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EuProGigant Resilience Approach: A Concept for Strengthening Resilience in the Manufacturing Industry on the Shop Floor.

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Abstract

Crises lead to adverse effects in the value creation ecosystem. In the long term, they lead to uncertainties that can destabilize the system. Resilience is getting more and more critical in connected, value-added ecosystems. Crises such as the Corona pandemic, the Suez Canal blockage, the chip crisis, and rising energy prices can cause sudden change in the market demand-supply equilibrium. Those can be expressed as calamities. This concept aims to create calamity-avoiding mechanisms in the manufacturing industry based on a common data infrastructure and smart use of data and services. Calamity-avoiding mechanisms are essential for unplannable and unknown disturbance factors connecting enterprise value creation networks in multiple layers. Resilience mechanisms must be distributed, decentralized, and interoperable to reduce the effect of self-reinforcement of calamities and enable self-orchestration functionalities. Gaia-X, the European initiative for creating a common and sovereign data infrastructure, offers data exchange based on the EU legal framework and is crucial for the (inter-)operability of the mechanisms. This paper presents the concept of such resilience mechanisms, the processing of data in the vertical plane (within a company), and the benefits at the horizontal level (across supply chains of companies). The concept is developed in the context of the EuProGigant project. It follows a bottom-up approach and starts with the Self-Descriptions (SD) of all assets on the shop floor. The resilience approach includes five key points: SDs, stress scenarios and stress mechanisms, system theory and control, anomaly detection services, and self-orchestration.

Keywords: resilience; data infrastructure; calamity; Gaia-X; EuProGigant

1. Introduction

Known crises lead to serious effects in the manufacturing industry. Examples include the Corona pandemic, which disrupts supply chains [30], the chip crisis, which represents a shortage of goods and paralyzes production facilities [26], or rising industrial prices and political regulations [8]. One approach to overcome these obstacles is to collaborate interdisciplinarily on projects and products. Open innovation through collaboration is becoming a decisive factor for sustainable value creation. In analogy with psychology, the ability to organize oneself in ecosystems and federations can be described as self-efficacy [31]. Ecosystems are complex systems with many networking possibilities. Digital tools are essential for harnessing these to overview and monitor transparency relationships and to develop resilience in the face of disruptions.

Cross-company exchange actions characterize these interaction relationships of ecosystems. The European data ecosystem initiative Gaia-X provides a technical architecture for the design of this exchange relationship via its Federation Services [11]. The current research question is how Gaia-X Federation Services and approaches of AI, statistical, and control engineering methods can be used to design a holistic digital resilience concept. Resilience is relevant at all levels of the automation pyramid. This paper presents a data-driven resilience concept,

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focusing on the micro and meso levels, and it addresses the cross-enterprise data exchange relationships on the shop floor of the manufacturing industry. The micro level is defined as the "local planning horizon (e.g., machine)" and the meso level describes the company-wide value chain according to Janzen et al. [17].

2. Related Work

Resilience in production systems is a cross-sectoral research topic. Understanding how production systems respond to change and how responses are influenced by management actions are important to describe resilience in production systems [10]. Maruyama et al. [20] mention resilience thinking as a prerequisite for addressing sustainable change and initiating operational actions [9]. In research, resilience is based on Holling's definition [14], which was further developed in socio-ecology. This definition describes resilience as the ability of a system to reorganise itself after the impact of a stressful momentum [14]. Zhang and van Luttervelt [37] understand resilience as the regeneration of failures. They define five types of failures: customer demand is not satisfied, the required resources are not available or sufficient, the infrastructure is partially affected, the structure of the substance as a product of the infrastructure is partially affected, the operation of the infrastructure attack human, machine and ecosystem. Furthermore they provide a guideline for design management of Resilience Manufacturing Systems with four basic pillars (redundancy at large (design), total function (management), learning and training, ontology modelling) [37].

Resilience thinking is used in various disciplines and domains. It is difficult to find a unique and relational definition. Ontology modelling and taxonomies deliver a common resilience overview and language to describe approaches in certain contexts [20]. Maruyama et al. define a horizontal taxonomy for general resilience: type of shock or perturbation, target system, phase of concern and type of recovery. A resilience strategy with cross-domain application should include the following aspects: redundancy, diversity, adaptability, controlled stress testing [20]. In today's manufacturing industry, the focus is on supply chain resilience. Exemplary is Singh et al.'s work with an ontology-based optimisation model to describe manufacturing sites [32]. This is the basis for a rule-based decision-making system using the Semantic Web Rule Language (SWRL). Öksüz et al. present an approach for the company-internal implementation of a resilience index across all enterprise levels based on key performance indicators in production [38]. The resilience index is calculated based on Smart Resilience Services (SRS) that use artificial intelligence. A manufacturing application related design method for specifying SRS is presented by Janzen et al. [17].

2.1. Information Interoperability

Manufacturing systems are considered as complex systems. The behavior of a complex system is not describable by the characteristics of the constituent subsystems and their interactions are also complex [35]. Assets in complex systems are interdependent and required to interact with other assets or react to environmental influences in terms of resilience. Assets are defined by IEC 62443-2-1 as: *"physical or logical object owned by or under the custodial duties of an organization, having either a perceived or actual value to the organization"*. The Self-Descriptions (SD) of the individual assets serve as a basis for their interoperability. The Plattform Industrie 4.0 [28] defines interoperability as the *"ability of different components, systems, technologies, or organizations to actively work together for a specific purpose"*. More precisely, SDs are associated with syntactic and semantic interoperability that are described in ISO/IEC 21823-1:2019-02 as the abilities of assets to exchange information (1) based on a standard syntax (e.g. XML, JSON, etc.) and (2) to understand the meaning within the application's context. Therefore, assets are required to provide a SD. Several standards exist that have been developed within the last two decades. Starting with the Semantic Web [2] in 2001, which defined the Resource Description Framework (RDF) Schema (RDFS) and the Web Ontology Language (OWL) [21], ontologies became popular in several domains. Nowadays, other standards have been specified in manufacturing trying to achieve semantic interoperability by providing a common vocabulary, data model, or ontology. OPC UA [24] provides Companion Specifications for multiple domains, modeled in OPC UA's graph-based language by different industrial consortia. MTConnect [22] has several predefined data models for machine tools currently defined as XML Schema Definition (XSD) that will transition to the XML Metadata Interchange (XMI) format in the future. Gaia-X [11] suggests the usage of JSON and RDF syntax with the W3C Verifiable Credentials Data Model semantics. The W3C Thing Description for the Web of Things uses JSON Schema for model validation. An aspect often neglected in SDs is behavioral interoperability. It is defined in ISO/IEC 21823-1:2019-02 as interoperability in which *"the results of the use of the exchanged information match the expected outcome."* It deals with the description of the expected outcome, pre- and post-conditions, and dependencies of operations, and thus is essential for the understanding and reasoning about the behavior of other assets and their interdependencies in an ecosystem.

2.2. Stress Testing Mechanisms

Across economic sectors, stress testing is an important method of evaluating the robustness of systems and is already used in various fields of application to assess the effects of external shocks on a system [6, 7]. Especially in the area of software development, numerous methods exist with which solutions can be examined for their vulnerability. Therefore, Vlacheas et al. develop a discipline-specific ontology and taxonomy of resilience in network and information security to define stress scenarios [36]. State of the art stress testing methods in the production environment mainly focus on the resilience of individual orders. This includes the shutdown and disruption of devices as well as temporary interruptions of connections among other things. These can be implemented both in terms of hardware and software. For example, temperature cycling can be artificially introduced to simulate a technical defect [15]. Likewise, the reaction of a system to the repeated sending of random data at one or more input interfaces can be checked as part of fuzzy testing [3].

Regarding an increasingly digitized, distributed and networked production, the consideration of entire production systems or networks is gaining in importance. Research regarding a holistic view of stress testing and mechanisms is still in its infancy. One approach for stress testing of entire production systems is the simulation of stress factors based on stress scenarios and investigating its effects using a simulation model of the production system. Rydzak et al. uses System Dynamic Models of refineries and chemical plants to investigate impacts of internal and external stress factors on the reliability. Countermeasures are derived for production managers [29].

2.3. Feedback Control Systems

Setting and driving stable processes in production is the central task of production and quality engineers. This is described in statistical process control, for example, with the stability map technique [23]. The automation of the approach follows in analogy to the control loop understanding of mechatronic systems. The aim is to minimise the control deviation between a reference variable and the measured variable by using controllers. If the analysis of a real system is too complex or otherwise not possible, states of the controlled system can be estimated by means of a state observer. The methods of control engineering are well applicable to linear systems or systems that can be linearized around the operating point. For multivariable systems, the state space representation is chosen to describe the controlled system. In the case of complex multivariable systems with a large number of describable input and output variables and non-negligible dynamics, controller synthesis methods are used [16]. Autonomous systems are characterized by a feedback loop that integrates the functionalities to perceive, understand and overcome obstacles. Fully autonomous production systems are described in [12].

2.4. Pattern Recognition Based on Known Disturbances

Designing a production process that reacts to and tolerates arbitrary changes is nearly impossible. Bécue et al. [4] investigate a resilience approach that uses the concept of a digital twin for a manufacturing facility, in which they implement a virtual model of the system to improve decision making for production planning based on simulated and stored data via anomaly detection. In the BigPro project [18, 19], failures and disturbances are classified by severity and expected frequency. Based on this, proactive error management decides when countermeasures are necessary to achieve a stable production process within a short time.

Fig. 1. EuProGigant Resilience Concept

2.5. Service-based Proposition of Alternatives

In terms of resilience, it may not always be possible or practical to return to the initial state. Therefore, a new stable state may have to be found in crises. This usually requires decisions to be made, primarily based on historical data. Recommendation Systems (RS) or Decision Support Systems (DSS) can be used to support these decisions. Adomavicius and Tuzhilin [1] describe three main categories of RS: Content-Based systems, where suggestions are proposed based on one's own decisions and how one has evaluated them in the past. Collaborative systems, where the relevance of the suggestion is inferred based on others' decisions. Moreover, hybrid systems combine content-based and collaborative approaches to improve quality. DSS models can range from optimization to knowledge-based and further to simulation models [25]. In general, DSS are very domain-specific [25], what they have in common is that they assist employees to make better decisions regarding processes and generalized business activities to improve profit, efficiency, customer satisfaction, but also resilience [33]. DSS have already been modeled based on ontologies for supply chains [32], but a concrete implementation is still missing so that DSS can be built dynamically on the contents of SDs. The project RESPOND defines a platform-based process modeling language to describe process scenarios. In a workflow-management-system, self-analysis and self-healing functions follow the semantic process model description [13].

3. Resilience Concept

Fig. 1 introduces the resilience concept of the EuProGigant[1] project. The SDs of the single assets within the ecosystem build the foundation of this resilience concept, as the assets substantial structure, data, operations, behavior, and dependencies are

[1] https://euprogigant.com/en/

described. The pillars describe the core functionalities in terms of (1) system theory and control, (2) anomaly detection, and (3) self-orchestration that may be used to achieve resilience. Upon these functionalities, a general layer focuses on stress scenarios and mechanisms to evaluate, validate, and learn from unpredictable behavior within complex ecosystems of assets. The resilience concept is described in a concrete practical context. A part assembly of a spindle shaft and a spindle housing is considered. The spindle shaft is manufactured on a turning center at location A and the spindle housing is manufactured on a machining center at location B. The aim is to control the production of the housing so that it ideally matches the shaft already manufactured. The parts are measured at both sites and the data transferred to the respective MES. The MESs at both sites are connected via the interoperable Gaia-X Federation Services. The MES at location A performs a comparison of the tolerance fields and identifies the two components as an ideal pairing. When the process chain is set up, in terms of resilience, the value-added production process chain is tested for faults, such as communication server failure. In the event of an unexpected machine downtime at location A, production of the spindle housing is relocated to location C in a predefined fall-back solution. Anomalies in the data exchange due to uncontrolled data outflow or lost data packets are automatically detected. Security and backup systems, e.g. redirection of the incoming data to a data storage, are activated simultaneously.

3.1. Self-Descriptions (SD)

The SDs of assets are essential for the proposed resilience concept. In a distributed system, assets, e.g., internal or external devices/services, announce their identification and state information, interdependencies, and relations to other assets. Therefore, behavioral interoperability is crucial for resilience and its core functionalities next to semantic interoperability. The SD is required to announce as much information and knowledge as possible, with information being semantically explicit data and knowledge of the known behavior between cause and effect of an action or a specific situation. The latter requires the SD of asset relations in a machine-readable format, including effects, and pre- and post-conditions of specific actions, to allow other assets to reason about the probable behavior and effects of their actions within the whole system. The Industry 4.0 component sees the references between Asset Administration Shell as important [27]. The concept is extended to include behavioral interoperability for all asset types and they are described in the SDs. Gaia-X proposes the RDF syntax and the W3C Verifiable Credentials Data Model in a machine-readable format. Following these suggestions, the rationale of the presented approach is to solve the representation of the relationship between devices via relationship triples in RDF. Fig. 2 depicts the horizontal and vertical relationships between interacting assets. Each SD of an asset describes the relation to other assets. These relationships can be described as a one-way or co-dependency between devices and services. This may allow conclusions to be drawn from the failure of one device to the complete system. However, a higher level of detail in describing the dependencies between assets also allows more precise statements about the expected system behavior based on an action. Assets can represent the relationships between their capabilities, thereby providing detailed guidance on using them in a particular context. As a result, they enable understanding about composed system behavior.

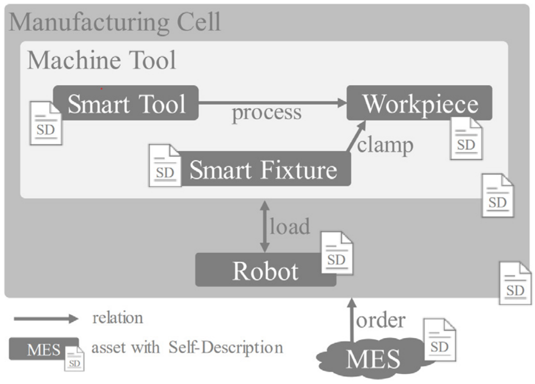

Fig. 2. EuProGigant Resilience Dependencies

3.2. Stress Scenarios and Stress Mechanisms

The stress scenarios and mechanisms occurring in highly interconnected and therefore complex value creation ecosystems are causal for the expression of resilience. Depending on the response to external disturbances, the resilience of the system under consideration can be induced. A prediction of stress reactions is only possible to a very limited extent in complex production chains. This is not least due to the fact that these systems are themselves composed of different, partly cascaded subsystems. Thus, looking at individual subsystems (e.g., machine tool) in the context of stress tests is not sufficient to draw conclusions about the resilience of the overall system. Therefore the Resilience Concept focuses on overarching stress scenarios in order to identify the behavior in the overall system. In this way, errors can be identified and behavioral patterns can be derived. These can than subsequently be used to recognize an escalation in time and to prevent its occurrence. In order to optimize production systems, possibilities for learning and training (e.g. via AI algorithms) are also considered when identifying stress mechanisms. This enables the use of Decision Support Systems as well as Recommendation Systems and hybrid approaches.

3.3. System Theory and Control

The solution extends the approach that the data-based links between the company segments are also examined across the border in order to define so-called Gaia-X nodes as vertical integrator and horizontal data connector computing resources at suitable points [5]. These can be edge computer or server units. Dumss et al. describe that data flow either horizontally to the next node or vertically for processing. The data are analyzed using methods of system theory and control engineering with regard to linearization at the operating point and the formation of descriptive transfer functions. Fractional rational functions are conceivable, which are composed of time series of physical and coding of non-physical variables (e.g. number of active orders in a production cell). In analogy to the closed control loop, the Gaia-X nodes are to be understood as measuring points. The transfer functions are used to model the controlled system of production or also development in combination with production planning. The state space representation is a suitable form for the representation of multivariable systems. For stability considerations a locus curve of the frequency response or a pole-zero diagram is investigated. From this, a controller design can be derived. In addition to the classic controllers, such as PI, PD and PID, advanced controllers that can be adaptively parameterized via artificial intelligence or fuzzy controllers and Kalman filters can be used. The synchronised time reference in control engineering is of high importance. Starting from a low cycle time of a few microseconds in the current control loop of drive modules up to the cycle time of intralogistics of a few hours or days, control loops can be cascaded in this way. The result are cascaded value creation control loops for evaluating the resilience of cross-company value creation based on the data, which become available via Gaia-X.

3.4. Anomaly Detection Services

In the proposed resilience approach, the goal of anomaly detection is to identify potentially arbitrary deviations of a system's usual behavior, e.g., unresolved or unforeseen disasters, in order to be able to react on such anomalies. An example for an anomaly would be when no controller can be identified automatically to return to the initial value or to keep a command variable in tolerance. This is done by comparing a system's current behavior with previously learned 'normal' behavior and the behavior of a system during a stress test. Tests are carried out in stress scenarios – as described above in subsection 3.2 – and the resulting data can be used for anomaly detection. Since anomalies from stress scenarios are known, they can not only be detected, but ideally also be classified. If anomalous behavior is detected, conclusions can be drawn and further actions can be initiated. For example, countermeasures can be taken, messages can be generated, or orchestration can be triggered.

The technological basis of the analysis is event-based communication, e.g., a manufacturing execution system (MES), with system states such as events, conditions, warnings, and error messages. For example, when a production line produces a workpiece, occurring error messages and warnings are linked to a MES. This shows a time delay for subsequent production stages, which in turn can create events again. When the occurrence time of these events and the types of the subsequent events and warnings are learned, anomalies can be recognized and other companies can be informed about the status of a production chain. This might result in causal relationships that can be investigated. The procedure allows to find out which production systems are linked to others and how they are linked. Countermeasures can be taken quickly.

3.5. Self-Orchestration

Another important pillar in this resilience approach, Self-Orchestration, can be used to find alternative resilient states and apply them. Self-orchestration may be an autonomous process for creating a service composition (service-offering) based on the behavioral interoperability of SDs. Similar to recommendation systems, these systems have to provide a wide range of functionality, from solving being stuck in a state (e.g., similar to a deadlock) to failings in the global supply chain. Based on the SDs already described, services can be built bottom-up, starting from single systems up to multi-systems in several companies, which can find weaknesses in resilience and possible alternatives in case of failures. Depending on whether there exists useful historical data, recommendation systems can be used. Otherwise, only systems based on decision support are available. In this case, behavioral knowledge similar to a machine-readable version of an operation manual is necessary. It should allow for inferring and reasoning to recover from those situations. This knowledge can be used to identify how to reach goal states [34]. Therefore, SDs should include this kind of information to move from a critical to a stable state. Self-Orchestration depends on the behavior, information, and failure patterns identified from the stress scenarios. Conclusions about stress scenarios must be drawn from system knowledge about behavior and used to identify resilience measures. Another critical aspect of the Self-Orchestration is acting dynamically on decisions at higher levels in the subsystems. So far, the focus has been on how the failure of individual systems affects the overall system and how these failures can be compensated. However, it is just as relevant to consider changes that relate to system networks. For example, this could be failures and changes in production schedules. A Self-Orchestration would automatically reconfigure large parts of the subsystems and thus reduce the sometimes-repetitive human activities. EuProGigant's resilience concept thus considers unresolved or unforeseen disasters.

4. Conclusion and Future Work

This paper has described a distributed, decentralized, and interoperable resilience concept based on an extension of GAIA-X Principles and Self-Descriptions, and stress testing mechanisms, that makes the manufacturing industry more robust to unplannable and unknown changes. Furthermore, approaches for data-driven services have been proposed and put into an inter-relational resilience concept in the European production giganet.

The next step in the EuProGigant architecture [5] is to implement the services of the described resilience concept, to define the SD resilience model and to test it in realistic manufacturing environments, like learning factories. Individual and more in depth work on the five key points (SD, stress scenarios and mechanisms, system theory and control, anomaly detection, and self-orchestration) is planned. Finally, in order to strengthen the resilience approach and make it more resistant as well as applicable to other domains, the proposed concept might be extended on a conceptual level. For example, there may be more than the described pillars or individual pillars may build on each other.

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