees that lack necessary qualification
Customization level	The assembly task is identical in every order	The assembly task is highly dependent on order-specific information
Change frequency	The assembly task is not influenced by product changes	The assembly task is frequently changing due to product changes

3.1.2 Execution Complexity

In order to quantify the Execution Complexity of an assembly task, the risk of an assembly error shall be evaluated. In risk assessment applications a *risk priority number* [14] is commonly used for evaluation. This method shall be applied for the Execution Complexity in manual assembly:

- *Severity (S)* describes the impact of an assembly error on product quality and human safety.
- *Occurrence (O)* describes the frequency of assembly errors in the analyzed assembly step.
- *Detection (D)* describes the probability an assembly error is detected before the final assembly step is completed.

According to the risk priority number, the three components are evaluated with integer values on a scale from 1 to 10. In order to quantify the Execution Complexity, the three complexity components are multiplied [14]:

$$\mathrm{EC} = \mathrm{S} \cdot \mathrm{O} \cdot \mathrm{D}. \tag{2}$$

Table 2 shows typical scenarios for the lowest and highest value for the three Execution Complexity components.

Table 2. Execution complexity components with lowest and highest value.

Execution complexity	Lower limit: 1	Upper limit: 10
Severity	An error in the assembly has no effect on the product quality	An error in the assembly task always has an hazardous effect
Occurrence	History shows no failures in the analyzed assembly task	Failures in the analyzed assembly task are almost certain
Detection	Every error in the assembly task is directly detected at the next process step	Every error in the assembly task cannot be detected in all following process steps

3.1.3 Documentation Complexity

In order to evaluate the Documentation Complexity, the reason for documentation and its effort are analyzed. Moreover, the reason for documentation can be divided into internal and external reasons factors. In order to evaluate the Documentation Complexity of an assembly task, the following three components are introduced:

- *Documentation Necessity (DN)* describes the importance of documentation caused by external factors, such as legal aspects or customer demands.
- *Internal Information Value (IIV)* describes if a documentation of the assembly step is important for internal assembly data evaluations such as productivity indicators or traceability of components.
- *Documentation Effort (DE)* describes the effort of manual documentation without digital assistance.

In order to achieve a compromise between accuracy and practicability, the three components are evaluated with integer values on a scale from 1 to 10. The three complexity components are multiplied and weighted equally to quantify the Documentation Complexity:

$$EC = DN \cdot IIV \cdot DE. \tag{3}$$

Table 3 shows typical scenarios for the lowest and highest value for the three Execution Complexity components.

Table 3. Documentation complexity components with lowest and highest value.

Documentation complexity	Lower limit: 1	Upper limit: 10
Documentation necessity	No external party requires a documentation of the essential task	Documentation of every aspect of the assembly task is required
Internal information value	A documentation of the assembly task creates no internal benefits	A documentation of the assembly creates a high benefit for internal evaluations
Documentation effort	The documentation effort of the assembly task is negligible	The documentation effort surpasses the value-adding assembly time by many times

3.2 Cognitive Assistance Functions

3.2.1 Framework

A cognitive assistance system is able to exchange information with the objects *assembly worker*, *IT systems* and *product* [15]. Figure 1 shows an illustration if the information flow framework.

Communication with the assembly worker consists of input given by the worker as well as information provided for the worker by the assistance system. An assistance system can also communicate with existing IT Systems such as enterprise resource

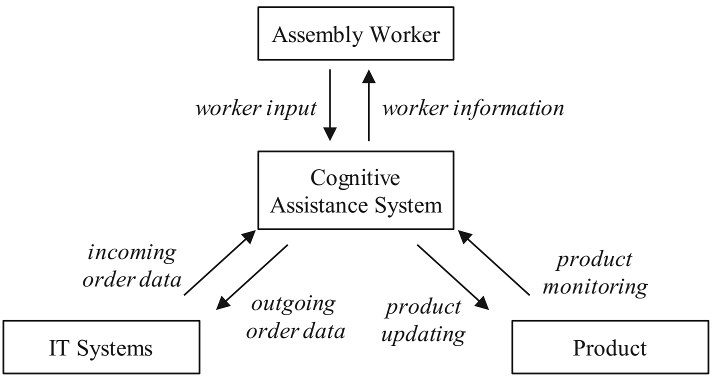

Fig. 1. Information flow framework for cognitive assistance systems in manual assembly [15].

planning systems or manufacturing execution systems. This communication is used to receive order information as well as to document an accomplished assembly. Furthermore, an assistance system can also read and write data from a product if it or the workpiece carrier is equipped with rewritable digital memory. An information flow with the product can also be realized by intelligent tools that are part of the assistance system.

Assuming in each assistance function an assistance system always has one data input and one data output, there are two possible outputs for every three inputs. In total, there are six possible assistance functions for the communication with assembly worker, IT systems and product. Figure 2 shows the information flow of the six assistance functions and the corresponding description. The six assistance functions are to be seen as a toolbox and can be combined as necessary for a given use case. The following section connects these six assistance functions with the evaluated complexity dimensions and gives a brief explanation how the six assistance functions can support manual assembly tasks.

3.2.2 Selection of Assistance Functions

In order to make a selection of the introduced assistance function, they are mapped in Table 4 with the three complexity dimensions. A high Perception Complexity indicated the need for *worker information* in order to provide the relevant information for the assembly task at the right time. A high Execution Complexity can be handled by the assistance functions *quality assurance* and product *manipulation*. In *quality assurance* the assistance system supervises the assembly process and only gives feedback if an error was made. A *product manipulation* can be realized in order to avoid manual mistakes, e.g. by introducing a torque-controlled screwdriver. Documentation can be assisted in several ways. A *manual documentation* can be integrated easily by using keyboard or touchscreen input. *Automatic documentation* can be realized using a camera at an assembly workstation. A *product documentation* is only possible if the product is equipped with digital memory, e.g. radio-frequency identification (RFID) transponders.

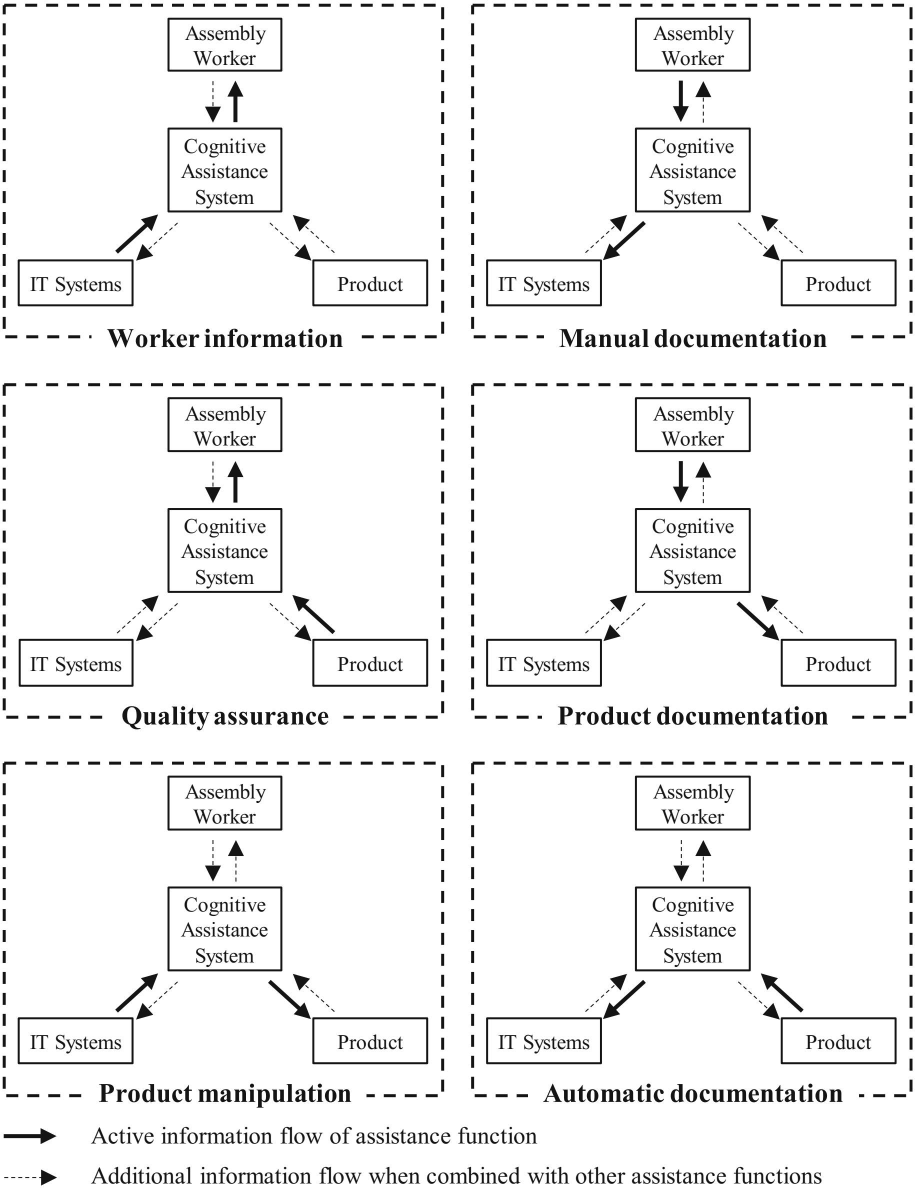

Fig. 2. Information flow of six developed assistance functions.

Table 4. Mapping of complexity dimensions and assistance functions.

Assistance function	Perception complexity	Execution complexity	Documentation complexity
Worker information	●		
Manual documentation			●
Quality assurance		●	
Product documentation			●
Product manipulation		●	
Automatic documentation			●

4 Application in the Learning Factory for Cyber-Physical Production Systems

This section shows an application of the method in the Learning Factory for Cyber-Physical Production Systems. The learning factory consists of six assembly stations for remote-controlled cars [16]. It is organized as a flexible workshop assembly with dedicated parts at each workstation. Depending on the customer's product configuration every product is only transported to the relevant workstations.

The method is applied on workstation #4 'Electronics' of an assembly system for remote-controlled cars. In workstation #4 there are five assembly tasks to be executed. At first a battery is installed for which a customer can choose from three different options. The installation of a wrong battery cannot be detected after that chassis has been put on. Then, one of two antenna sleeves is inserted. In contrast to the battery, a wrong antenna sleeve can still be detected when the chassis has been put on. If demanded by the customer, the car is equipped with a light. For every car the speed controller is connected and an electronic test is performed. The final two assembly tasks are identical in every order but essential for the functionality. Table 5 shows the evaluation of assembly tasks at workstation #4 which was performed by developers of the learning factory.

Table 5. Evaluation of workstation #4 in the learning factory for cyber-physical assistance systems.

Assembly tasks	PC			EC			DC		
	EQF	CL	CF	S	O	D	DN	IIV	DE
Battery installation	6	8	6	3	3	2	1	1	4
	PC = 288			EC = 18			DC = 4		
Insertion of antenna sleeve	6	6	2	3	3	5	1	1	4
	PC = 72			EC = 45			DC = 4		
Light installation	6	4	6	3	2	3	1	1	2
	PC = 144			EC = 18			DC = 2		
Speed controller connection	4	1	1	7	4	10	1	1	2
	PC = 4			EC = 280			DC = 2		
Electronic test	6	1	1	7	1	10	5	1	2
	PC = 6			EC = 70			DC = 10		

The evaluation of the Perception Complexity results in high values for the battery installation and light installation. As a consequence, *worker information* has been applied by introducing tablets with order-specific information. In addition, the implementation of a pick-by-light system would be possible.

The Execution Complexity results in high values for the speed controller connection. However, this connection is already ensured by the electronic test. A possible quality assurance system would require a connection of the speed controller with the assistance system. Then a quality assurance procedure could be integrated into the assembly workflow.

A documentation of the installed components is currently not required. However, it is planned to implement a tablet-based documentation at a later station in order to perform additional quality checks.

Besides the evaluation of workstation #4, the presented approach is applied at every workstation of the learning factory. If new product variants are introduced, the evaluation will be reviewed in order to identify chances for the need of assistance.

5 Summary and Outlook

Producing companies face several challenges today. Cognitive assistance system can help to master rising complexity in manual assembly systems. In order to realize an application-specific and needs-based design of cognitive assistance systems a method for complexity evaluation and a framework for cognitive assistance functions have been introduced. Complexity is evaluated for each assembly task in dimensions of perception, execution and documentation. For each complexity dimension the most important influences are evaluated in order to make a needs-based selection of assistance functions. The developed framework for assistance functions introduces six directions of information flow that can be used when applying a cognitive assistance system at a manual assembly station.

In the future, the method has to be evaluated in different industrial applications. The method has to be extended in order to select technologies and components to configure to realize a cognitive assistance system. Furthermore, an economic evaluation has to be introduced in order to identify the appropriate degree of assistance during the assembly process.

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