# Towards Adaptive Quality Assurance in Industrial Applications

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***Abstract*—We propose the AQUILA framework (Adaptive Quality Assurance in Industrial Applications) for digitalization in Industry 4.0 to support the entire industrial manufacturing chain, laying the groundwork for adaptive quality assurance in times of disrupted supply chains and, due to the COVID-19 pandemic, restricted travel possibilities. To that end, our proposed framework allows for the definition and description of industrial processes, quality assurance and testing protocols, and training scenarios in a comprehensive notation based on BPMN, and supports users in task execution, documentation, and evaluation by providing smart glass-based HCI with eye tracking technology, delivering a combination of process documentation, context-sensitive AR visualization, gaze-based interaction schemes, and remote maintenance and assistance functionality.**

***Index Terms*—smart manufacturing, process modelling, cyber-physical systems, smart glasses, augmented reality**

## I. Introduction

Supply chain disruptions and rapid changes of customer demands, along with the increasing complexity of supply networks and globalization, are just some of the multitude of elements that threaten supply chains and the viability of manufacturing companies [1]. Flexibility is one of the antecedents of resilience, i.e. the capability of an entity to return to its original or a better state after absorbing a disruption. The transition to modular technologies and sustainable production to enable varying batch sizes and reconfigurable manufacturing systems can be one crucial element for companies to face the changes, as it lowers financial risks and costs while increasing flexibility and response capacity to changing circumstances. These features are particularly relevant for companies operating in volatile markets and providing innovative products with short life cycles [2], [3]. However, the efficient use of modular manufacturing systems requires frameworks, models and relevant identified use cases to highlight its applicability, especially for SMEs.

In the AQUILA framework (Adaptive Quality Assurance in Industrial Applications), we propose the implementation of a digitalization methodology for automated or semi-automated assistance in modular production environments. The framework would enable industries to create, structure, document and evaluate manufacturing processes in an adaptive, modular fashion. This methodology would be applicable for small and medium enterprises, as well as large production enterprises.

The methodology is based on the following principles:

- **Production Formalization**: define and formalize a production station, step or process.
- **Quality Assurance**: based on the formal description, create a quality assurance procedure of the industrial process.
- **Workflow Monitoring**: using process-appropriate sensor systems, create a method for automated workflow monitoring and quality assurance.
- **Standardization**: ensure conformity of the industrial process to relevant regulations and standards.
- **Employee Well-being**: use process data to minimize employee health risks and limit both physical and mental strain, while ensuring the user's privacy and data protection rights.
- **Remote Assistance**: enable knowledge transfer and ensure production efficiency by allowing users to remotely connect to distant colleagues, using the framework to support processes from afar.
- **Training**: use the framework to create and deploy training material, and evaluate training progress in a competency- and evidence-based fashion.
- **Security and Data Protection**: collected data on processes, available training data and access to visual information on production processes need to be secured and only available to assigned users.

All steps above would be linked together using modern software tools, allowing a high level of automation and digitalization. The goal is that this methodology can be applied by companies of different sizes and with different requirements, negating the need for specialized software or tools by a third party. The framework will be implemented in different use cases which span the spectrum from small-scale SMEs to large batch manufacturing enterprises. In cooperation with other partners, a baseline will be established that binds standards, user experience and other topics related to the overall story, aiming to prove that this methodology is scalable also to larger production processes and that it can be applied as a generic blueprint when building new production lines. To ensure the success of such an endeavour, the industry relevance has to be ensured by considering also the scalability of use cases, humans, ethics and privacy.

The greater aim of the endeavour is to improve industrial manufacturing and quality assurance processes, making them more worker-friendly, energy- and resource-effective, and to render them more resilient against the increasing risk of disrupted supply chains. Furthermore, in times of COVID-19, a particular focus is set on remote assistance, allowing for expert guidance over long distances without the need for travel or direct personal contact.

## II. Objectives

The AQUILA framework combines different methodologies from along industrial process chains, from process notation and documentation over adaptive guidance techniques to quality assurance and training evaluation. It aims to deliver a comprehensive solution that effectively addresses all these aspects and to realize them in industrial use cases. To that end, the framework is structured along four key objectives:

*1) Architecture:* AQUILA will evaluate methodologies and tool sets, in particular based on open-source protocols, to create a framework in which quality assurance functionalities can be created, applied, and evaluated for a range of industrial manufacturing scenarios. Based on a modular design paradigm, the framework will establish the network and module structure with a focus on interoperability and lay the groundwork for documentation, quality assurance and evaluation functionalities. The framework will further support flexibility in operation by allowing for secure remote connectivity, enabling users to provide remote assistance to colleagues across the globe.

*2) Documentation:* Based on the Business Process Model and Notation (BPMN) standard, the framework will realize a system which allows for the automated creation of process documentation. By integrating relevant industrial standards, the system will establish a common language for use case processes and quality assurance protocols, ensuring straightforward adaptability of modules under rapidly changing circumstances, the automatic generation of evaluation and testing protocols, and the provision of key metrics such as quality assessment, energy consumption, and environmental impact. Furthermore, the framework will establish thorough security analyses and ensure user anonymization and data protection.

*3) Quality:* AQUILA aims to ensure production quality by focusing on two main aspects of data in manufacturing. First, data pertaining to the manufacturing process will be collected and evaluated, based on the process documentation system in objective 2, and the modular integration of use case-relevant sensor systems. Second, the user in the manufacturing process will be provided with data based on adaptive and pervasive principles, i.e. supplying appropriate data only when necessary, and when the user is receptive. To that end, users will be equipped with eye tracking smart glasses, allowing for both the display of relevant process data and implicit control schemes based on gaze movement. Remote maintenance and assistance functionality will be realized using the smart glasses hardware. Where appropriate, user parameters such as attention state and cognitive load will be integrated into the evaluation of training processes.

*4) Relevance:* The AQUILA framework is intended to realize industrial use cases, ranging from small-scale assembly processes to large batch-size precision manufacturing. For each use case, the framework will be used to generate process documentation and QA evaluation, demonstrating the system's capacity to both react to shifting environments, and to improve upon operational parameters such as resource and energy efficiency. As industrial use cases will differ both in scope and purpose, the modularity of the framework will be demonstrated by utilizing only the relevant modules in each use case. Training scenarios will be realized, going beyond industry standards by being built on competency-based principles: integrated sensor assessment allows for an evidence-based evaluation of training progress both in terms of the trainee's attentive state, and the outcomes of the training task.

## III. Methodology

### A. Architecture

AQUILA aims to realize secure, distributed, and reconfigurable modular manufacturing systems based on Service-Oriented Architecture and micro-service principles. To that end, frameworks and toolsets suitable for modular manufacturing systems will be evaluated, considering digital twin concepts to represent as proxies machines and other assets used for production, thereby providing high availability, persistent state, protection, and security [4], [5].

We will also study means for them to connect with each other to create Systems-of-Systems (SoS) that can be changed at run-time to dynamically introduce, change, reorder, and/or remove production steps. Such capacities can be developed based on secure-enhanced flexible, reliable and timely completion of IT-related processes, known as DevSecOps [6], combined with concepts introduced by Eclipse Arrowhead [7], [8]. With these capacities, we aim at facilitating modular and flexible production systems that can easily be adapted in response to varying customer demands and disrupted supply chains.

We will furthermore utilize the digital-twin approach to enable proactive production planning, quality assessment, analysis of environmental aspects and energy use, exploration of end-user aspects, and investigations of alternative business models related to demand and supply chain variations. Functionalities connected to the industrial use cases will be in focus, including real-time remote assistance functionalities [9] and situational impact on quality in terms of sequencing and automatic assembly line kitting [10].

### B. BPMN Integration

Precise modeling of organizational business processes is essential for their correct execution and their further use in other domains, e.g. translation into software artifacts [11]. Business process management (BPM) recognizes this need for modeling and documenting business processes with several notations developed over the years, of which BPMN is the de facto standard for hierarchical process models in the industry [12]. Redesigning business processes can be an appropriate matter to facilitate organizational resilience and respond to volatile market environments. These redesigns rely on robust existing models that can be analyzed, refined, or replaced [13]. Documenting business processes is often conducted manually with significant effort. In contrast, more innovative ways to automatically document processes rely on event logs in process mining operations, referred to as automated process discovery. The process model is the output generated from the event log as input. One example of automated BPMN model generation is the BPMN miner [14], which relies on a specific set of event records to create a relational table and then utilizes dependency discovery techniques to produce advanced BPMN models. The model is only functional for small-sized logs with predefined and specific data attributes. Other approaches for automated discovery methods have been developed, like the Inductive Miner [15] or, more recently, divide-and-conquer techniques [16]. However, these methods suffer from producing flat and large models that often poorly fit the real-life processes [17]. These issues are also due to the need for targeted documentation of the processes in the event logs. This aspect becomes more relevant, especially for adaptive and flexible processes in modular manufacturing, as remote capability and support by Industry 4.0 technologies add to the importance of accurate documentation.

AQUILA thus aims to advance the state-of-the-art by developing a method to automatically document modular manufacturing workflows, including deriving suitable data structures and integrating existing standards. The automatic documentation in BPMN allows for the subsequent analysis and refinement by qualified experts and re-use in other information systems to evaluate key metrics, including quality assessment and environmental impact of modularity.

### C. Smart Glasses and Eye Tracking

Smart glasses are head-mounted wearable electronic devices enabling human-computer interfaces. Unlike other kinds of head-mounted devices, smart glasses do not obstruct the user's visual field, allowing the overlay of digital content onto the real world visualized by the user. Using different sensors and transmission protocols [18], together with diverse display technologies [19], they allow for the acquisition, transmission, and visualization of key information for the user's interaction with his environment.

Although in 2011 the optical technology company Vuzix announced a line of augmented reality glasses with transparent displays [20], the world's first major milestone in the development race for smart glasses was the I/O Google 2012 [21], in which Google released the Google Glass. After that, many other technological companies such as Microsoft, Sony, and Epson released or announced their own smart glasses. Although much progress has been made in recent years in relation to ergonomics, weight, and processing speed, there is still a way to go, especially when considering user comfort [22] and display technology [23].

Smart glasses are making headway in different fields, such as industry, health care, service and education, amongst others [18]. A study from 2015 showed that 93% of large industrial companies were either using or evaluating their use [24]. In 2016, an estimate from Forrester predicted over 14 million workers will use smart glasses by 2025 [25]. Furthermore, the disruption caused by the COVID-19 pandemic has accelerated digital transformation, and due to the social distancing measurements and travel restrictions, has broken down many barriers for the adoption of new technological solutions, especially those related to remote support [26], [27].

Industrial production is reaching astonishing levels of automation and digitalization. However, digitalization and automation investments must be justified with product demand and in line with company productivity and growth plans. Small and medium enterprises often lack both capital and long-term strategic plans to be able to cover these costs. Therefore, it is essential that there are open methodologies and frameworks where all types of enterprises can effectively perform digitalization and automation in a standardized and verified way. These tools and methods need to be industry-agnostic and scalable such that they could follow growth of the enterprise in the future. Smart glasses have the potential to serve as an essential technology for a modern, safe, reliable, and worker-friendly factory, and to effect an increase in awareness of employees, augment classical interfaces, monitor physical and psychological health of a person, increase efficiency and ensure remote presence and assistance.

In the AQUILA framework, the use of smart glasses in the field of modern computer-based industries will allow for an efficient process formalization and quality assurance. It will achieve this by integrating automation and standardization; workflow monitoring, analysis, and simplification; monitoring and assurance of employee well-being; hazard identification and risk reduction; greater effectiveness of training and workforce interaction; and remote assistance.

A particular benefit of smart glasses technology combined with AR overlays, such as offered by the VPS 19 system [28], is that a single wearable solution can be used for user-state tracking, input modalities and visual guidance. By observing a user's gaze behaviour, valuable information can be gleaned into whether they require assistance or are interacting with the relevant piece of equipment at the time; the AR overlay allows for hands-free display of process-relevant information, giving the user access to data pertaining to their current work step; the combination of AR display and eye tracking technology allows for gaze-based interaction schemes, where simply by looking at a specific part of the display or moving the gaze in a specific pattern can trigger control signals to the system [29]; and by means of pupillometry, a measure of the user's mental load can be derived from their pupil size adjusted for ambient light conditions via a modeling of the pupillary light response [30], [31], allowing for valuable input in training scenarios, where the state of trainees can be monitored for optimal training progress and evaluation. Tracking of such person-specific data will be handled to the highest standards of ethics and privacy, establishing anonymization or pseudonymization standards where appropriate, ensuring transparency in communication, and making all participation in use case and training scenarios fully voluntary.

### *D. Remote Assistance, Maintenance, and Training*

Remote maintenance applications are already used in modern computer-based industries to save important time and money for various manufacturing sites, and the adoption is on the rise. The internet of things (IoT) offers novel solutions and technologies to increase remote applications in manufacturing sites and external remote applications, and AR applications are becoming more accessible and easy to integrate [9], [32].

In precision manufacturing with increasing automation and digitalization levels, loading and unloading in modern facilities is done by fully automated systems. Operators and maintenance specialists within the shift have to monitor and control the factory automation from control stations using remote functions to ensure stable production. Such production must be controlled 24h / 7d per week and the first level is controlled remotely during the shift. The second and third support level is normally provided outside the shift by highly educated and qualified engineers. In case of troubleshooting or highly complex failure analysis, most of the problems are remedied by phone calls or exchange of emails between different experts. Especially during the COVID-19 crisis, with limited access to factory buildings, there was a strong need to increase remote capabilities and possibilities to control different machines and processes externally. Training of operators and maintenance experts are performed using targeted training plans and units; if new tools are ordered, there are training slots available at the supplier and experts are trained within the guarantee / warranty period of the equipment. The training is performed outside the companies, so travelling costs and time is spent on training, and the documentation is often only available in script form.

First virtual training programs have already been implemented in the precision manufacturing industry [33], helping to improve the efficiency of the maintenance workers and providing training for new employees. Using more cyber-physical training programs, as well as digital twins and virtual and augmented reality, valuable time and cost-savings could be made: repetitive tasks in the production line could be reduced if these tasks — which are comparatively easy for an operator to solve, but difficult to automate — could be instructed remotely by a qualified employee using smart glasses. Furthermore, evidence-based training methods can be realized, with quantified insights into the trainees' task execution performance being made available for review.

The AQUILA framework proposes an approach to formalize production processes and provide non-invasive automated quality control methods for these processes using smart glasses or other wearable devices. Functionally, this will be built upon the process modeling described in section III-B, integrating object or event recognition based on either computer vision or machine learning approaches, and combining remote maintenance support capabilities with smart glasses AR and eye tracking technologies as described in section III-C. This combination will enable automated quality control of the process while maintaining the health status of a human worker monitored in real-time. Finally, training schemes that go beyond rote learning of protocols can be realized by evaluating data obtained pertaining to trainee attention, mental load, and task execution performance, and by using this data to supply feedback and assistance to the trainee.

## IV. Industrial Use Cases

The AQUILA framework is designed to be applicable to a range of industrial use cases. Three types of use cases are presented here, demonstrating the industrial relevance and applicability of the approach.

### *A. Use Case 1: Digitalization of complex assembly processes via Smart Glasses*

The vision of use case 1 (UC1) aims at digitization of assembly processes in production lines, where it is essential that each precision step can be adequately verified and that the output from a production process or stage can be attested on quality.

The goal is to create a methodology where a strict precision assembly process can be described in a formal way, and then verified and tested using the VPS 19 [28] smart glasses. The glasses will be used to visually acquire the environment (tags, markers, objects) and to monitor behaviour of the person operating the station (eye fixations, eye movements, cognitive state), constituting a next-generation human-machine interface that allows for a combination of information from the environment with biometric data from the human body. By merging these data, it is possible to extend the capability of an ordinary person, and also to observe emerging behaviours and interactions between a human and its digital or physical environment.

This methodology can be applied to observe experienced personnel to avoid potential health risks that could occur due to overworking or increased cognitive stress. This method can also be used to support personnel in training where we would be:

- Allowing for documentation of processes, identification of components, and creation of testing and validation procedures using BPMN notation;
- incorporating the VPS 19 smart glasses in a formal process, allowing for automated verification of steps and components;

- creating improved training scenarios using the eye tracking hardware to measure quality-related metrics, allowing for better feedback and improved learning uptake; and
- evaluating the human-centered production tasks and the cognitive load imposed on the employees during certain tasks or operations.

### *B. Use Case 2: Enabling Large-scale Precision in Manufacturing*

The vision of UC2 is to enhance manufacturing efficiency and stability in highly automated workplaces using remote control and smart glasses.

With the increasing automation and digitization level in the front-end manufacturing, the efforts for monitoring and controlling the different components are strongly increasing. In parallel, the knowledge and efforts to maintain the technologies are also drastically increasing. The aim of the use case is to improve quality and process efficiency in different aspects of the production process by expanding remote and predictive maintenance activities, and by improving training quality, reducing training time and dropout rates. The IoT and sensor integration offers new methods to increase the remote level even for older tools, which will help to increase production and maintenance efficiency.

The key goals are:

- Enabling large-scale precision manufacturing and increase and improve remote maintenance activities, support and advice using advanced remote capabilities and smart glasses to enhance the remote level in maintenance and manufacturing areas;
- introducing and expanding predictive maintenance, e.g. by monitoring anomalies in the factory with the aid of smart glasses;
- utilizing the framework to provide training and teaching material (competence-based and evidence-based training) for junior workers and enhance working efficiency by detection of quality-related metrics; and
- improving up-time and maintenance efficiency of high automation components e.g. material automation and handling components using enhanced remote capabilities, advanced control technologies and training for line experts and engineers to enhance the supply chain stability and factory output.

### *C. Use Case 3: Constraint-based Modelling for Component Assembly*

The use case vision is to increase productivity in assembly lines and to better assimilate variance and unforeseen disturbances.

In many industrial applications, assembly sequences are mapped out in advance and are made with a ”sunny day” assumption many days before, meaning that everything must thereafter work perfectly according to the plan. Plans may be released only days before production, and have strict sequencing of the operations to be performed per component and the order of the components on the line. Consequently, any “real life” changes hitting the plan cannot be treated in a given day’s solution.

The goal of UC3 is to develop a solution where plans are based on partial ordering rather than being strictly ordered, and where serialized schedules can be generated and simulated beforehand by software. We will develop a conceptual decision support tool (software) for engineers to create partial orders and to auto-generate proposals for serialized schedules per vehicle. We will develop a simulation tool to test and review proposed serializations. The tools can be used to find and validate serializations per assembly product and sequences between products before approving them. Recalculation can be done when reasons occur, something which is not possible today. In this, constraints relevant to the objective must be defined on the components and the assembly line (e.g. some assembly tools may be fixed to some stations and cannot be moved, while others can be moved around) to generate realistic schedules that can be tested and validated through the assembly line simulator.

This use case constitutes a fundamentally complementary application of the AQUILA framework when compared to UC1 and UC2, as it does not rely on smart glasses technology. Instead, it constitutes a testing ground for the process modelling and quality assurance capabilities of the framework, demonstrating the modularity of the approach and its ability to adapt to different use-case geometries and requirements.

## V. Summary

The proposed AQUILA framework intends to realize functionalities along the full industrial manufacturing process chain, aiming to deliver a solution in which industrial processes and products can be formalized in a standardized setting building on BPMN, and protocols for quality assurance and testing can be generated. By integrating smart glasses technology, the framework will utilize wearable eye tracking combined with an AR display to enable hands-free display of process-relevant interaction, mental load monitoring, and gaze-based interaction schemes. The combination of these technologies will allow for quality assurance and testing protocols to be implemented and evidence-based training scenarios to be realized. The framework is planned to be applicable to a range of industrial applications for larger organisations as well as SMEs, where use cases can be designed, implemented and refined. The partnership is looking forward to realizing a shared vision of an improved industrial manufacturing process, which will allow for better use of energy and resources, increased resilience to supply chain disruptions, and integration of workers with improved information provision, input modalities, and training schemes.

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