How to Make Augmented Reality a Tool for Railway Maintenance Operations: Operator 4.0 Perspective

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Abstract: In the last few decades, several initiatives and approaches are set up to support maintenance procedures for the railway industry in adopting the principles of Industry 4.0. Contextualized maintenance technologies such as Augmented Reality (AR) overlay can integrate virtual information on physical objects to improve decision-making and action-taking processes. Operators work in a dynamic working environment requiring both high adaptive capabilities and expert knowledge. There is a need to support the operators with tailor-based information that is customized and contextualized to their expertise and experience. It calls for AR tools and approaches that combine complex methodologies with high usability requirements. The development of these AR tools could benefit from a structured approach. Therefore, the objective of this paper is to propose an adaptive architectural framework aimed at shaping and structuring the process that provides operators with tailored support when using an AR tool. Case study research is applied within a revelatory railway industry setting. It was found that the framework ensures that self-explanatory AR systems can capture the knowledge of the operator, support the operator during maintenance activities, conduct failure analysis, provide problem-solving strategies, and improve learning capabilities. This study contributes to the necessity of having a human-centered approach for the successful adaption of AR technology tools for the railway industry.

Keywords: augmented reality; railway maintenance; Operator 4.0

1. Introduction

Maintenance, repair, and overhaul (MRO) are critical areas in railway asset management and are crucial for industry growth and seamless railway operations. Asset management, also referred to as engineering management, ensures proper management of assets throughout their entire lifecycle [1]. Having a holistic approach to asset management establishes an important link between operational performance and management practices [2]. This holistic approach is key when managing risks and opportunities to achieve the desired balance between cost, risk, and performance. Attention should be paid to align asset management strategies with the overall organizational strategy across different levels of decision-making to contribute to practice-oriented and technical aspects [3]. In light of the above, maintenance plays an important role in physical asset management and contributes to operational performance.

1.1. AR Technology

Globally, the railway industry is focusing on attaining efficiency in MRO by accelerating the maintenance and repair activities through industry specialized augmented reality (AR) technology solutions [4]. The global augmented reality industry for the MRO market was valued at $403.3 million in 2018 and is expected to reach $3319 million by 2024 [4]. AR-based innovations have received a lot of traction in the last few years.
In just over a decade, AR has matured and proven to be an innovative and effective solution to help solve a number of the critical problems to assist and improve maintenance processes before they are implemented [5]. This technology is based on human-computer interaction and overlays digital virtual information in the real-world environment. The information display and image overlay are context-sensitive and user-dependant, meaning that they depend on the perceived objects in combination with the user’s expectations. This technology enables railway companies to examine, monitor, and analyze rolling stock components with great effectiveness and efficiency. The evolution of technologies such as cloud computing, cognitive computing, and machine learning is paving the way for the growth of AR in MRO [6].

1.2. AR Application Fields

Besides maintenance, other AR application fields can be specified like medical, military, robotics, education, and geospatial [7]. AR assists in standardizing and making workflows more user-friendly and efficient by contextualizing and personalizing information. Although AR has great potential, the hardware is not yet user-friendly [8]. Recent work introduced the use of AR as a tool for processing and visualization of imaging data which can be subtracted from medical devices such as MRI scanners, simulation of surgical tools, and other assistive data [9]. This integration of the physician with the data and sensors ensures the visualization of patient data in 3D and collects and analyzes newly generated data. However, subjective assessment of ergonomics and functionalities from end-users was used for minor improvements on the interfaces. Besides this, the AR tool must be seamlessly integrated into the daily workflow of the clinical site. To accomplish this, further developments on the AR hardware are required.

In the context of geospatial experiments, research has been conducted on defining requirements for hologram positioning and display [8]. The presented work contributes to optimized experimental user testing in a real 3D spatial layout. It was concluded that as long as reliable and accurate tracking cannot be provided by the AR tool, the use of the device will be limited to spatially confined environments.

The construction industry faces the problem of determining the location of underground utilities before excavation work can be carried out [10]. AR can be useful for field workers for work planning and during excavations. Research showed that field workers want to implement a finished version of the AR prototype-tool of utility excavations [10]. Important functionalities for the operator were distance measuring, an estimate of leakage locations, and planning and coordination with other professionals.

Other new research describes innovative methods to integrate AR technologies with other technologies such as positioning sensors, tools for managing and visualizing geospatial data (GIS), and systems using high precision real-time kinematics (GNSS) [11]. The main criticism from the end-user was directed to the casing of the device. Additionally, work needs to be done in delivering a physical and cognitive ergonomic device which will facilitate the job of the operators and make their life easier during the field activities. Moreover, the maintenance industry is facing significant challenges nowadays in which costs, safety, availability, and reliability are demanding objectives [12]. In recent years, the evolution of digital technologies has given analog devices a digital footprint. This enables greater connectivity and provides possibilities to achieve higher levels of productivity and thus contributes to the objectives of the maintenance industry [13]. The integration of new digital technologies becomes possible and introduces the term “Industry 4.0”. This requires a quick and efficient maintenance service to guarantee that companies implement an efficient production system [14]. An important characteristic of Industry 4.0 is the exploitation of data to evolve from scheduled, control-based processes and systems to smart processes and systems.

Opportunities arise to predict the behavior of operators, machines, and systems allowing faster decision-making and less downtime [15]. Predicting maintenance enables getting a holistic view of data sources, collection, and analysis to preserve asset reliability and
management [13]. Integrating the Industry 4.0 paradigm in maintenance operations will have far-reaching consequences for the interactions between humans and technology [16]. The role of the human shifts from mainly being a spectator and machine operator towards a strategic decision-maker and a flexible problem-solver [17]. Due to the increasing complexity of production, humans need to be supported by assistance systems [18]. These systems need to aggregate and visualize information in an understandable way such that humans can make well-thought-out decisions and solve urgent problems on short notice. The focus in this research has turned to operators and the support given to them when performing a maintenance task. This study focuses on critical activities that take place on the shop floor of the maintenance facility.

AR can be useful for many situations in maintenance where users require real-time additional information tailored to the activity. Furthermore, if properly used and developed, AR visualization capabilities can transform maintenance processes [19]. Despite the visualization capabilities AR offers, the use of contextualized and customized information supply can be further explored. Not only will this contribute to the development of novel AR adaptive tool devices, but it will also convince users that they will forego traditional methods and opt for AR-assisted solutions.

New interactions between humans and AR support tools and the digital and physical world will directly influence the operator and the nature of work. Operator 4.0 is an experienced operator who can work cooperatively using human-machine interaction technologies to address complex problems [20]. However, not all operators have the same level of expertise, skills, preferences, expectations, and learning capabilities. An appropriate level of detailed instructions should be provided to the operator, tailored to their needs and expectations. Through AR, virtual information that is needed to support maintenance operators can directly be overlaid onto the real workspace. Novice operators can easily get real-life and real-time instructions, whereas off-site experts can collaborate remotely with them. AR guidance could significantly increase the efficiency and effectiveness of the maintenance operation, increase people and process safety, and minimize unplanned downtime [21]. Moreover, it is needed to support the operator to understand, map, and develop his/her competencies by developing an adaptive tool to provide tailored information to enhance the operator’s task performance. To reach this goal, it is needed to provide a structured process that allows having a systematic approach for using the adaptive tool.

1.3. Scope

The purpose of this work is to propose an adaptive architectural framework for a structured procedure that enables a systematic approach to provide support to operators using an AR tool. This tool should support everyday practices and facilitate adaptive capabilities. This adaptive architectural framework can be used for everyday maintenance tasks by capturing the know-how and helpful tips of more experienced operators. Based on experience, expertise, external factors, and the current condition of systems, the operator will be able to get access to tailored information at the right time.

Figure 1 shows the main focus points that will contribute to the need for a dynamic tool. This research mainly focuses on the following aspects: (1) Operator 4.0, (2) AR capabilities, and (3) maintenance operations.
2. Theoretical Background

The research objectives identified in the previous section indicate the need to review the existing literature. The description of the focus points is presented in Figure 1. Each step is explained in detail in the following subsections.

2.1. AR in Maintenance Operations

To ensure continuous system performance in their present operating context, efficient maintenance planning and task execution are required. A maintenance plan contains consolidated listings with descriptions of the condition monitoring, time or usage-based interventions and failure-finding tasks, the re-design decisions, and the run-to-failure decisions [22]. To systemize the process for determining the appropriate maintenance task requirements, the application of the AR tool will be explored using the adapted Reliability Centred Maintenance (RCM) process steps [22].

- **Step 1:** Select equipment. In the first step, the operator must decide what to analyze. Each system component has a unique combination of failure modes and failure rates [22]. When a failure occurs in a system, the operator should prioritize and analyze the impact each failure has on the process. High impact failures have high priority.

- **Step 2:** Determine the functions. The function of a system determines the action that it will perform. AR spatial mapping and tracking systems can be used for finding all major and less obvious failures in a system [23]. An operator can overlook less obvious failures, whereas the AR tool can capture and report all failures.

- **Step 3:** Describe failures. Overlapping virtual information to physical components, according to their real-world position, ensures identification of the failure. The operator can see that the virtual image and the real object are not in the same place.

- **Step 4:** Describe failure modes. A failure mode indicates how the system fails to perform its function [22]. Maintenance interventions such as checking, changing, and condition monitoring can be performed using AR.

- **Step 5:** Select maintenance action. Based on predefined actions and instructions, the operator can address the failure using tailored AR guidance and contextualization.

- **Step 6:** Document results. Technical manuals often recommend a maintenance method for certain equipment and systems. However, manuals or work descriptions are not often tailored to a particular operating environment and actual environmental conditions. The technology can capture the time needed for addressing the failure and what sequence of tasks has been performed. Hereafter, the technology provides a periodic intervention to eliminate failure to occur.

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Figure 1. Focus points of the adaptive architectural framework.
• **AR solution**: Select a flexible tool. This tool should assist the operator by systemizing the maintenance procedure. Besides this, the tool should contextualize and customize the information supply to the need and skills of the operator. This support tool should easily be embedded in everyday maintenance operations.

Figure 2 presents the use of AR within a maintenance problem-solving process. The focus of the AR support tool is put on sensing all failure causes, providing visual guidance in problem-solving, and alert the operator if a task is performed incorrectly. The tool also monitors and reports the time and sequence of steps required to perform the maintenance task. An accurate indication of the time needed to perform a task can be captured. Maintenance planning and schedules can be adapted to this information.

![Figure 2](image.png)

**Figure 2.** Added value augmented reality (AR) offers maintenance procedures adapted from Campbell [22].

2.2. **Operator 4.0: Augmented Operator**

Maintenance operations, in which the human workforce has a crucial role, need instruments able to manage complex systems. Nowadays most of the lower-skilled human jobs were eliminated and replaced by technology. This results in the remaining jobs becoming more complex, comprehensive, and increasing the importance of interdisciplinary cooperation [24]. Consequently, numerous complex, high-precision processes are and will be managed manually. However, many of them could collaboratively be executed by humans and interactive technology cooperation.

Several factors are important regarding work satisfaction and dissatisfaction, including the work environment, work organization, and whether the work is interesting [18]. The operator’s cognitive ergonomics, interests, and expertise should be included carefully since interaction with the real and digital systems is established. During this process, the operator’s physical and mental workloads are affected by both system and process features as well as by external factors. Operators produce a subjective experience depending on the surrounding environment, individual skills and characteristics, and task features [24].

In an augmented environment, the Operator 4.0 typology considered is the augmented operator [25]. More specifically, the augmented operator owns a superior knowledge of the working environment which is not only derived from the daily interactions related to the maintenance task or procedures, but it incorporates a variety of value-added contents that are suited to augment his/her skills and abilities to perceive and act within the working environment [26]. Operator 4.0 is expected to benefit from the information and guidance generated within the virtual context. Applicable resources that usually may not be available should be made available directly using interactive technology. Besides this, a remote consultation tool to get easy and fast information and advice, and a tool for safety and security enhancement has to become available. The AR technology ensures lowering the cognitive load of the operator, as the operator does not have to manually search for filter
according to the current context, or interpret information on a screen, rather they can visualize it directly on the target object [27].

From a business perspective, maintenance KPIs can be analyzed that allow managers to have a proper overview of workstations and production lines in real-time monitoring [27]. It becomes possible to identify, analyze, diagnose, and resolve errors to keep maintenance processes moving towards operational efficiency.

2.3. AR Capabilities

Nowadays, the operator knows the current state of a component by consulting a paper or digital work description containing the right configuration and information. Instead of forcing the worker to waste time consulting paperwork and interpreting the information provided into the work instructions, the proposed technology projects directly on the component giving accurate maintenance instructions and relevant information.

AR is considered key for improving the transfer of information from the digital to the physical world of the smart operator [28]. Moreover, AR has incorporating capabilities to new human-machine interfaces to maintain IT applications and assets. It displays real-time feedback about the smart maintenance processes and assets to the smart operator to improve decision making. This technology supports the smart operator in real-time during manual maintenance procedures by becoming a digital assistance system [27]. Hereby, the operator reduces the time used for reading printed work instructions and documents, looking into computer screens or tablets, and following strict procedures. Operators no longer need to run the risk of using old or outdated paper documents and instructions. Digital information systems provide operators with the latest updated information. Other advantages the tool provides for the operator are its ability to offer intuitive information and combining operator intelligence and flexibility with error-proofing systems to increase the efficiency of manual steps [29]. AR offers a powerful tool for supplying the operator with contextualized and customized information [30]. Altogether, AR can improve the quality, reliability, maintenance time, and reduce the failure rate.

Operator 4.0 will have access to the data coming from the train components and sensors in the maintenance facility. Besides this information source, knowledge can be gathered from other operators in the maintenance facility or even outside the facility from professional (social) networks. All information needs to be delivered to the operator and adapted, contextualized, and transformed to make it understandable such that decisions can be made resolutely and thoroughly.

2.4. The Need for a Dynamic Tool

As the complexity of the maintenance operations grows, proper support tools and approaches are required for the operator [18]. Research suggests that Operator 4.0 is required to be highly flexible and should demonstrate adaptive capabilities in a very dynamic working environment [31]. Therefore, a need exists for an AR tool to support the operator in his/her daily work. Depending on the task environment, condition of the asset, failure description, level of expertise, and operator experience, the AR tool must provide tailored contextualized and understandable information into the operator’s space in coexistence with real-world objects. To implement AR in the railway industry, the system has to be easy to maintain and modify. New content management tools are required as well as reconfigurability systems. The visualized information must be tailored to the operation and environment. Additionally, the way information is brought to the operator has to be studied. Future AR systems must be adaptive and able to systematically capture the operator’s intentions in performing a maintenance task. Besides this, it should collect the data of any maintenance procedure. The information collected could be used for improving the training process of the tool or the maintenance procedure itself.

Before the tool can function as a support system for the operator, a structured approach should be proposed to systemize the adaption process. As can be seen in Figure 1, the realization of the tool requires a structured framework.
3. Methods

The developed adaptive architectural framework aims at accelerating the adaption of information supply assistance that AR provides to the augmented operator. The framework will help to understand what information should be captured, why this should be captured, how it must be captured, and how the data is being reused for future AR experiences. In the following, the basics of the underlying decision support system, as well as boundary conditions and requirements are presented as they form the basis of this work.

3.1. Decision Support System

A human-centered approach to capture the knowledge of an operator is the decision support system. The AR tool is used to capture expert knowledge on maintenance task performance. The aim is to mimic how experienced operators make decisions based on using their experiences to form plausible approaches for new situations. Incremental learning for modeling complicated decisions support systems is required to quickly retrieve information by representing and organizing experts’ knowledge [32]. Gathering expert knowledge is vital for the development of (1) specific domain knowledge, needed to generate example solutions, and (2) general domain knowledge, needed to develop the reasoning structure. Applying an adaptive tool to a decision support system could assist a novel operator in a similar way to how an expert would use their experience to solve a problem.

The distribution model of cognition has been adapted for this framework and focuses on developing an ensemble of distributed individuals and artifacts [33]. This model considers two indispensable parts: internal and external representations. Internal representations are the knowledge structures in the operator’s head that can be retrieved from memory. External representations are the knowledge structures coming from the environment. The environmental elements help to make sense of the dynamic working situation by providing information on physical symbols, objects, dimensions, constraints, and relations embedded in physical configurations [33]. Besides this, the environment provides information on what task is expected to be executed and who will participate in the procedure.

The task that needs to be performed, together with both external and internal representations, contributes to the mental representation of a task solution.

Opportunities arise for human and intelligent systems to collaborate, learn from each other, and work together to achieve common objectives. Effective collaboration can be established if the interactive technology is logical, explicable, and able to understand the human cognitive processes [34]. A cognitive and interactive tool can learn and improve with an operator acting as a mentor for the system, based on his/her experience and knowledge, whereas the system provides feedback to the human in return [35]. For the operator, the process of providing feedback and interactions ensures both increased efficiency and developed confidence in the system [33].

3.2. Boundary Conditions

Technical and technological issues related to the development and implementation of AR are debatable elements. Most studies that review technological solutions for visualization either use mobile devices with camera-overlay AR or head-mounted displays (HMDs) with see-through AR [36]. Mobile devices need to be held in the hand when used and therefore potentially hinder maintenance tasks. HMD solutions leave the hands free, allowing for a more natural and intuitive hand-based interaction with virtual objects. However, sometimes a limited view can be experienced by the operator using HMDs.

Initializing an operator’s knowledge level must be established to verify the level of expertise an operator has. However, in real-life situations, it can be difficult to obtain an exact and reliable assessment of human competence. To estimate an operator’s competence, different data collection methods could be explored, such as interviews, testing at the workplace, using empirical methods, and maintenance task simulations [31]. The collection of input data for competence analysis can be achieved by measuring the execution time of
the maintenance task in the facility and evaluating the experiences of the technicians. For knowledge capturing, experienced operators must be recruited. To increase the effectiveness of the knowledge capturing method, a large number of operators should be involved which is important for providing decision support.

3.3. Architectural Requirements

The proposed architecture, apart from bringing together information from different digital databases, combines five major features by exploiting AR: (1) capturing the knowledge of the operator, (2) providing maintenance support, (3) performing failure analysis, (4) providing problem-solving strategy, and (5) providing learning capabilities. The adaptive architectural framework has been designed simultaneously while performing case studies. The studies are proving the value of the framework. The framework is based on the methodological decision support system and its main requirements include:

- Provide the augmented operator with real-time feedback and augmented reality content on tasks/procedures execution. Operators are guided by the supplying of visual and audible instructions to give tangible feedback.
- Based on expertise, experience, external factors, current conditions of the component, it is required to ensure the operator has a personal tailored digital knowledgeable assistant to interact with. Depending on the operator’s ability, noncritical information can be supplied using subtle instructions in different visible frequencies.
- By capturing the knowledge of the operator and procedural steps, the system can learn from previous maintenance procedures. The time and sequence of steps used to perform a maintenance task can be captured and reported. This can indicate how much time is needed in the future to perform the task. Moreover, failure rates can be compared to this information, providing insight on the most sustainable procedure. Maintenance planning and schedules can be adapted to these accurate findings. Therefore, the efficiency of operation support will be increased.

Based on the architectural requirements, a functional analysis is presented to structure and identify potential solutions that exist for the adaptive tool. In Figure 3, the most viable solutions are proposed. The analysis explores potential solutions for a given function, the solutions are variable.

Based on the functional requirements from Figure 3, the architecture in Figure 4 has been designed and implemented in the maintenance process analysis of Figure 2.

- **Step 1:** Select equipment. The goal to be achieved is formulated. The operator will be guided by visual and audible instructions which also give tangible feedback.
- **Step 2:** Determine functions. The task that needs to be selected to reach the goal is stated. Besides this, the adaptive AR tool provides all failure causes and digital information on all potential solutions. It will let the operator be aware of the context to gather relevant information and/or services, relevancy depends on the operator’s tasks [37]. Using context awareness systems, such as AR, accurate access to maintenance information is provided such that the operator’s performance efficiency can be increased.
- **Step 3:** Describe failures. Initiation and evaluating the operator’s expertise is currently based on the operator’s or manager’s perspective. The level of expertise varies from having no clue what is going on up to being an expert and able to train others. In this framework, initiating the level of expertise is performed manually but can become an automated process in the future. Operators can be equipped with sensors to activate psychomotor and cognitive responses that are beyond what operators can verbalize. Capturing gestures of experts can improve interactions with AR and ensures future knowledge capturing [33].
- **Step 4:** Describe failure modes. Dynamic behavior capturing is required to perform a successful fault diagnosis [33]. Based on time and process tracking, the operator should know what initiated the fault, what the current situation is, what is needed to solve the issue, and what time is required to solve the task. Varying business demands changes
in work routines, resource availability, and environmental conditions. Depending on the complexity and nature of the maintenance task, the operator adapts his/her maintenance concept.

- **Step 5:** Select maintenance action. The tool presents the task that aims to restore the functionality of a system. The actions that can be performed to restore the functionality of the product can be technical, administrative, and managerial [30]. Continuous assessment takes place of the operator’s performance, task condition, and other external conditions. Besides this, the tool will send warning messages of improper maintenance operation execution. When the task or business demand increases, mental demand increases resulting in negative effects on physiological variables [38]. The likelihood that the operator fails in performing his/her task becomes subsequently larger, it is therefore needed to have a control or monitoring system that alarms the operator when tasks are not performed adequately.

- **Step 6:** Documents results. Documentation can support the detection of schedule derivations or the search for sources of defects and the responsibility of the operator [39]. Adequate process monitoring methods help managers and operators to document the current status of the maintenance work as well as to understand origins and defects. Some maintenance tasks require inactive input, for instance, to leave comments on specific objects. AR allows storing these annotations directly in relationship to the real environment.

- **AR solution:** Select a flexible tool. Incorporating different types of data, interfaces, visualization systems and sensors makes the adaptive tool applicable to multiple solutions.

![Figure 3. Functional analysis of adaptive capabilities and potential solutions.](image-url)
4. Case Study

The purpose of a case study is to explore and depict a setting in which the researcher exploits data from direct observations, systematic interviewing from public or private archives [40]. This case study aims to increase understanding of the need for having an adaptive architectural framework to support Operator 4.0. The case study helps to identify technology adaption patterns, defining requirements needed to support the operator, and providing future steps needed for application in maintenance operations.

4.1. Case Study Characteristics

In this research, one single case study is examined for validation of the framework creating the opportunity for in-depth observation. This framework allows for a two-way learning system. More specifically, not only does the case study present the effects of the framework, the framework iterates after the case study is explored. An example of using one single case to examine reengineering service operations is performed by Narasimham and Jayaram [41]. Other research focused on motivating operators to take active decisions when transforming IT function profiles in healthcare organizations using one single case study [42]. More recent work examined the process of resource alteration underlying the digital manufacturing journey using a single case [43].

The Dutch Railway company (NS) is a Dutch state-owned company and the principal railway operator in the Netherlands. The Dutch rail network is Europe’s busiest and will only become busier [44]. Among others, NS aims to achieve safe, sustainable, and reliable operations in which technological developments are key [45]. The company recognizes the added value Artificial Intelligence (AI), Internet of Things (IoT), and AR have to improve
services and contribute to efficient operations. Additionally, they have noticed that the coronavirus is accelerating digitization and technological developments. In short, NS offers great opportunities to exploit a case study for framework verification.

Several information sources have been used through the research such as interviews, managerial presentations, student thesis on maintenance operations, public, and internal documents. Multiple interviews with managers and operators were held online. The participants were selected based on their knowledge of innovative technologies, data collection and management, and maintenance operations. In total, 28 participants were interviewed of which the majority are part of the NS technical department. This sample size represents 35% of the total sample size and is sufficient for this specific knowledge field [46]. The length of the interviews varied from 30 minutes to 1 hour. The interviews provided deep insight into actual focuses, potentials, and challenges that the case should include. Based on the information sources, a case description was prepared and verified by the company. To increase the validity of the framework, the completed version was discussed, completed, and improved together with the company.

4.2. Investigation of the Retractable Step

Previous research was conducted within the Dutch railway industry for adopting VR technologies for training and skilling of employees, and to assist train drivers during specific operations [47]. In this research, the focus was put on increasing operational and training efficiencies. Notwithstanding the positive results AR can achieve, there are still a few questions that remained unanswered about the employability of this emerging solution. The verification of the usage of this adaptive architectural framework can be performed by exploring a case study for NS. For this case study, the Fast Light Innovative Regional Train (FLIRT) type is further examined. This train is a passenger electric multiple unit trainset [48]. All interviewees agreed on the validity of the framework using this case. The railway company investigated the failure mechanism of the FLIRT electric door system in which the retractable step caused the system to fail repeatedly [49]. This system serves to bridge the gap between platform and vehicle. Within 50 operation days, 187 services were requested for the door system. Since the deployment of the FLIRT train series on the Dutch railways in 2016, 1099 service requests were already made in 2017 [47]. The door system failure accounts for 17.4% compared to other failing components and is only surpassed by the communication system of the train which represents 27.5% of all failures [47]. The failing door system has, therefore, a high priority since it has a direct and great impact on train operations.

4.3. Failure Description Retractable Step

Product description of the system is based on the technical documentation of the retractable step [50]. The entire system consists of the sliding step and the connection cable to the control unit. The extension unit basically consists of a frame in which the walking zone is stored. The walking zone is equipped with a step sensor and anti-slip coating. The drive takes place by means of a DC motor. The motor is mounted on a compact drive-bearing unit. The driving force is transmitted from the motor shaft via a hollow shaft to a toothed belt wheel. The toothed belt wheel drives the central drive belt. A carrier on the toothed belt established the connection with the sliding step and converts the motor drive power into the extension movement of the extension unit. The sliding step is guided by profile rollers on the extension unit. The upper and lower rails are both made of stainless steel. The profile below the lower rail is made of aluminum. If a vertical load of 150 N or more is applied to the sliding step during extension or retraction, the movement is stopped immediately. A schematic overview of the train door retractable step system is provided in Figure 5.
According to the research performed by NS, the FLIRT sliding step causes many problems [49]. The most critical problem is that the retractable step gets stuck due to clamping. In that research, clamping was caused by the fact that the left rail was raised about 2.4 mm. To find out why the bottom rail came up, a destructive test was performed. The part of the aluminium profile at the height of the elevation was cut out and the lower rail was removed. Details of the side profile with rollers are presented in Figure 6.

The rise of the lower rail was caused by the formation of aluminum oxide between the stainless-steel rail and the aluminum profile. More specifically, it was caused by galvanic corrosion of the sliding step. The volume of aluminum oxide pushes the bottom rail up by 2.4 mm.

4.4. Application Adaptive Architectural Framework

The application of repairing the retractable step in the designed adaptive architectural framework is presented in Figure 7. General specifications for the application of the framework to this case are:

- Decisions are made based on the operator’s perspective on his/her level of expertise. Let the amount of AR information and frequency of information supply be adapted to the specific user, task demand, and business demand.
• Knowledge is captured from expert operators to use their experience to assist a novel operator to solve a problem. General and specific domain knowledge should be gathered to provide an incremental learning method. The time needed and sequence of steps of the procedures involved can be derived from the task performance. Hereby, the operator and the company capture detailed knowledge on the procedure to become more efficient and adequate problem solvers.

• Safety and security measures should be taken into account more consciously. The framework ensures sending warning messages if procedures or tasks are not performed according to procedures or safety standards.

Figure 7. Applied case study for the designed adaptive architectural framework.

Some functional solutions from Figure 3 can be used for the case study by setting adaptive capability requirements. All solutions directly affect the user’s interactions with the AR technology.

5. Discussion of the Main Results

The case study represents a unique endeavor about the importance of having a structured process to ensure support is provided to Operator 4.0 using AR. This adaptive architectural framework reveals what technology adaption patterns are identified. Besides this, requirements are provided to support Operator 4.0 in his day-to-day work. Finally, future trends are examined from the point of view of maintenance work.

5.1. Technology Adoption Patterns

Looking for technology adoption patterns, this research emphasizes the perceived ease of use of AR technologies, the perceived usefulness of the technology, and having self-explanatory systems. This contributes to better expectation management interaction and acceptance between the operator and the AR tool. Still, a lot of other technology adoption patterns can be found due to a lack of understanding of key challenges and success.
factors. Multiple hardware solutions can be proposed to enable adaptive instructions to operators. Research has been performed to assess AR tools to be implemented for practical everyday use [20]. This research investigates usability together with the achieved levels of productivity and quality. It was concluded that facilitating the operator with adapted displayed instructions is not only useful for novel operators but also experienced users. Not only hardware is important when it comes to technology adoption, ergonomics includes even more aspects of user acceptance. The study revealed that an inadequate design of the user interface can lead to distraction or disorientation [51]. Apart from the adoption patterns mentioned before, the case revealed the importance of having an analysis of mental and physical demands. A recent study supports the main findings of the case study and identifies success in adopting AR in the industry by achieving: user acceptance, visibility of information, ergonomics, and usability of the user interface [52].

5.2. Support Requirements for Operator 4.0

This research suggests information provided to the operator should be based on real-time, contextualized, and customized data. The information supply (and the related user interface) should be tailored to the expertise and experience of the operator, component condition, and other external factors such as organizational demand. The application of different visual computing technologies in industrial operator tasks was presented by Segura et al. [27]. They presented several cases to show how proper visual analytic systems can support the operator to better understand and easily detect wrong production situations. Their research emphasizes the need of adapting and balancing procedures with the experience and expertise of the operators. As suggested by earlier research, Operator 4.0 can be empowered by adapting the machine-user interface, machine behavior, and planning [18]. Based on the operator, user interfaces of the AR tool could be adapted to allow only showing functions that the worker understands. This will facilitate in identifying the role of the operator, AR capabilities, and maintenance operations.

5.3. Future Trends in Maintenance Operations

The case study depicts the ability to have an automatic data capturing process while also having a dynamic multiple feedback system. Capturing maintenance operation data and knowledge of the operator contributes to incremental learning capabilities. Consequently, maintenance planning and schedules can be adapted to this. Hence, future operations support increases. Digitized systems recognize changes in operations and continuously updates component performance [13]. Thus, ensuring optimum efficiency is always achieved. The maintenance operators can be supported with real-life instructions, diagnostic information, and remote assistance. However, the economic, environmental, and social challenges faced by the AR industry still require further investigation [21].

6. Conclusions

Although much progress in AR has been made in recent years, little attention has been paid to correct the integration of humans in the emerging context of AR in professional industrial (engineering) environments. A human-centered approach is necessary for the successful adaption of AR technology tools for the railway industries. Operator 4.0 will play an important role in facilitating the transition from traditional maintenance procedures to remotely, digitized, and autonomous operations. Few in-depth studies assess and evaluate human factors and interaction in (industrial) AR systems [27]. Attention has been drawn to operators as a key element to address new and unpredictable behaviors in AR. Since operators experience an increased complexity of their daily tasks, an adaptive tool is desired to support the operators. Based on the operator’s competence, expertise, component condition, and external factors, the tool will provide contextualized and customized information. Looking at the spread of previous research, we conclude that they were all considering the need of (1) supporting Operator 4.0 interactive technology and (2) supplying tailored based information [18,25,53]. However, before tailored-based
information can be supplied to support the operator, it is required to structure the process to enable systemizing this approach. Therefore, this research bridges the gap between the need to support operators using an AR tool and the approach of providing this.

The main research contribution is twofold: (1) proposing an adaptive architectural framework aimed at shaping and structuring the process that enables a systematic approach to provide a support tool to operators using an AR tool, and (2) a case study that implements the aforementioned framework. As a result, an adaptive architectural framework is suited to augment the operator’s skills and abilities to perceive and act within the working environment. This digital assistant tool supports the operator with vocal and visual interaction capabilities. It is meant to provide quick, tailored, and efficient information on maintenance tasks.

The adaptive architectural framework can: (1) capture the knowledge of the operator, (2) support the operator in performing maintenance tasks, (3) conduct failure analysis to find all potential failure modes, (4) provide all problem-solving strategies, and (5) improve learning capabilities by documentation of procedural task performance. This framework can be adapted to be able to absorb and immerse the environment for preliminary training on new or complex procedures. To this end, the proposed adapted architectural framework is scalable and modular since the principle can be applied to different industries and infrastructures.

Many companies are considering implementing AR solutions to their maintenance operations and are willing to perform several experiments using the technology [52]. From the proposed framework, we suggest managers start exploiting opportunities for AR technology application fields. In a maintenance workshop, operators are directly linked to AR solutions. In our case company, we witnessed the relevance of structuring the process of providing customized and contextualized data to operators. Using this framework, operators will find all potential failure modes of a component and define all problem-solving strategies needed to solve the issue. Therefore this framework increases the safety, efficiency, and availability of the operators. However, managers should be aware that the decision of this trajectory is costly. Besides the costs, managers should bear in mind that using AR strategies is only an intermediate element of the digitization of the company structure. Furthermore, the development of AR technologies continues and, therefore, organizations should be ready for frequent iteration and adjustments in application strategies.

Industry 4.0 is still an open research field where already much has been done but there is still more to do to accomplish its vision. This research proposed a forward-looking adaptive framework for Operator 4.0. From a technical point of view, additional work can be done to improve and optimize the technical performance of the framework in terms of capturing the operator’s knowledge and transforming this expert knowledge into a database for the development of a decision support technology [32]. More specifically, future work is required in the specification of the expert-level of the operators. Capturing knowledge is currently based on the perceived perception of the operator or manager. However, knowledge capturing should become autonomous [54]. In addition, verification and validation of the framework can be performed in a simulation and experimentation setting. A methodological limitation of this research is the use of one case study. Adding to this, the case was based on a limited number of interviews. The case provides useful information on an emerging topic like AR. But one case is still not enough to draw generalisable conclusions. The external validity of the research could be enhanced by examining other companies in a similar situation. In terms of research perspectives, future work will be needed toward the development of prognostic capabilities. Integration of sophisticated algorithms for real-time monitoring and process control will support maintenance operations.

Finally, the close relationship with the case study enables us to follow up its journey in the future. Efforts and the involvement of other managers bear the opportunity to continue the current case.
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