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Event-driven IT-architectures As Enabler For Industry 4.0

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Abstract

Originating in 2011, Industry 4.0 describes the digital revolution of industry and has since become a collective term for smart, mutable and data driven factories. During the last decade, systemic and methodical solutions were designed and implemented that enable corresponding data-driven use cases for producers. While an assessment of expectations around Industry 4.0 results in requirements within the domains of modifiability, connectivity, data and organisation for an IT-architecture, many such solutions are found to be violating essential requirements such as systemic flexibility and data-availability. Not only is this a relevant matter for architectural purists, but it highlights real problems that the industry is still facing while applying digitalisation measures in pursuit of Industry 4.0.

While event-driven architectures go back to the design of modern operating systems, the emergence of powerful, resilient and cheap broker-technologies has risen the polarity of event-driven IT-architectures for businesses in the last decade. Many prominent manufacturers have since begun their transformation into an event-driven IT-architecture. Reasons for this architectural adaptation include exceptional data availability, resilience, scalability and especially data sovereignty. An assessment of event-driven IT-architecture's properties and implications reveals an excellent fit for the architectural requirements of Industry 4.0.

In this work, the subject of Industry 4.0 is analysed along with literature to derive a collective understanding of expectations from a factory implementing Industry 4.0. Subsequently, IT-architectural requirements are derived that describe an architecture capable of satisfying these expectations. Then event-driven IT-architectures are analysed regarding their structural composition and capabilities. Finally, the fit of event-driven IT-architecture is evaluated against the architectural requirements of Industry 4.0, discussing congruence and divergence.

Keywords

event-driven IT-architecture; EDA; Industry 4.0; Smart Factory; Digital Transformation

1. Introduction

Digitalisation in the producing industry offers a fertile ground for scientists, engineers and businesses alike, to shape and utilise digital technologies for the realisation of modern use cases and the generation of rewarding benefits in the competitive market. Origination in Germany, the term Industry 4.0 has since been adopted internationally to shape a common vision and describe the common goal of adapting digital technologies for a digitally enabled production. While many showcases of Industry 4.0 have been realised [1] and system providers offer a wide range of such product-integrated solutions, the overall progress of extensively beneficial digitalisation in real-life productions is, in experience, perceived as poor.

From experience, the identified problem lies within the current approach towards digitalisation measures. A realistic approach to the grand showcase of Industry 4.0 often boils down to focused "lighthouse projects", designed to address a specific digitalisation use case and increase the attractiveness for further measures.

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Often these use cases do work as intended but do not integrate into the overall business landscape well, as their design was limited to the scope of a single application. Existing IT-architectures do usually not support a broad distribution of collected data. An alternative approach is the acquisition of a complex third-party system designed for a collection of specific use cases. From experience, those systems do indeed increase the extent of digitally enabled use cases (usually after a lengthy implementation phase) but do not solve the complexity of procedurally adapting to the ever-changing landscape due to new use cases as envisioned by Industry 4.0. While solving an acute problem by extensively incorporating complex third-party systems without the need for comprehensive technical expertise, the almost always associated dependency towards the vendor can be expected to hinder the long-term pursuit of Industry 4.0.

The proposed solution to this problem lies in the architectural view of the communicated target: the pursuit of Industry 4.0 describes a data-driven system landscape that is open to adapting itself to new challenges. Instead of focusing on the realisation of specific use cases or the development of systemic solutions a more fundamental look at the IT-architectural design should be made. Considering the IT-architecture early in the development stage, allows for building a resilient digital base as a fertile ground for a flexible and business-wide data-driven ecosystem. During research and industry projects event-driven IT-architectures were perceived to be a suitable match for the proposition, which is to be investigated.

This investigation hence focuses on determining the match between traits of event-driven systems and the requirements of Industry 4.0. It aims to further answer the following research questions: Which goals and aspects are associated with Industry 4.0? What architectural requirements does Industry 4.0 place on information systems in companies? What properties and characteristics distinguish event-driven IT-architectures in the context of producing companies?

2. Methodology

To determine the generally perceived definition and architectural requirements of Industry 4.0, extensive literature research was conducted on works taken from the platforms Science-Direct, IEEE, Google Scholar and the Library of RWTH Aachen University and their corresponding sub-references. The architectural requirements were consolidated using the qualitative content analysis by Mayring [2] and are clustered into related subjects analogous to the separation of concern method [3]. A second research iteration focused on more recent works from the last three years, to weigh-in a more recent understanding into the investigation.

The analysis of event-driven IT-architecture was conducted similarly. The actual comparison was then carried out in pair-wise qualitative comparison of requirements and traits. The results are visualised in a matrix and rated along the dimension of fit using Harvey Balls.

3. Digitalisation in the producing industry

The investigation´s base lies in the analysis of Industry 4.0 and event-driven architectures. The following chapter describes the vision of Industry 4.0, as collected from various sources, an introduction to event-driven architectures and a short overview of the current adaption trend regarding event-driven architectures.

3.1 Vision of Industry 4.0

The term Industry 4.0 has, since its emergence over one decade ago [4], been the main talking point around digitalisation in the production industry. The ex-ante declaration of the next industrial revolution not only delivered an orientation for development but also allowed a broad and mutable understanding of its actual, realised composition. Hence the vision of Industry 4.0 not only varies along advocates and representatives but was also shaped over time along the ideation of Industry 4.0 use cases. Therefore, such investigations need to compile a common understanding of Industry 4.0, as represented in literature and workings.

The vision of a digitalised and smart industry, namely Industry 4.0, was motivated in Germany by its economy's urge to use digital developments around the turn of the millennium for faster-paced product development, a high degree of individualisation in production and a general increase of a production's flexibility and decentralisation [5–7]. The subsequent vision of such a digitally enhanced production was first introduced in 2011 at the Hannover Messe under the title of Industry 4.0 as the working title of the academy for technical research called acatech [4]. With the foundation of the Platform Industry 4.0 in 2013 the vision of the fourth industrial revolution was specified towards basic definitions, goals and first approaches [8]. This ex-ante specification offers by no means a handbook for digitally enhancing a production but can rather be interpreted as a marketing strategy, which is supposed to lay the foundation for a shared, target-oriented development [9]. Hence definitions and interpretations vary widely across pursuers.

The general interpretation of the Platform Industry 4.0 defines Industry 4.0 as an "intelligent networking of machines and procedures within the industry enabled by information and communication technologies. There are many possibilities for companies to use intelligent networking" [5]. Additionally, the definition lists flexibility of production, changeable factories, customer-oriented solutions, optimised logistics, extensive usage of data and circular economies as exemplary realisations of Industry 4.0. Interpretations from other sources extend the term towards a demand-pull from the customer side and technology-push from the industrial side [7], a tautologic self-evidence by the sheer use of digital technologies in the industry [10], a completely new level of flexibility and automation [11] and an inclusion of technologic structures (as Big Data) or specific optimisation potentials [6]. These interpretations occasionally substantiate specific use cases encapsulated within the production's domains.

The term Industry 4.0 gained popularity in international research regarding digitalisation within the following five years of its origination [6,4]. Similar concepts like the Internet of Things (IoT) or the Industrial Internet offered anchors for discussion and joint research. The term Internet of Things describes an ecosystem of internet-based connected objects [12,13]. The term Industrial Internet describes the similarly declared IT-Revolution from the United States, which focuses on the whole product life cycle and connectivity-enabled products and services [12], in contrast to Industry 4.0's machine and process focused approach. Overall, the investigation focuses on the definition of Platform Industry 4.0 since it focuses on the substantial connectivity of processes and endpoint in the producing industry. Core aspects are the general digitalisation and interconnectivity of IT-systems and processes in the value chain.While the interpretations of Industry 4.0 currently transform into tangible products, offered by prominent system providers in the production domain, the experienced state of digitalisation within the production does not meet the proposed vision. Complex system solutions not only increase the perceived complexity of the system solution but also hinder the users in the horizontal and vertical interconnectivity of a multitude of heterogeneous data sources and sinks. The presumed problem lies in the encapsulation of data within (third-party) systemic ecosystems that shift the required expertise from widely usable programming skills towards system-specific knowledge. Hence users, who try to bypass self-responsible digital development, end up configuring third-party systems and still have limited capabilities in flexibly manipulating the system for new needs. The result is reduced scope for self-determined, autonomous action and in the worst case a future vendor lock-in.

In summary, Industry 4.0 aims towards more data-driven and modular approach to allow for incorporation of learnings and optimisation into an ever-changing landscape of technologies and use cases. The overall goal lies within optimisation and flexibility of processes and system-landscapes.

3.2 Event-driven architectures

The event-driven architecture (EDA) describes an architecture, in which its components communicate predominantly through the distribution of events and corresponding data payload. In contrast to a more procedural structure of conventional architectures motivated by synchronous business processes and hierarchies, the event-driven architecture relies on a broad distribution of domain-specific information in a network of information producers and consumers. In short, any status change or yield of information caused by both real-life events and data transformation within systems is communicated and distributed as an addressee-agnostic (no need for a specific addressee) event. Consumers of events obtain these from a central hub ("broker") instead of the source, which effectively decouples components in these kinds of architectures (compare Figure 1). [14–16]

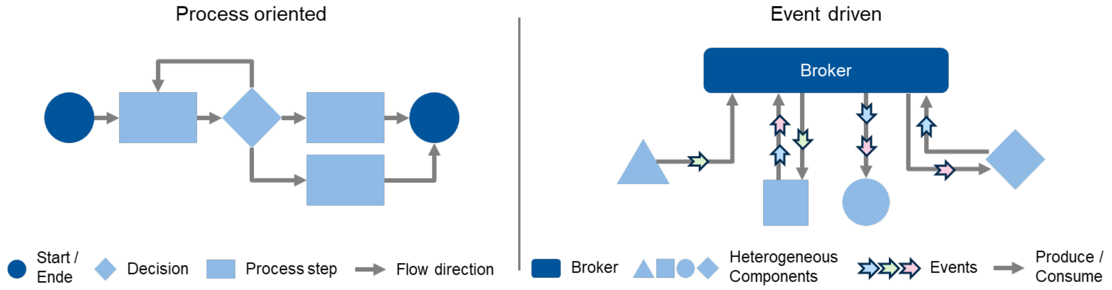

Figure 1: Schema of an event-driven architecture in comparison to process oriented procedures

Event-driven architectures are usually deployed in complex systems with distributed functionality and a multitude of specialised domains. Hence, they historically became an integral part of modern operating systems and are a favoured design principle of complex software products, which are composed of numerous modular software components like prominent ERP- and ME-Systems [14]. Since the development of performant open-source brokerage systems in the last decade, like Apache Kafka and RabbitMQ, event-driven architecture became easily adaptable on an enterprise level as a fundamental IT-architecture.

3.3 Rising popularity of event-driven IT-architectures

With the rising interest in digital solutions by conventional businesses and the emergence of e-commerce, IT-landscapes need to digitally represent and manage several modular business domains. This results in an increase in complexity of IT-landscapes, which in turn impedes their concurrent development and management [17,18]. With the development of high-performance event-brokers (also known as event-streaming platforms), businesses started to adopt the event-driven principle as an IT-architecture to interconnect and manage business functionality implemented in distributed systems, services and applications [19,20,15,21]. Prominent representatives of event-driven IT-architectures are for example Netflix, Intel, Bosch, BMW and Tesla [22–26].

The application of event-driven IT-architectures in the producing industry consists of a manageable set of prominent producers, mainly in the automotive industry. Even though the producing industry with multiple business domains (such as planning, production and logistics) and "smartifiable" physical assets (such as machinery, sensors and material) possesses great potential for the adaptation of such an open data platform, in experience its actual spread is comparably low. The assumed problem lies in a combination of the complicated interdisciplinary field of technical and digital expertise, the deeply rooted system solutions that have historically evolved into a highly complex system and the rapid appearance of smart assets integrated into proprietary data ecosystems. To open the field for further research and workings into realisations of an event-driven smart factory, the actual architectural fit between Industry 4.0 and EDA is to be investigated.

4. Investigation of the architectural match between Industry 4.0 and EDA

This investigation aims to determine the architectural fit between event-driven IT-architectures and the requirements derived from the vision of Industry 4.0. Hence the architectural requirements of Industry 4.0 and the traits of event-driven architectures are evaluated. This chapter presents the identified requirements of Industry 4.0, the traits of EDA and their corresponding match.

4.1 IT-architectural requirements of Industry 4.0

A compilation of the investigated sources led to a general understanding of a common vision of Industry 4.0, as shown in 3.1. The central vision of Industry 4.0 lies within the extensive digital integration of processes and "things" both horizontally along the value stream & product life cycle and vertically across hierarchical IT-layers within the company [27].

The vertical integration describes the interconnectivity of low-level components as sensors and actuators, mid-level as control and management systems and high-level planning and business systems. Its goal is the improved transparency through different hierarchical layers, the availability of precises real time information in abstract business processes and the abolishment of layers of gateway systems that can impact data consistency. The motivation lies in direct availability of data, regardless of organisational structures, and the establishment of more extensive monitoring and analysis functionality to improve/optimise processes and manage the production's rising complexity. [28–30]

The horizontal integration describes the connectivity of business resources towards a value creation network [28]. The digital representation of machines, operating resources and products tie processes along the object's life cycle and can span across company borders. The goal is data consistency and improved availability across the stages of development, production and servicing (incl. maintenance and diagnosis) [30]. The motivation spans from extensive transparency over forecastability to adaptability empowered by the usage of data. Hence the realisation of a fully integrated value creation network requires a horizontal integration of components, a vertical integration of IT layers and a broad adaptability of included systems and processes, to utilise data-driven learnings [30]. The result is often depicted as a digital and intelligent "smart factory", which can digitally represent real-life states and information [31–33,4].

On a more precise level, a smart factory requires the real-time availability of data points across system domains, to enable use cases proposed under Industry 4.0 such as early warning systems, advanced planning and feedback loops [30]. A direct and responsive system design is of the essence, as it is vital for the continuous productivity of costly assets. The use case of predictive maintenance makes use of such readily available data to not only generate a measurable economic benefit, but also offers a foundation for data-driven value creation [32,33]. Furthermore, the increasing amount of collected data and data-driven use cases raises questions about data usability, to actually generate a tangible use of vastly collected data [12,27]. A corresponding IT-architecture is hence not only required to reliably transport data but also be able to manage its usability via e.g. contextualisation [33].

Considering digital technologies such as cloud computing and the imminent growth of complexity due to increasing numbers of smart components, another requirement lies in the manageability of complexity by e.g. the domain-oriented divisibility of system components and functionality. This ability is identified to be a relevant factor for competitiveness [10]. The actual technological implementation is thought to be of lesser essence than the ability to individually offer suitable solutions for each functionality and still be able to manage the integration of several domains.

At last, the proposed usage of data envisions a higher degree of automation [34], which with respect to complexity requires domain autonomy or more commonly a higher degree of decentralisation. Aged depictions envision automation layers which are doomed to be deprecated in light of intelligent and decentralised cyber-physical systems (CPS) [30]. Conservative layers of ERP and MES are replaced by a service-oriented network of decentralised and autonomous CPS [30]. By replacing the top-level, centralised intelligence with a more essential centralised understanding of shared data, the data-oriented components are more flexible and adaptable as envisioned by Industry 4.0 [35,30].

This investigation summarises the derived architectural requirements of Industry 4.0 into four categories, namely *Change* (architectural development and adaptability), *Interconnectivity* (of components), *Data* (nature and usage of information) and *Organisation* (business organisational aspects). The results presented in Table 1 and are further described below.

Table 1: Categorised requirements of Industry 4.0 toward IT-architectures

Change	Interconnectivity	Data	Organisation
• Flexibility • Speed and agility • Complexity management and control	• Openness and interoperability • Scalability • Downwards compatibility • IT-Security	• Integration • Data consistency • Data-driven-ness (analytics and smart factory)	• Globalisation and culture • Ergonomics and human-machine-interaction (HMI) • Autonomy (production domains and smart factory)

The category *Change* addresses the ability of a production to react to drastic changes in regional and global conditions due to accelerated technological progress. The IT-architecture must enable its components to adapt to new problems and potentials and hence promote **flexibility** in IT-systems and components. This requirement is often addressed in the context of Industry 4.0 but contrasts the experienced rigidity of big-scale and complex system solutions, which promote inflexibility due to vendor lock-in. To allow incorporation of disruptive technological changes without disrupting the whole system, the IT-architecture must be **agile** enough, and to enable change efficiently, it must be able to do so **quickly**. This addresses the ability to conduct the more frequently expected change (preferably) independently and with manageable effort. Lastly, implemented changes should not have a significant impact on the overall complexity, which is addressed by appropriately **managing and controlling complexity** in the IT-architecture. This is to allow the sustainable development of the systemic landscape, without negatively affecting the ability to conduct change in the future.

Interconnectivity addresses the full IT OT integration of production processes and systems to fully enable the digital landscape depicted by Industry 4.0. Most significantly this requires an overall **openness** (non-proprietary and interfaceable) and **interoperability** (standardisable on at least a corporate level) of architectural components. This is to combat systemic data encapsulation which directly hinders the broad use of already captured data. **Scalability** addresses the resilience of interconnectivity with respect to change. This not only includes overcoming technical limitations, such as bandwidth but also allows for structural modularity promoting growth and continuous comprehensibility in the growing data space. This architectural requirement is tied to the **downward compatibility** of the whole system. The increasing interconnectivity must allow its components to be resistant to external changes. An overall identified fourth requirement regarding interconnectivity is the need for effective **IT-security** [12,36,30], which is (also in disregard of Industry 4.0) generally accepted as an underlying requirement for IT-architectures. The ever-increasing number of smart devices and hence endpoint increases the overall vulnerability of the network.

The *Data* category comprises the heart of the data-driven vision of Industry 4.0. The overall **integration** describes the unification of information available in the company. This translates into ensuring the capturing and faultless distribution of relevant data. The requirement of **data consistency** then extends the integration with a unified distribution of data aided by structural organisation and contextualisation. This is intended to promote an overall consistency of the perceived data truth. Lastly, the actual usage of data is described in the **data-drivenness** of the components as a data sink (like analytics) or a part of the complex system (smart factory). The architecture should enable components to function data-driven and promote endpoint intelligence.

The category *Organisation* offers an (business-)organisational view to the requirements of the IT-architecture, which ties the technological and processual views regarding a company's strategies and goals. More often companies pursuing digitalisation find themselves competing in a more **globalised**

environment. This requires the IT-architecture to be able to handle internationally distributed value chains and harmonisation of corporate culture (like varying processes and conventions) across multiple production sites. Furthermore, the enhanced digitalisation of oftentimes still manual processes needs to be able to allow for **ergonomics** for users and support for human interaction. Hence the architecture needs to be able to provide suitable endpoints and structuring to promote human interaction and manageability. The overall rising complexity and trend towards decentralisation need to be accompanied by an IT-architecturally enabled **autonomy** of production domains. Specifically, this describes a rejection of strictly hierarchical delegation mechanisms in favour of a self-determining role within an individually specifiable domain.

In summary, Industry 4.0 requires IT-architectures to manage heterogeneity than forcing homogeneity more significantly, in prospect of anticipating changes in use cases and system-landscape. Specifically, this means that connectivity towards an open (independent) but common data truth, feeding decentralised intelligence, is of essence. This directly contrasts conservative IT-system oriented solutions, which favour system-connectivity over data availability, effectively unifying data and systemic functionality. In short, Industry 4.0 should not require the user to know, which specific system to connect to, to receive and use data.

4.2 Traits of event-driven systems

The investigation of the traits of event-driven systems allowed a compilation of characteristics and core properties regarding an IT-architecture. The identified features are listed in Table 2, based on [14], and further elaborated in 4.3 in comparison with Industry 4.0.

Table 2: Features of event-driven architectures

Structural features	Functional features
Central broker / middleware	Publish-subscribe (or similar) principle
Distributed system / multiple components	Asynchronous communication
Event-driven communication	Decision-making at the sink (intelligent endpoints)
Encapsulation and modularity	
Loose coupling	

Event-driven architectures, as described in 3.2, can be classified as **distributed** systems enabling **service-oriented** functionality, which mainly borrows its traits from modular and encapsulated service-oriented architecture [37,38]. Its core features include a centralised broker (or **redundant** broker-cluster) that **enables communication** in the format of generally addressee-agnostic events which effectively **decouples components** of the network, analogous to event-driven software design [39,37,40]. The **asynchronous** nature of event-driven communication contrasts conservative request-response patterns not only by decoupling components but also **increasing the availability of data** towards the whole network (one-to-one vs. n to n) [14,41]. More often these architectures encourage a "**smart endpoint**, dumb pipes" philosophy which promotes **autonomy** across the participating domains [14]. By leveraging a **standardised structure of events and topics**, organisations can enforce domain-specific **contextualisation** and hence better **usability** due to congruence with domain-specific language [42,43].

From experience, these traits are found generally within specific IT-ecosystem within the IT-landscapes of producing companies, e.g. SAP [44], but not as an overall IT-architecture. Their benefits are hence mostly limited to development by the vendor, but not fully utilisable by producers. Thus, producers still need to either deploy synchronous interfaces between IT-system or predominantly commit to a vendor. EDA does hence mostly distinguish itself from common production IT-architectures, by decoupling the data from systemic functionality and creating an open, centralised data space within the producer's influence. This not only promotes data sovereignty for the producer, but also inverts the communication style towards reactive functionality, which promotes more flexible and manageable distributed components.

4.3 Comparison of architectural requirements and traits of EDA

To evaluate the suitability of event-driven IT-architecture regarding the architectural requirement of Industry 4.0 the identified requirements are compared to the traits of event-driven systems. The features of EDA are evaluated towards each requirement as either *irrelevant*, *relevant* (contributing to/partial fulfilment of requirement) and *significant* (compliance/fulfilment of requirement) and presented in Table 3.

Table 3: Examination of suitability of event-driven IT-architectures for Industry 4.0

	Change			Interconnectivity				Data			Organisation		
	Flexibility	Speed and agility	Complexity management and control	Openness and interoperability	Scalability	Downwards compatibility	IT-Security	Integration	Data consistency	Data-driven-ness	Globalisation and culture	Ergonomics and HMI	Autonomy
Central broker / middleware	4	2	4	4	4	4	0	4	2	4	2	2	0
Distributed system / multiple components	2	2	0	0	4	0	0	4	0	2	4	2	4
Event-driven communication	0	4	0	4	4	4	0	4	2	4	2	0	2
Encapsulation and modularity	4	2	4	2	4	2	0	2	0	0	0	0	4
Loose coupling	4	2	4	4	4	0	2	0	0	2	0	0	4
Publish-subscribe (or similar) principle	0	4	4	2	4	0	0	4	4	4	2	2	4
Asynchronous communication	0	4	4	2	4	0	0	2	0	2	0	0	2
Decision-making at the sink	4	2	2	0	4	0	0	2	0	4	0	0	4

irrelevant 0 relevant 2 significant 4

The **centralised broker** structure of the event-driven architecture effectively decouples systems via a centralised communication platform by separating systemic functionality from exchanged data. This greatly contributes to the *flexibility* and *complexity* of the systemic landscape by breaking (otherwise exponentially increasing) one-to-one interfaces and thus making systems replaceable. The centralised approach to data accessibility via a unified format addresses *openness, downward compatibility, integration* and *data-drivenness*. The available broker technologies often allow for clustering and replication which introduces *scalability* by design.

The resulting **distributed system** landscape eases the division of functionality into specific domains which again promotes *scalability* (analogous to microservice-architectures [45]) but is also suitable to map a distributed corporate structure in the context of *globalisation*. By distributing systemic functionality into domains, EDA increases overall *autonomy* and hence the overall *integration* by counteracting dominant systems enforcing proprietary frameworks.

The eponymous **event-driven communication** replaces the conservative exchange of (mostly system-specific) commands with the broadcasting of state changes and information yields. This greatly increases *speed and agility*, as system integrations can primarily occur without the adjustment of other systems. The unified language of centrally specified events immensely promotes *openness and interoperability, scalability, downward compatibility and integration*. The reactive nature of events (with attached payload) consumption inherently accounts for the *data-drivenness* of components.

The ability for **encapsulation and modularity** within the system landscape greatly reduces interdependencies, which allows for the exchangeability of systemic functionalities. Hence *flexibility*, *scalability* and *autonomy* are supported. *Complexity management and control* are provided with the ability to maintain the system landscape more easily by purging deprecated functionality or conducting isolated testing.

The **loose coupling** of components is achieved by merging the EDA features above and promotes the overall inter-independency. Independent components can conduct *autonomy* more easily and result in reduced *complexity* of the system landscape regarding managing dependencies. Hence loose coupling offers great *flexibility* and *scalability* while still allowing *openness and interoperability* via a central, common interface.

The **publish-subscribe (or similar) principle** used in the exchange of events and the EDA-nature of **asynchronous communication** provides a lightweight mechanism to consume data without the need to cooperate with the producer. The communication allows both real-time reactions to new data and delayed consumption (without blocking the producer) making it a good contributor towards *speed and agility, scalability* and interface *complexity management*. Additionally, **publish-subscribe** provides a mechanism for a central data truth that is potentially consumable by every component, regardless of knowledge by the publisher, which promotes systemic *integration*, overall *data consistency*, *data-drivenness* and *autonomy*.

The **decision-making at the sink** describes the decentralisation of intelligence towards the endpoint, as the broker by design does/should not execute business logic. This allows the broker to act as a simple distributor of data, unaffected by continuously changing business logic. Thus, the principle incorporates *flexibility* and the components' *data-drivenness* and *autonomy*. Furthermore, the IT-architecture offers better *scalability* when the broker does not need to adapt business logic when scaling it into a cluster of brokers.

EDA inherently does not address *IT-security*, as it focuses on reshaping the format of communication. This by no means does not result in event-driven systems being inherently insecure or hindering the implementation of a secure environment but rather emphasises the need to separately address IT-security measures (as common with other IT-architectures like Rami 4.0 and analogous to Porter and Heppelmann's Capability Model for Smart, Connected Products).

The introduction of event-driven IT-architectures is, by experience, coupled with the need for an active rethinking of established procedures and inter-domain cooperation, which generally complicates the adoption of pro-event-driven *culture* due to laggards and adversaries. The *ergonomics and human interaction* are not supported by EDA inherently but need to be addressed separately by incorporating adequate systemic endpoint solutions, which make use of the event-driven capabilities.

In summary, EDA offers several traits suitable for the implementation of an IT-architecture covering the requirements of Industry 4.0. The not inherently filled demand for organisational architecture and IT-security do not revoke the overall suitability, but need to be addressed separately. The conclusion and the overall applicability of EDA as a solution for Industry 4.0 is discussed in more detail in the following chapter.

5. Conclusion and Outlook

Overall, the investigation identifies a significant fit for event-driven IT-architecture to handle the architectural requirements of Industry 4.0. The shift from systemic ecosystems to an open data platform, which is strategically situated within a company's sphere of power, delivers an excellent fit to fulfil Industry 4.0's requirements of extensive interconnectivity and data-driven decision-making. With an effective separation of connectivity/data and functionality, event-driven systems enable decoupling, modularity and scalability which increases the resilience and sustainable interoperability of the whole system in an ever-evolving landscape of use cases, technologies and changing IT-systems.

Still, issues such as IT-security and the immense shift in culture as well as human interaction need to be addressed separately, because event-driven architectures do not inherently offer a solution for these requirements. The demand for IT-security need be addressed by implementing an active authorisation management and technical solutions like SSL-certificates, ensuring trust in components, on top of existing broker technologies. Depending on the individual data-sensitivity, the implemented solution of an event-driven IT-architecture should be considered regarding the rollout in cloud or on-premise solutions and the structure of broker clusters spanning sensitive domains. The shift in communication patterns, usually not intuitive in the context of systemic interconnection, would need to be addressed with active architecture management and education of stakeholders in the use of event-driven systems. The definition of a standardised stack of tools for interaction with the event-driven system can be key in ensuring HMI.

In conclusion, these results emphasise the occurring trend of procedural transformation of productions into event-driven architectures by extensively incorporating technologies such as Apache Kafka and Solace PubSub+, as well as deployable building blocks in prominent cloud computing services. The overall perceptible trend from monoliths and complex third-party ecosystems towards distributed modular functionality and intelligent endpoints is well supported by such technologies. Crucially, their usage signals an evolving understanding of the data-driven nature on a more fundamental level and the need for a long-lasting and manageable architectural base that enables growth along the future development of digital technologies.

However, the incorporation of event-driven IT-architectures does not represent a fit-for-all solution in the prospect of Industry 4.0. By experience, the self-reliant management of such a data space requires know-how in the design of data schemas and organisation of a corresponding change management. While suitable methods are already publicly available [46,42,43], the correct implementation and continuous pursuit still requires motivation and active confrontation by the producer. Without the goal of pursuing an individual IT-strategy and hence conducting active architecture management, tackling Industry 4.0 with event-driven IT-architectures will, just by itself, not be a beneficial solution.

In prospect, future works on event-driven IT-architectures need to address the incorporation of unfulfilled architectural requirements, namely IT-security and support for organisational matching. Considering an adaption of IT-architectures, the nature of a centralised and contextualised data truth is expected to require the definition of a standardised event (data) model for each component to adhere to, to fully preserve the architectural advantages. For now, adaptors of this architecture are required to define such a model from scratch, which highly increases the effort in implementation and hinders especially small and medium enterprises from fully benefiting from this technological development. At last, organisations need to adapt to manage and develop these kinds of architectures. While software developers already successfully manage projects incorporating event-driven architectures, it is yet to be determined to what extent these procedures help in the corporate organisation of a large-scale IT-architecture across multiple technical domains.

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