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An Approach for the Development of an Adaptable and Human-Centered Rework System

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Abstract

Today's challenges require production companies to make their operations adaptable in order to be able to efficiently respond to variant changes and volume fluctuations. Even though there has been a large focus on zero-defect production and quality improvement, errors nevertheless occur, making adaptable rework systems essential. Since rework is often manual, it is vital to design rework stations in a human-centered manner to adapt to individual worker needs. This paper presents an approach for the design of an adaptable and human-centered rework system, which is subsequently validated in a rework scenario in the field of automotive production research.

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Keywords: Adaptable assembly; Human-centered assembly; Rework systems

1. Introduction

Shorter product lifecycles, high fluctuations in production volumes, and a wide variety of product variants are compelling manufacturing companies to continuously adapt in order to remain competitive in a dynamic market [1]. In recent years, particularly within the context of Industry 4.0, a plethora of new technologies and applications have been developed to help companies in addressing these challenges [2]. However, despite these innovations, ensuring high quality persists as one of the most challenging and significant tasks for manufacturing companies, not only to differentiate from competitors but also to ensure long-term success. To achieve this, substantial efforts have been directed towards minimizing errors in production, especially in assembly, which is widely regarded as the most critical stage for error accumulation, as it represents the final stage of production where all prior production issues and disturbances converge [3].

Given the existence of several methods and techniques for preventing errors in production, and the impracticality of achieving zero-defect production [4], this paper focuses on rework processes. As with manufacturing in general, rework is subject to the aforementioned challenges of today's marketplace. As a result, rework processes must exhibit a high degree of adaptability. Achieving this adaptability renders the human workforce essential in most rework scenarios due to its flexible cognitive and motor skills, as well as its steep learning curve [5,6]. To guarantee the optimal deployment of the human workforce in terms of ergonomics and productivity, rework systems should be designed and operated in a human-centered manner.

The objective of this paper is to propose an approach for the development of rework systems, with a focus on single rework stations, drawing upon two current scientific topics in the context of assembly: adaptability and human-centered design. Thereby, the paper examines how the theoretical foundations of adaptability enablers and human-centered design principles

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can be applied in practice, considering the interdependencies between worker-specific work station adjustment and the dynamic requirements of rework processes. This is demonstrated through the design of a rework station for automotive water pumps.

2. Essentials and related work

This chapter covers the fundamentals necessary for the realization of an adaptable and human-centered rework system, including rework in assembly, adaptable assembly systems, and the role of the human workforce in rework, as well as its influence on the design of assembly systems. These topics are considered separately, as there are currently no approaches that effectively combine them.

2.1. Rework in Assembly

During assembly, the product passes through a significant part of the value chain. However, this area is often a reservoir for technical and organizational challenges and errors that often occurred in earlier phases of the production process [3]. Since it is not possible to prevent all errors, rework plays a central role in assembly.

Rework is the process of restoring the quality of products that have become defective during assembly. The term covers all work steps required to correct potential defects [7]. In general, two types of rework can be distinguished. Firstly, rework can occur on the assembly line itself if the product is still incomplete, for example, if an error is identified during an immediate inspection. Secondly, rework can take place at the end of the assembly line after the product has passed the final inspection [7]. In this paper the second case is considered. Due to the high number of variants and fluctuating quantities in assembly, which also have a major impact on reworking, adaptability is a decisive factor in making reworking efficient.

2.2. Adaptable Assembly Systems

Adaptability (also: changeability) refers to the potential of a system to respond to changes even beyond defined corridors [8]. Adaptable systems thus have no explicit boundaries in their implementation [9], which distinguish them from flexible systems [10].

In order to guarantee responsiveness to changes, an assembly system must possess characteristics that facilitate adaptation. While the primary adaptability enablers in production are universality, compatibility, modularity, scalability, and mobility [11], there is also a multitude of secondary enablers that are subordinate to these primary ones [12]. In the context of this paper, only the primary adaptability enablers will be considered henceforth. It is crucial to recognize the existence of several interdependencies between these adaptability enablers [13]. The primary adaptability enablers are shown in Table 1.

Table 1. Primary Adaptability Enablers (in reference to [12])

Adaptability Enabler	Explanation
Universality	• Dimensioning for different product or technology requirements
Compatibility	• Networking capability with regard to material, information, media and energy
Modularity	• Standardized, functional units or elements
Scalability	• Technical, spatial and personnel expandability and reducibility
Mobility	• Locally unrestricted movement of objects

2.3. Human Workforce in Rework

As previously stated, rework systems are often realized as manual workstations. This is particularly the case in the automotive supply industry [14]. A key characteristic of such rework systems is the rotation of tasks among different workers, with individuals being assigned to rework tasks and related stations flexibly based on the given rework scope and their availability [15]. Due to this high degree of worker rotation, rework systems are especially affected by the challenges faced by manual assembly systems in general. These challenges are especially pronounced in industrialized countries like Germany, where ongoing demographic changes have resulted in a shortage of skilled workers [16] and where the human workforce is characterized by an increasing heterogeneity in terms of age, skills, and experience [17].

In light of these challenges, there is a growing focus in industrial assembly on the efficient and sustainable utilization of the human workforce. As a result, the objectives in the design and operation of assembly systems have shifted from tasked-centeredness to human-centeredness, particularly affecting rework stations [18]. To achieve human-centeredness, assembly systems must be designed to be worker-specifically adaptable, allowing workers to adjust the system according to their individual characteristics and skills.

2.4. Design of Human-Centered Assembly Systems

In order to enable such worker-specific adjustments of an assembly system, it is essential to identify assembly system parameters relevant for this. A synopsis of corresponding assembly system parameters has been devised by [19]. Thereby, the identified parameters were aggregated into seven dimensions of individualizability, in which an assembly system should be worker-specifically adjustable. As this paper addresses single rework stations, only those dimensions that can be adapted within the workstation itself - considering the work station as an environment-independent entity - are relevant for the further proceedings. A proposal for classifying relevant assembly system dimensions and dimension-related configuration options, respectively parameters, under these limitations was put forth by [20] and is presented in Table 2.

Table 2. Relevant dimensions and dimension-related configuration options in terms of the realization of a single rework station (in reference to [19,20,21])

Dimension	Related configuration options/parameters
Working Height	• Height of work surface
Range of vision, gripping area, handedness	• Height and angle of material provision elements (e.g. material shelves, swivel arms) • Position of small part containers along the work surface and material provision
Use of information and assistance systems	• Design and setup of system interaction • Information extent and granularity
Lighting	• Pivoting of light sources • Light intensity and color

In regard to the worker-specific adjustment of the given configuration options, two aspects specifying the type of adaptation need to be considered before further explanations are provided: the time and the manner of adaptation. Concerning the time of adaptation, a distinction can be made between static adaptation, where the configuration of the work station is adjusted prior to the worker's task commencement and in-process adaptation, where the work station parameters are modified after the worker has already begun working. With respect to the second aspect, the manner of adaptation, an overall distinction can be drawn between self-adaptation (= self-adaptable system) and worker-made adaptation (= adaptable system) of work station parameters [22]. In self-adaptable systems, parameters can automatically adjust to the worker based on the system's assessment of the worker-specific optimal parameter settings for the work station, which may, e.g., be determined through an in-process worker tracking [21]. In contrast, adaptable systems require the worker to manually adjust work station parameters. A hybrid approach between the two is the recommender system-based adaptation of work station parameters, as presented in [23]. In this approach, the worker receives recommendations for optimizing the work station settings if needed, but retains the final decision on whether or not to follow them.

3. Development of the approach

Based on the previously described essentials and related work, this chapter serves to derive an approach for developing an adaptable and human-centered rework system, focusing on single rework stations. It addresses the engineering aspects by systematically combining adaptability and human-centered design and applying them within the context of rework stations.

3.1. Basics of development

In order to realize an adaptable and human-centered rework station, it is essential to consider the influences of product, process, and human factors on it, as illustrated in Figure 1.

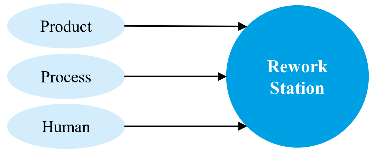

Fig. 1. Influencing factors at a rework station

To develop a rework station that can respond to these influences, it is necessary, on the one hand, to tailor the adaptability enablers outlined in Chapter 2, along with their specific characteristics, to the rework context. On the other hand, it is essential to integrate the dimensions and configuration options of human-centeredness in manual assembly stations, as presented in Table 2, with these enablers. To realize a corresponding approach, the ensuing discussion will first delineate the necessity of each adaptability enabler in the rework process. Subsequent to this, the specific characteristics and abilities that a rework station must possess in terms of these enablers to accommodate potential changes and specificities of product, process, and workforce are systematically derived and summarized.

3.2. Need for adaptability enablers in the rework context

Adaptability enablers play a pivotal role in addressing the complex and fluctuating demands of rework processes. Each enabler targets specific challenges within the rework context, thereby establishing the foundation for stations that are both adaptable and human-centered. The following sections outline the distinctive role and necessity of each adaptability enabler in the design and operation of adaptable and human-centered rework systems.

Universality: Given the diversity of product variants in modern assembly, a rework station must be universally adaptable to accommodate different types of products and efficiently address their range of defects. Additionally, universality is crucial with respect to the workforce. Rework tasks and related stations, as delineated in Chapter 2.3, are often assigned flexibly to workers based on the rework scope and their availability. Thus, rework stations must be able to universally adapt to different workers, considering their individual characteristics and skills.

Compatibility: Compatibility is crucial for ensuring seamless integration and efficient performance of a rework station. It allows for the networking and control of various systems and operating equipment, including assistance and monitoring systems, through standardized software and hardware interfaces. This integration facilitates the smooth exchange of information, media, and energy between different systems and devices, enabling the rework station to respond swiftly to diverse product requirements and modifications. Moreover, compatibility can streamline and enhance the worker-specific adjustment of work station parameters by providing standardized data of workers' anthropometry, skills and user preferences. This enables a straightforward transition of workers from other work stations to a rework station with minimal effort and disruption.

Modularity: The modularization of station components allows for the specific adjustment of station elements in response to product and process changes, without the need to modify station elements unaffected by these changes. This streamlines station adaptation, minimizing downtime and ensuring an efficient and cost-effective rework. Furthermore, modularized workstations enable workers to independently adjust modules, allowing for an individualized configuration of station elements without altering the entire system.

Scalability: Rework stations must be scalable in order to accommodate fluctuating production volumes and defect rates, common in dynamic assembly environments. The ability to adjust the size and capacity of a rework station is pivotal to efficiently manage these variations, avoiding delays or increased costs. Regarding the use of the human workforce, scalability typically denotes an increase or decrease in the number of workers in response to rework demands, which can be achieved through specific flexible work time models [12]. However, since this approach is limited to single rework stations, simultaneous work by multiple workers at the same station is not considered. As a result, scalability can focus entirely on the scalable characteristics that an individual worker can have, which is the case for the process-specific competency growth of a worker that naturally develops when performing a task repeatedly [24]. Thus, in this context, scalability refers to the adaptability of assistance and support tools tailored to the worker's skills and experience when starting assembly, as well as during the assembly process.

Mobility: Mobility is essential in rework as it facilitates the movement and rearrangement of a rework station or its modules. Effective mobility allows the rework process to be situated close to error detection points on production lines, thereby reducing transport time and increasing overall efficiency. Moreover, mobility enables the flexible positioning of station modules in ergonomically optimized locations, minimizing physical strain for workers, enhancing their productivity and well-being.

3.3. Derivation of process, product and human related rework station characteristics

The preceding explanations concerning the necessity of adaptability enablers in rework establish the foundation for the subsequent definition of the specific characteristics a rework station must possess to address the dynamic requirements of rework.

Table 3 provides a comprehensive overview of the derived characteristics categorizing them into product and process-related aspects and human-related aspects.

Table 3. Product, process and human related rework station characteristics

Adaptability Enabler	Product and process related	Human related
Universality	• Product and process specific adjustment of station components without requiring major modification to unaffected elements	• Worker specific static adjustment of station components in all dimension of human-centeredness (cf. Table 2) before rework
Compatibility	• Standardized communication interfaces and protocols	• Company-/ plant-wide transfer of worker specific data using standardized databases
Modularity	• Division of the workstation into independent base, transport, supply and process modules	• Independent control of each configuration option (cf. Table 2)
Scalability	• Sufficient provision of work surface space to accommodate spatial expansion • Flexible integration or removal of equipment, tools and components	• Competency specific adjustment of the information extent and granularity given by integrated assistance technologies considering worker's learning curve
Mobility	• Simplified relocation and reconfiguration of station elements • Facilitated movement of the station to different locations along the production line	• Free shiftability of part containers within the rework space • Pivotability of light sources

4. Implementation and Validation

Based on the approach developed in the previous chapter, which integrates adaptability enablers with human-centered design in rework stations, this chapter demonstrates its practical application to the rework of automotive water pumps.

Adaptability is particularly important in this context due to the frequent introduction of new products and variants and the fluctuating production volumes usual in the automotive sector.

Each adaptability enabler will be presented individually, with the developed rework station, depicted in Figure 2, serving as the foundation.

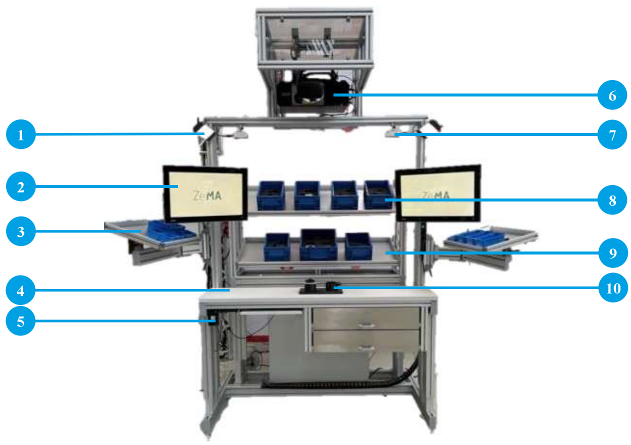

Fig. 2. Developed work station for the rework of automotive water pumps

Universality: Based on the preceding explanations universality can be considered the overarching goal in designing an adaptable and human-centered rework station, building on the other adaptability enablers, which will be discussed in their implementation subsequently. Currently, the developed rework station is configured to handle three different water pumps, with the potential for expansion through further modularization.

Regarding worker adaptation, the station is equipped with an NFC reader (5), facilitating the registration of newly assigned workers prior to assembly. This enables a worker-specific adaptation of the station by referencing an overall company worker database, using the worker's card ID to retrieve pertinent worker data, which will be detailed in the following section.

Compatibility: To enable access to company-wide databases, the rework station incorporates an industrial PC (IPC) that is integrated into the company network. This IPC is station-internally connected to various station components, including the NFC reader (5), two monitors (2), the integrated assistance system realized in form of a dynamic beamer (6), the electric control units for adjusting the work surface height (4) and the height of the material shelves (9), as well as the integrated cameras (7). This connectivity enables the system to adapt the entailed error detection processes, which are based on matching standardized error descriptions with the images captured by the cameras, in case of product or process changes.

Regarding the worker-specific adaptation of the station the IPC-based access to the overall worker database enables the retrieval of worker-specific anthropometric data, preference settings, and performance logs, which can then be utilized to facilitate the worker-specific optimal configuration of the station, as outlined in the subsequent sections.

Modularity: The modularization of station components is crucial in achieving universality and putting compatibility into practical use. In response to possible product and process changes, the station allows for the quick exchange of material provision elements, either by swapping small part containers (8), or, in case of larger changes, by replacing swivel arms (3) using quick-release mechanisms. Additionally, the joining aid (10) used to facilitate assembly can be exchanged to accommodate different water pump variants.

In terms of worker-specific adaptation, the station is modularized to allow individual control of all configuration options listed in Table 2, except for the Light color option, which was excluded due to cost considerations. The configuration options included are partially self-adaptable and partially adaptable. Self-adaptable are the options Height of work surface, Height of material shelves and the Information extent and granularity of the assistance system, as well as the Design and setup of its system interaction. These can be adjusted recommender system-based utilizing the station's IPC-based compatibility, with optimization suggestions communicated to the worker via monitor (2). The remaining options - Angle of material shelves and swivel arms, Position of small part containers along the work surface and material provision, and Pivoting of light sources - must be manually adjusted by the worker.

Scalability: The modular design of the rework station also enables scalability, as material provision modules and assembly equipment can be easily added or removed. In the event that additional material provision space is required due to a new product variant or an increase in product demand, the material provision surface of the integrated swivel arms (3) can be expanded by swapping it using its quick-release mechanisms. Moreover, the number of swivel arms can be readily altered by means of these mechanisms. Furthermore, the material shelves (9) offer sufficient space to add further small part containers (8). For new product variants, new joining aids (10) can be easily produced as they are 3D-printed, with three currently available for the existing flexibility corridor.

To worker-specifically tailor the extent of information given by the integrated assistance system (6), a four level based competence management model, called ILUO-model, as presented in [25] is applied. In this model the provided assistance is scaled based on the worker's error rates and process times. Competency is assessed prior to assembly through performance logs retrieved from the worker database described in the Compatibility section. In-process adaptation is achieved by continuously tracking worker actions via the integrated cameras (7). As these are RGB-D cameras it is possible to derive process times from the captured depth frames and error rates by comparing the captured color images with the standardized error descriptions referenced in the compatibility section.

Mobility: As previously described, mobility is, on the one hand, enabled through the swivel arms (3), which are equipped with quick-release mechanisms, allowing for quick repositioning as needed. Furthermore, the integrated cameras (7) are embedded in the station's profile in such a way that they can be swiftly shifted along the horizontal base module profile. This allows for a quick adjustment of the cameras' field of view, accommodating product or process changes that require new regions of interest for capture.

Additionally, in terms of worker-specific adaptation, the two integrated light sources (1) are fitted with swivel fastening mechanisms, enabling workers to manually pivot them.

5. Conclusion and Outlook

This paper highlights the importance of adaptability and human-centered design in rework processes, particularly in highly dynamic assembly environments. A structured approach was developed to enable the realization of an adaptable and human-centered single rework station, integrating the five primary adaptability enablers - universality, compatibility, modularity, scalability, and mobility - with essential dimensions of human-centered assembly system design. The practical application of this approach was demonstrated through the development and implementation of a rework station for automotive water pumps.

The implementation of the approach demonstrated that the developed station successfully fulfills the majority of the defined requirements for adaptability and human-centeredness.

Key features, such as modular and scalable station elements, standardized data exchange for worker-specific adjustments, and process adaptability, significantly enhance the station's ability to adapt to dynamic rework scenarios.

However, balancing adaptability, human-centeredness, cost, and technical complexity remains a significant challenge. Each of these factors is interdependent, meaning optimizing one often results in trade-offs with the others. Although the developed station is successful in meeting the majority of the defined requirements in terms of adaptability and human-centeredness, it does not fully comply with all of them. The overall station is not fully mobile, as achieving complete mobility would come at the expense of human-centeredness, cost efficiency, and technical feasibility, thereby restricting its flexibility within the production environment. Additionally, the implementation of adjustable lighting conditions was omitted due to cost constraints, which limits the station's ability to fully accommodate individual worker preferences.

Future work should explore innovative ways to optimize this balance without compromising essential features.

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