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Enhancing resilience on the shopfloor through data and service ecosystems - an industrial pre-pilot

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Abstract

In volatile markets, resilient supply chains and shopfloors are essential to mitigate the impact of disruptions, such as crises, machine failures or quality issues, which result in significant costs. To address these challenges, information about products, processes and resources is required to design, test, and deploy resilience assessment and reconfiguration tools. Nowadays, this information is intended to be made available through data spaces and ecosystems, which necessitates preserving the data sovereignty of the respective companies involved. The architecture proposed by the Flex4res project accommodates these requirements. The implemented pre-pilot use case allows testing and eases the transition for companies.

Keywords: Asset Administration Shell; Ecosystem; Data Space; Gaia-X; Resilience

1. Introduction

Resilience has become a fundamental concept across various domains, commonly associated with "the capability and ability of an element to return to a stable state after a disruption" [1]. Especially, in today's volatile economic and industrial environments, resilience is particularly relevant as it enables organizations to respond effectively to disruptions, sustain operations, and adapt to changes [2]. Building resilience in industrial and manufacturing contexts requires comprehensive data integration along value chains, encompassing both inter-organizational participants and intra-company levels [3]. To enable data sharing across various levels: from supply chains to shopfloors and down to specific resources and equipment, Alexopolous et al. [4] suggest the application of data spaces to enable data exchange between different participants [5]. Strnadl and Schöning [6] give an extensive explanation of data space terminology and also define data ecosystems as a subset of ecosystems allowing core value propositions enabled by the sharing of data. They furthermore argue for the importance of maintaining data sovereignty in data-driven marketplaces.

On the shopfloor, high reconfigurability and resilience are required due to the high variability in production demands and product specifications. Discrete production usually follows production steps with varying manufacturing technologies e.g. sawing, milling or drilling, each requiring specialized machinery or necessary operation capabilities limited by product parameters like size or shape. Machine capabilities vary due to factors such as tool type and condition (e.g., saw bands on sawing machines; wear of cutting tools), necessitating flexible and responsive production planning and scheduling that considers current machine states and resource availability. Thus, an agile manufacturing approach with real-time transparency is advantageous to quickly adapt production schedules to the dynamic requirements of product features and machine capabilities.

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Currently, most work regarding resilience in data and service ecosystems is conceptional or in proof-of-concept laboratory environments, characterised by a low Technology Readiness Level (TRL) of 2-4. Industry-relevant TRL case studies (TRL 5-7) are still missing. This work aims to integrate industrial-grade solutions focusing on applying industry-proven hardware and software to create a resilient production schedule. This industrial pre-pilot enables an easy transition from laboratory to industry, preparing the transition to higher TRL.

2. Related Work

Resilience in organizational and manufacturing contexts refers to the system's ability to withstand and adapt to disruptions, enabling it to continue operations under adverse conditions. Hollnagel et al. [7] define resilience as “the ability of an organization (system) to keep or recover quickly to a stable state, allowing it to continue operations during and after a major mishap or in the presence of continuous significant stresses.“ This foundational perspective highlights resilience as a property of stability and recovery. However, specific applications, such as manufacturing, may require a more nuanced interpretation, as returning to a predefined "stable" state may not always be feasible or necessary in highly dynamic environments [8].

In the context of manufacturing systems, Zhang et al. [8] describe resilience as the "system’s capability of leading to success from failure on the system’s own". This shifts the emphasis from mere recovery to the ability to adapt, suggesting that resilience may involve transformative processes rather than simply restoring prior states. This notion is further expanded by Caillaud et al. [9], who propose the concept of "transformative resilience," wherein resilience encompasses the system’s ability to adapt and evolve in response to changes, rather than just reverting to a prior state. Such transformative resilience is increasingly important in manufacturing, where rapid changes and disruptions require systems to adapt dynamically.

Research on resilience also highlights its categorization and application across different hierarchical levels: macro, meso, and micro [4, 10, 11]. This multi-level approach allows resilience to be examined not only at a macroscopic scale along the supply chains, but also within the companies/shopfloors (meso), and single machines or below (micro). For example, Janzen et al. [10] research different narratives for resilience, with one focusing on the macro level by analyzing consumer market trends to enable proactive production planning adjustments and through scenario simulations to anticipate responses to external disruptions. Our work adopts this hierarchical categorization, concentrating on resilience at the meso level, specifically within shopfloor planning, where systems must address the complex challenge of adapting to operational changes and interruptions coming from both micro and macro level.

Similarly, Bakopolos et al. [12] address resilience through a comprehensive framework for scheduling within different sites of a company operating on both macro and meso levels. Their work integrates the Resilience Assessment (RA) using the Penalty of Change (POC) measure [13] and Reconfiguration Services (RS) proposed by Alexopoulos et al. [4], providing a structured approach to assess and dynamically adjust operations in response to disruptions. This approach is instrumental in creating resilient manufacturing environments that are flexible and adaptive at multiple organizational levels. Our study aligns with this work by concentrating on resilience specifically at the micro to meso levels, with a particular emphasis on minimizing downtimes.

Especially on the macro level, data spaces are applicable to share data between stakeholders. A data space can be defined as a "coordinated set of technical standards, organizational policies, and data space services under a specified governance model to enable and facilitate data exchange between its participants" [5]. The development of data spaces has been significantly shaped by various initiatives aimed at enhancing collaboration across industries. Currently notable among these initiatives are Gaia-X, Catena-X, and Manufacturing-X, which seek to establish frameworks for secure and efficient data exchange among stakeholders in the manufacturing sector. Siska et al. [14] show a comparison of different technologies Eclipse Dataspace Connector (EDC), Gaia-X Federation Services (GXFS), and Pontus-X that allow building such a data space. Next to data spaces, Strnadl and Schöning [6] mention that regarding the goal of sharing data the term ecosystem or data ecosystem is used, but propose the term service ecosystem, when not only exchanging data, but also services. Gast et al. [15] further conclude that the term ecosystem must be more general than data space, and that "every data space-enabling technology can also be seen as ecosystem-enabling." Thus, within this work, we adopt the term data and service ecosystem, as the general concepts can also be adopted in data spaces, but we focus not only on data sharing but also containerized algorithms, using Compute-to-Data (CtD). Through this, critical data is not exchanged among ecosystem participants, and computed by the algorithm in a local environment, allowing for secure and controlled data usage while maintaining ownership and confidentiality. A similar approach has been shown by Gehrer et al. [16] for federated learning, in which instead of uploading raw data to a centralized platform, training is done through CtD in each data owner's environment, then the model parameters aggregated on the side of the model owner. Similarly, the authors use the Pontus-X [17] ecosystem, which is based on the Ocean protocol [18] to create a decentralized federated infrastructure using validation nodes in the network. An integration of the Pontus-X ecosystem within an industrial platform called Elements for IoT (E4IoT) is shown by Dickopf et al. [19], tackling the problem of semantic interoperability using the Asset Administration Shell (AAS) to provide and describe the data offered in the ecosystem.

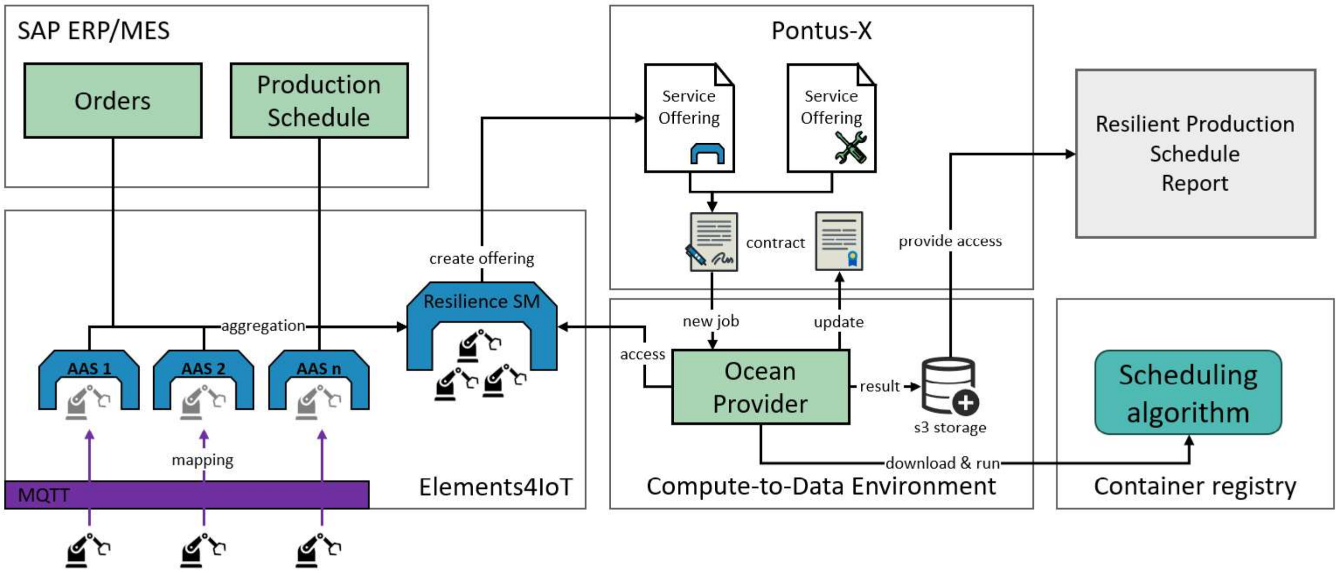

Fig. 1: Proposed Architecture for the integration of the resilience assessment and scheduling algorithms.

Quadrini et al. [20] elaborate in a case study on the suitability of AASs as a standardized data representation for interoperability. AASs offer defined data structures through the submodels defined and standardized by the Industrial Digital Twin Association (IDTA). Neubauer et al. [21] propose an architecture combining AAS, OPC UA and the EDC. They show the importance of standardising AAS content in a dataspace environment. In our work, we tackle this standardisation requirement using a resilience submodel.

Some common tools that offer AAS-hosting and/or modelling are BaSyx, AASX Package Explorer and AAS Server and or Fa³st. Dickopf et al. [19] integrate AAS type 1 and type 2 into E4IoT using the BaSyx Python SDK. E4IoT is an extensive IoT Platform offering e.g. MQTT connectivity, a REST API, PLM or a GUI [22]. As these functions are required for our pre-pilot we use E4IoT within this work.

3. Methodology

This work introduces an architecture aimed at enhancing resilience on the shopfloor by leveraging technologies such as the AAS, the Pontus-X ecosystem, CtD, and the E4IoT platform. The primary objective is to facilitate integration into an industrial environment, as demonstrated in an initial pre-pilot. The approach emphasizes usability for industrial applications. Initially, a general architecture was defined along with specific methods to assess and enhance resilience. For this purpose, we present a method for resilience assessment and demonstrate its application within a shopfloor scheduling algorithm. This algorithm is integrated into the architecture, allowing its deployment via the Pontus-X ecosystem using CtD. Industrial requirements were gathered and analyzed within the context of the pre-pilot, encompassing both the integration of industrial machinery (micro level) and of order data and production schedules (meso level).

3.1. System Architecture

The applied architecture is shown in Fig. 1, showing five different domains (i) ERP/MES, (ii) E4IoT, (iii) Pontus-X, (iv) the CtD environment, and (v) the container registry, with the overall goal of generating a resilient production schedule. **E4IoT** is responsible for data acquisition from proprietary data sources via MQTT, mapping this data to AASs, and aggregating all relevant information into a single resilience submodel. This submodel includes orders, the current schedule, and metrics such as the Mean Time To Repair (MTTR) and Mean Time Between Failure (MTBF) of all machines. The AAS is provided as type 2, accessible through a REST API with credentials for authentication and authorization. The **ERP system/MES** provides current orders and the production schedule in a proprietary format. The **Pontus-X** ecosystem offers a portal for the Flex4Res project to publish and consume service offerings. E4IoT provides a Pontus-X connector [19] that is currently used for publishing the AAS as type 2, either as a downloadable asset or for use in CtD. The **CtD environment** within Pontus-X includes a dedicated CtD environment, which can later be switched to a private one to ensure data sovereignty. This environment runs an ocean provider [23], which is a REST API accessible from outside the network to execute jobs on the data. In this configuration, only the algorithm is shared, not the underlying data, making algorithm auditing a relevant consideration. Also, a **container registry** hosts the Docker image of the scheduling algorithm. This image is downloaded and executed by the ocean provider to produce the resulting production schedule, and save it in a local s3 storage.

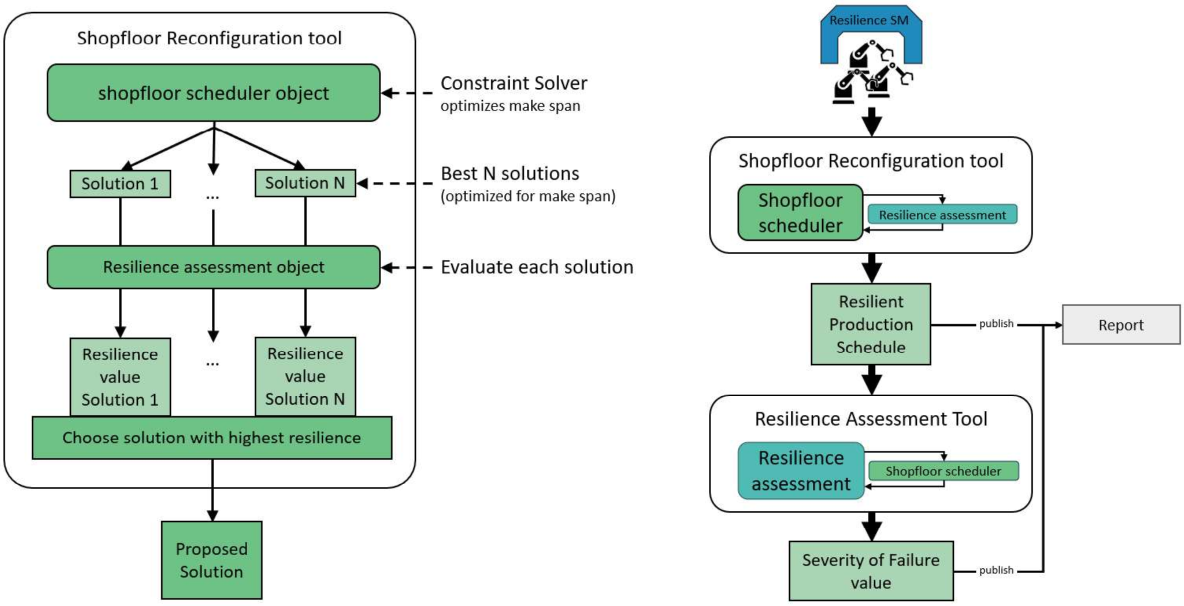

Fig. 2: (a) Shopfloor reconfiguration tool and (b) resilient scheduling using resilience assessment.

3.2. AAS Data Models and Machine Integration

E4IoT offers the functionality to maintain manufacturing assets through the product life-cycle. It allows the definition of asset types and the instantiation of assets out of those. Within the platform, the AAS is an add-on functionality for those assets. It is possible to upload pre-modelled AASX-JSON files via the REST API or to define the required AAS parameters and submodels inside the platform. One current restriction is the limited amount submodels available per default. Although submodels can be added by defining all the properties manually, there is no automated way to import submodels directly from the IDTA. To connect the assets with the devices, MQTT is used. E4IoT provides a HiveMQ MQTT broker, offering the topic-based redirection of the messages to the corresponding assets. MQTT messages are encrypted via SSL/TLS, and authenticated via username and password. Currently, the ocean provider for CtD can only access a single resource, requiring that all relevant data is aggregated into a single AAS.

3.3. Resilience Assessment

Our approach to measuring the resilience of the shopfloor is based on assessing its production schedule. Since every uncertainty on the shopfloor affects the execution of individual tasks in the production schedule, we are assessing each scheduled task for its severity of failing on the whole production schedule.

Our method was initially inspired by the Penalty of Change (POC) method by Chryssolouris and Lee [24] and Alexopoulos et al. [13], which calculates the expected cost of a potential changes. For each potential change, the cost of this change is multiplied by its probability of occurring. We have further developed this method and tailored it specifically to the production plan on the shopfloor.

Our Severity of Failure (SoF) method is calculated with the following steps: (1) Calculate the binomial failure probability for each machine using the machine's MTBF and the number of tasks assigned to that machine. (2) Calculate the severity of each individual scheduled task failing by replacing it with a repair period, the MTTR, and rescheduling the remaining tasks to get its impact on the schedule. (3) Calculate the overall SoF by building the mean of the multiplication of each task's severity of failing and its failure probability.

3.4. Scheduling / Reconfiguration regarding Resilience

The chosen approach to solve the flexible job shop problem on the shopfloor is constraint programming to find a feasible and resilient solution which considers the constraints of the shopfloor, see Fig. 2 (a). Firstly, an initial resilient schedule is calculated and operated. As soon as there is a disturbance like a machine failure, a rescheduling is triggered, the affected machine is blocked with a repair period and a new resilient schedule (considering the repair period) with the remaining jobs is calculated. To get the resilient schedule, the algorithm first finds several feasible solutions optimized for makespan, from which the best solutions are evaluated for resilience using the SoF method, and the most resilient schedule is chosen for the operation.

The flow of the (re)scheduling and evaluation is depicted in Fig. 2 (b). The individual machines are represented by AAS. which, as soon as a disturbance occurs, sends a trigger signal to the tools via MQTT. The tool requests the contact points for each machine AAS from the AAS registry, connects to the AAS of the machines and retrieves the machine data. To demonstrate these two tools in the use case, first an initial schedule is calculated, which is then evaluated for resilience. It is also worth pointing out that the resilience assessment and the scheduling tool depend on each other

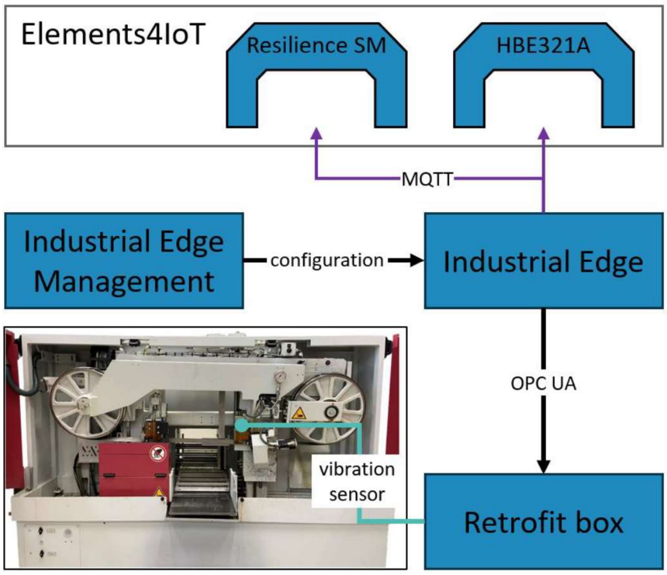

Fig. 3: Mirrored industrial setup for a bandsaw in the laboratory.

since the scheduling tool needs the resilience assessment to produce resilience schedules, and the resilient assessment needs the scheduler for calculation.

3.5. Pre-pilot development

To successfully set up a suitable pre-pilot to be later integrated into an industrial environment, several requirements must be met. First, the existing IT infrastructure must be replicated in a laboratory setting, enabling faster testing without the constraints of extensive corporate guidelines. This setup ensures a smoother transition when deploying the solution in the actual environment. The laboratory must handle real operational data used within processes to accurately simulate and validate outcomes. Additionally, data security is essential; no data should leave the company's boundaries, and only anonymized results may be shared externally, ensuring strict compliance with data privacy standards.

Testing a system architecture with the AAS, E4IoT, and Pontus-X in a controlled, university setting before deploying it in a large-scale industrial environment offers substantial benefits. Firstly, a university pilot allows for rigorous experimentation in a low-risk setting, enabling researchers to identify and resolve critical integration challenges early on. Complex IoT architectures, like those incorporating the AAS and Pontus-X, often involve nuanced interactions between hardware, software, and network components, which are best understood in an iterative, exploratory setup. By refining the system architecture and addressing scalability and interoperability challenges in this preliminary environment, the team can ensure a more robust, mature solution that is better equipped to meet the demands of a larger, real-world deployment in an industrial context. The integration of the pre-pilot is described in the following section.

4. Pre-pilot integration

Voestalpine group is a globally leading steel and technology group active in the production and processing of high-performance materials. voestalpine produces metal products in their value-added service division (e.g., tool steel, high-speed steel, valve steel, special engineering steel) in different shapes and sizes with a range of manufacturing processes from sawing, milling, grinding, heat treatment and coating. The pre-pilot is create for one of their production sites.

4.1. Infrastructure Assessment

To create a pre-pilot setup for an industrial application, several key steps were essential. First, a thorough analysis of the existing IT infrastructure on the industrial partner's side was conducted. This infrastructure is set up of a retrofit box, a custom-developed device designed to upgrade steel saws for data collection, allowing older machinery to connect with modern IoT systems. Additionally, a Siemens Industrial Edge Device is used to process and transfer data to a cloud system via MQTT, serving as a critical link between on-site equipment and remote digital platforms. New and historical order data including scheduling are available through an SAP ERP system, and can be retrieved in a proprietary format. Currently, only a manual export is possible for testing purposes

4.2. Mirroring of Infrastructure and Integration

The setup that has been mirrored in the TEC-Lab of the Institute of Production Engineering and Photonic Technologies was set up similarly to the industrial partner's setup, see Fig. 3. Including a retrofit box with different sensors, e.g. a vibration sensor, and the Siemens Industrial Edge infrastructure, which consists of an edge device and a device fleet management service hosted on a server. The edge device continuously collects the data from the retrofit box via OPC UA protocol, and is publishing the data via MQTT to E4IoT. In E4IoT a mapping was created to map the MQTT message objects to the variables in the different AASs.

5. Findings

The focus of this article lied in the development of a system architecture to increase the resilience on the shopfloor. Utilizing technologies such as AAS, the Elements for IoT platform and Pontus-X an industrial pre-pilot was set up and subsequently mirrored in a laboratory environment. The whole development process led to three major key findings:

1. Utilizing the AAS is helpful in structuring the data points and enabling semantic interoperability across systems. It can act as a primary interface through which information is accessed and provided.
2. The E4IoT platform proved to be valuable, primarily due to its seamless integration with the Pontus-X

environment. It further creates a good basis for enabling the usage of the AAS in industrial applications, facilitating the mapping of shopfloor and machine data to different assets.

3. The Pontus-X environment shows great potential, due to its secure data access capabilities, as well as because it enables CtD. A novel concept, where algorithms are deployed directly on the data, ensuring the data sovereignty of manufacturing companies, by not having to share their data with other ecosystem participants, e.g. service providers.

6. Conclusion and Outlook

The development of the pre-pilot demonstrated the feasibility and usefulness of the proposed architecture in enhancing resilience. However, certain limitations exist. First, the pre-pilot in the laboratory environment might not consider challenges regarding the deployment in a large-scale industrial application, such as higher data throughput, or other performance related issues. Second, the laboratory provides a closed environment and therefore there is no need to specifically consider cybersecurity and compliance aspects. Third, in the industrial setting, the architecture must be embedded within legacy software systems and predefined protocols, potentially causing connectivity issues and necessitating the creation of middleware software. Fourth, company internal workforce operating the machines have not been considered yet in the scheduling. However, an alignment with these factors is essential for a successful deployment. Addressing these limitations and challenges in future research is essential to develop resilience enhancing methods.

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