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Towards a model for holistic mapping of supply chains by means of tracking and tracing technologies

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Abstract

The usage of tracking and tracing technologies not only enables transparency and visibility of supply chains but also offers far-reaching advantages for companies, such as ensuring product quality or reducing supplier risks. Increasing the amount of shared information supports both internal and external planning processes as well as the stability and resilience of globally operating value chains. This paper aims to differentiate and define the functionalities of tracking and tracing technologies that are frequently used interchangeably in literature. Furthermore, this paper incorporates influencing factors impacting a sequencing of the connected world in Industry4.0 supply chain networks. This includes legal influences, the embedment of supply chain-related standards, and new possibilities of emerging technologies. Finally, the results are summarized in a model for the holistic mapping of supply chains by means of tracking and tracing technologies. The resulting technological solutions that can be derived from the model enable companies to address missing elements in order to enable the holistic mapping of supply chain events as well as the transparent representation of a digital shadow throughout the entire supply chain.

Keywords: Supply Chain Mapping; Tracking and Tracing; Transparency; Industry 4.0

1. Introduction

Supply chains have become increasingly complex with globalised multiple-tier networks of suppliers, making it difficult to have visibility and to ensure product traceability throughout the whole supply chain [1]. At the same time, companies have to deal with the growing interests of customers, governments, and non-governmental organisations in having greater transparency of brands, manufacturers, and producers throughout the supply chain [2, 3]. As a result, social and environmental sustainability issues have become increasingly important for manufacturers in order to maintain the flawless reputation of their brands [4].

In this context, a distinction can be made between supply chain visibility and supply chain transparency. Even though in literature these terms are often used interchangeably, this paper defines supply chain visibility as "the extent to which actors *within* [emphasis added] a supply chain have access to or share information which they consider as a key or useful to their operations and which they consider will be of mutual benefit" [5]. Supply chain transparency, by way of comparison, extends the aspect of supply chain visibility to the disclosure of all information to *all* stakeholders, including the customers [6]. According to Khan and Yu [7], transparency includes even the ability for customers to gain access to information without actively participating in the supply chain system landscape or architecture.

For Roy [8] the assurance of traceability represents an important element when increasing supply chain transparency and visibility. In this context, "the key logistical inhibitors impeding transparency via traceability involves standardization of traceability objectives within and between firms, variation in product and process properties, lack of interoperability due to complex identification of goods,

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technology-friendly workforce, lack of social/regulatory influence, technology trust, and confidentiality/data security [8]". Literature uses a variety of different definitions of the terms 'traceability' as well as 'tracking and tracing' [9]. In this paper, traceability refers to every (processing) event in the supply chain, which is divided into the aspects of tracking on the one hand and tracing on the other [9]. The term tracking describes the determination of the ongoing location of a product as well as product-related elements during their (downstream) way through the supply chain [9–11]. Here, a distinction can be made between discrete tracking and continuous tracking. While discrete tracking only determines the location of a product at a specific time, continuous tracking determines a product's localization at any time during its way through the supply chain [12]. Tracing, however, refers to the origin of produced products (upstream) in the supply chain, including their location and specific product-related information [9, 11]. For Hofman et al. [13], the tracking of material flows and an improved transport handling represents an enabler for Industry 4.0 (I4.0) and its envisioned "highly flexible mass production, real-time coordination and optimization of value chains, reduction of complexity costs or the emergence of entirely new services and business models [13]".

In an I4.0 context, the digital transformation and the implementation of connected intelligent and cooperative systems enable to increase the efficiency and transparency of modern supply chains. However, the increased complexity of such supply chain networks requires novel multi-layered models that facilitate the implementation of I4.0 driven Supply Chain Management (SCM) systems by structuring processes, workflows, and the associated objectives of implementation scenarios [14].

2. Rationale of the paper

The Reference architecture model for Industry 4.0 (RAMI4.0) represents a well-established model introduced by technical experts and engineering associates in the field of I4.0 in the year 2015. It aims at facilitating the applicability of workflows and tasks (in the context of I4.0) by breaking them down into different layers and levels [15]. Figure 1 shows the three-dimensional RAMI4.0 model consisting of vertical layers in combination with the horizontal Life Cycle & Value Stream and Hierarchy Levels.

The RAMI4.0 reference model extends the hierarchy levels defined in the IEC 62264 and IEC 61512 standards with the two levels 'product' and 'connected world'. The term 'connected world' goes beyond the level of the 'enterprise' defined in the standard and describes the higher-level networking beyond the boundaries of the factory or the enterprise [15]. It describes the networking of different enterprises by means of the internet and the involvement of suppliers, manufacturers, and customers [16, 17].

The Asset Administration Shell (AAS) represents an essential element for the implementation of smart factories within the RAMI4.0 reference model. It describes the I4.0-specific digital representation of a physical asset [18]. The AAS and the associated asset form an I4.0 component that communicates and acts within the networked factory and serves as a data foundation for the connected world [15].

Despite the many advantages of the reference model RAMI4.0, it is not free of limitations. For example, according to Hang [16], RAMI4.0 does not include other standards besides the IEC standards. Additionally, Hang [16] criticizes the unclear relationship between the spatial axes of the hierarchy levels and the layers [16]. Furthermore, RAMI4.0 only includes a very simplified idea of the connected world. In the context of SCM, this limitation of the RAMI4.0 model and the AAS becomes clear when the ownership of an asset changes (within an enterprise or the connected world).

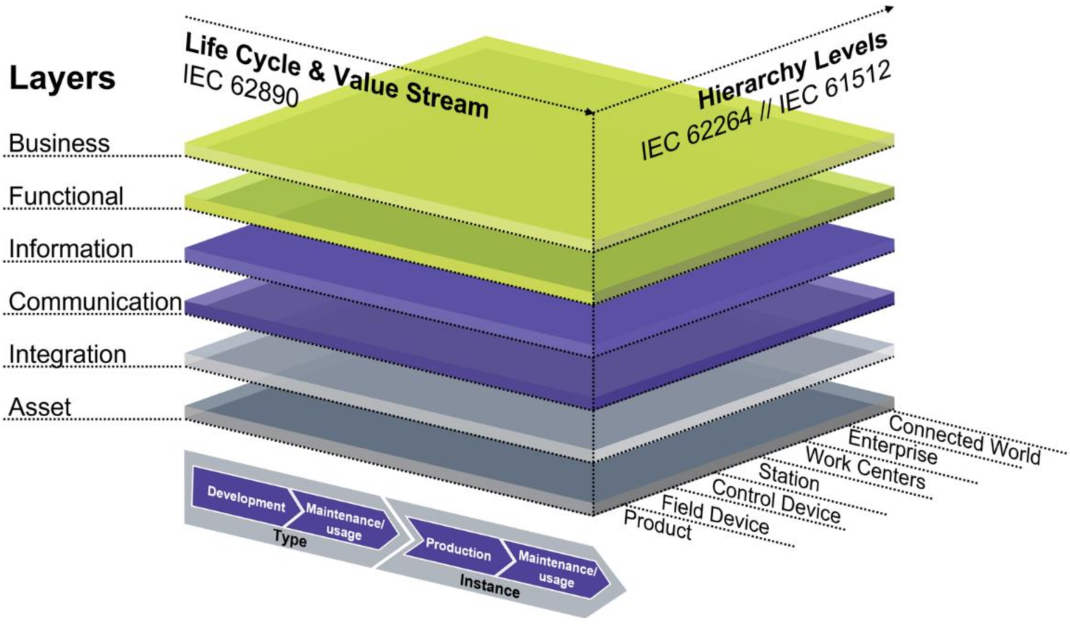

Fig. 1. RAMI4.0 Model [15]

Here, the AAS does not consider its transfer to the subsequent owner of the asset. Instead, a new AAS, with a new (unique) identifier must be assigned to the asset [19]. Depending on the complexity of supply chain networks, this reallocation complicates a holistic and continuous mapping of assets in the supply chain. Even several European research initiatives have discovered the demand for a stronger distinction between the enterprise layer and the connected world, none of the approaches proposes a sequencing of the connected world and its characteristics [20].

This paper proposes the first draft towards a new model taking into account legal requirements, the involvement of further relevant standards, and possibilities of emerging technologies such as the blockchain. The model sequences the connected world and thus aims at providing a foundation for increasing transparency and supply chain resilience in complex networks.

3. Model development

In order to develop the model, this paper incorporates influencing factors impacting the sequencing of the connected world in I4.0 supply chain networks. This includes legal influences, the embedment of supply chain-related standards, and new possibilities of emerging technologies. The sequencing is described in ‘model layers’, which are described in detail in the following sections.

3.1. Enterprise Layer

The first layer of the model is the Enterprise Layer. This layer is closely connected to the layers and hierarchy levels of the RAMI4.0 Model and therefore does not require a comprehensive description in this paper. The Enterprise Layer describes the closed system of a factory or a sum of factories, in which data streams have no interaction with external partners in the supply chain network. The Enterprise Layer, with all the elements of RAMI4.0 except the connected world, represents an important data foundation for all other layers of the model. Here, assets are linked to their digital identity for the first time and the corresponding metadata is stored. If the company only aims at improving internal processes and increasing transparency within the factory, no decision needs to be made here regarding the private or public availability of information. If, on the other hand, the enterprise aims to be part of a holistically mapped supply chain, it is necessary to select what data should be stored within the enterprise and what data must be made available to the network.

When conceptualizing such larger information systems, Strong et al. [21] recommend a holistic view on data qualities (DQs). In this context, larger information systems “cover the organizational processes, procedures, and roles employed in collecting, processing, distributing and using data [21]“.

Strong et al. [21] define four DQ categories: Accessibility, Representational, Contextual, and Intrinsic. The Accessibility DQ and the Representational DQ are technical in nature and must be ensured within the information system. The Contextual DQ and the Intrinsic DQ, however, must be ensured during the transfer of data into the information system. Therefore, Dietrich et al. [22] recommend firstly considering all processes and events with a high Contextual DQ – meaning, they are of high relevance for the traceability objectives within *or* between enterprises. Based on this, it can be determined, what data needs to be stored within the Enterprise Layer and what data needs to be pre-selected in preparation for layers of the connected world.

A wide range of technologies can be used for tracking and tracing within the Enterprise Layer. It is important to connect the assets by means of identification technologies such as RFID [9] or QR-Codes to their digital identities in order to track them within the enterprise or throughout the connected world. This allows the tracking and tracing of assets after leaving the enterprise in subsequent stages of the supply chain. For storing and processing the data, central systems and distributed cloud services represent suitable solutions. For processing time-critical data, EDGE-Clouds can be considered [23].

3.2. Supply Chain Structure Layer

The Supply Chain Structure Layer represents the first layer of the connected world and therefore extends the traditional RAMI4.0 model. It focuses on the mapping of all entities in the supply chain network and their relationships to each other. Therefore, the Supply Chain Structure Layer describes the “who is involved” in the respective supply chain network. A specific emphasis on supply chain structures in a separate layer is necessary due to emerging legal requirements. In July 2021, Germany passed as the first European country the so-called ‘Act on Corporate Due Diligence Obligations for the Prevention of Human Rights Violations in Supply Chains’ (German: Lieferkettensorgfaltspflichtengesetz - LkSG) [24]. The law will come into force on 01.01.2023. As of this date, German companies are legally obliged to “prepare an annual report on the fulfilment of its due diligence obligations in the previous financial year and make it publicly available free of charge on the enterprise’s website no later than four months after the end of the financial year for a period of seven years” [24]. Thereby, the reporting obligation mainly comprises the disclosure of supply chain structures. The law focuses particularly on compliance with human rights throughout the supply chains to prevent issues such as child labour [25].

The German Act on Corporate Due Diligence Obligations in Supply Chains represents the first execution of a pan-European project and therefore serves as a role model for cross-European laws with similar objectives. A First draft “Towards a mandatory EU system of due diligence for supply chains” extends the focus on human rights in the German law with the inclusion of sustainable corporate governance [26]. With the extension of the legal requirements to all European companies, the transparency regarding supply chain structures is gaining global significance. Such due diligence for supply chains pressure companies to make their supply chain network transparently available to the public. These laws aim at disclosing all business partners and their business relationships – the supply chain structure – irrespective of the assets themselves.

Technologically, the supply chain structure layer can be supported by decentralized and/or distributed systems. All companies affected by the reporting obligation can access decentralized databases in order to map their supply chain structures. Due to the dynamic nature of I4.0 supply chains, difficulties can arise in maintaining these structures, as the entire supply chain structure must be mapped and not only the relationship to direct suppliers. In addition, individual suppliers must eventually participate in many different supply chains from different end producers. This increases the administrative efforts of suppliers with multi-organizational collaboration. As an alternative to the distributed database, decentralized databases such as blockchain technology can be used in this layer to serve as a common technological standard for the entire supply chain. A recent study shows that even competing firms in a shared supply chain can benefit from a blockchain collaboration and an increased supply chain network visibility [27].

3.3. Supply Chain Event Mapping Layer

The Supply Chain Event Mapping Layer extends the visibility of the supply chain structure with the incorporation of supply chain events that can possibly affect assets throughout the supply chain. Therefore, this layer enables a discrete tracking of all core supply chain events. In order to define the extent of supply chain events, this layer integrates the Event Product Code Information Services (EPCIS) standard of GS1 [28].

The EPCIS standard enables “different applications to create and share event data with visibility, both within an enterprise and across enterprises [28]”. Each event is described with the four dimensions of the generic ‘EPCIS-Event’. These four dimensions are the object(s) or other entity(ies) that are the subject of the event, the date and time, the location where the event occurred, and the business context [28]. In summary, the generic EPCIS-Event describes “what, when, where and why” something happens. The ‘what’, in turn, is differentiated into the four core event types Object Event, Aggregation Event, Transaction Event, and Transformation Event [28]. According to GS1, the definitions of these core SCEs are as follows [28]:

- *Object Event.* “The Object Event represents an event that has happened to one or more physical or digital objects”.
- *Aggregation Event*. “The Aggregation Event represents an event that has happened to one or more objects that are physically aggregated (physically forced to be in the same place at the same time)”.
- *Transaction Event*. “The Transaction Event represents an event where one or more objects are associated or disassociated with one or more identified business transactions".
- *Transformation Event*. “The Transformation Event represents an event in which input objects are fully or partially consumed and output objects are produced, such that any of the input objects may have contributed to all of the output objects”.

As envisaged in the AAS, central systems can be used for the holistic mapping of supply chain events. Here, the metadata of an asset must always be copied to the next system under a new identification number when having transaction events [19]. Alternatively, distributed central cloud systems such as cloud manufacturing can be used. In this case, supply chain networks can join forces and connect their assets and materials with virtual identities in the cloud in order to increase the flexibility and efficiency of their manufacturing processes [29]. Furthermore, it is possible to map and trace supply chain events holistically with decentralized blockchain-based applications. Such a solution provides assets being represented by smart unique tokens on the blockchain. This creates decentralized and free token ecosystems that can map even unforeseen changes to the composition of assets and supply chain structures [30].

3.4. Continuous Tracking Layer

The Continuous Tracking Layer describes the mapping of all parts of the supply chain network going beyond the intermittent nature of mapping supply chain events. Consequently, this layer describes the tracking of a continuous data flow of information that occurs ‘in between’ the respective supply chain events. This particularly includes the transport routes between transaction events. Such continuous tracking information flow not only increases the reaction time to negative supply chain impacts for individual organisational units but also increases the efficiency of the entire supply chain network [31].

The technological solutions used in this layer include localisation technologies, mobile communication technologies, as well as technologies for data processing and data storage. One established technology to enable continuous tracking is the Global Positioning System (GPS) [32]. Apart from GPS, the 5G technology with its integrated localization service represents another emerging technology to meet the requirements of the Continuous Tracking Layer [33]. In addition to the localization service, 5G technology offers companies the possibility of setting up their own non-public networks [33]. Thus, 5G represents a holistic solution enabling the coverage of transitions between public transport routes and factory sites. Due to the required storage capacity and the continuous data flow, central database systems are suitable for data processing and storage. Furthermore, in application scenarios with high requirements in terms of localization accuracy Edge Clouds can be considered [32].

3.5. Digital Shadow

In an I4.0 context, the Digital Shadow describes a “sufficiently accurate” mapping of processes aiming at creating a real-time evaluation basis of all relevant data [34]. It can be understood as a platform that integrates

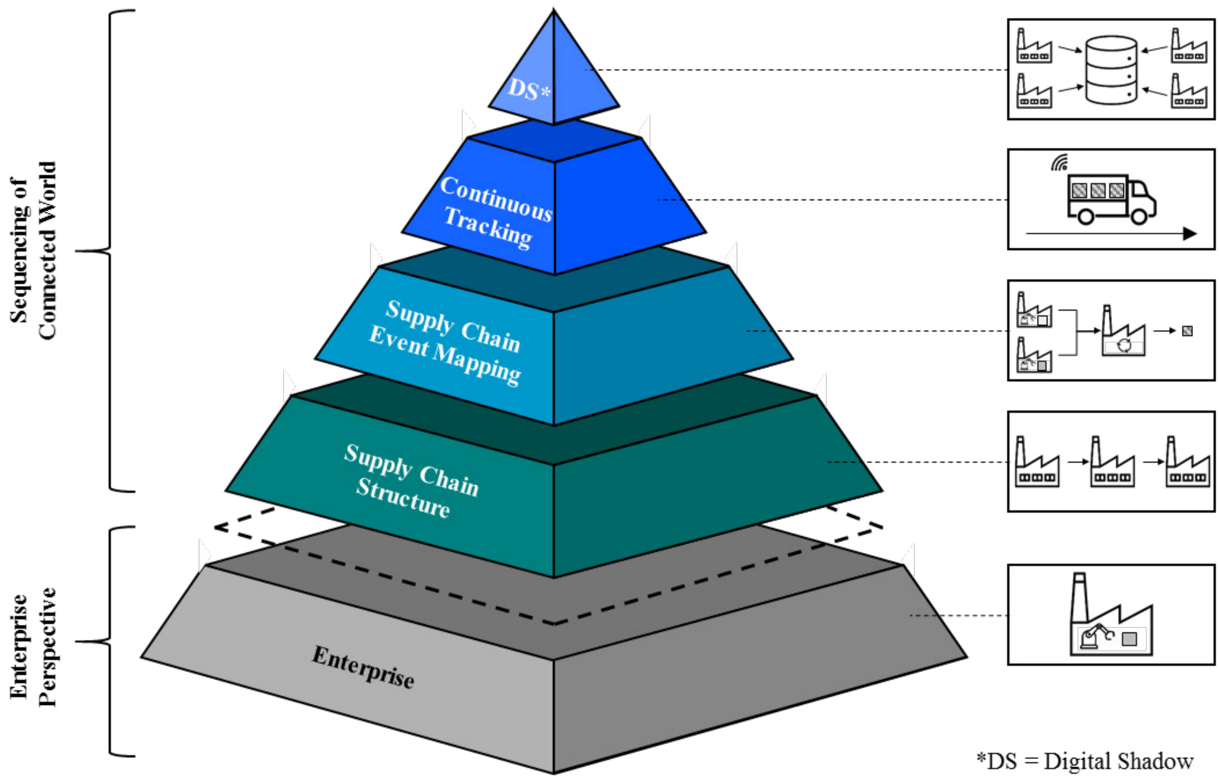

Fig 2. Model for holistic mapping of supply chains by means of tracking and tracing technologies

heterogeneous data from different sources to enable miscellaneous real-time analyses for decision-making [35]. A common feature of the Digital Shadow is the fusion of multiple inputs into a coherent digital representation [35], which can be used for data analytics [36]. Based on the Digital Shadow and the evaluation of past events, the question "why did something happen?" can be answered.

In contrast to the digital twin, the Digital Shadow only contains a small amount of information. In order to choose the most appropriate information, there has to be a precise definition of the required information quality [37]. Therefore, in the proposed model the Digital Shadow fuses and processes the supply chain data gathered in the previous layers to create a holistic digital representation of the involved enterprises, their supply chain structure, supply chain events, and continuous processes. Due to the size of the data and the computing power required for processing and analysing the data, cloud services from powerful data centres are particularly suitable to support the Digital Shadow.

3.6. Model For Holistic Mapping of Supply Chains

The proposed model consists of five identified layers. The Enterprise Layer represents the data foundation and its structure is strongly oriented towards the well-established RAMI4.0 model. The other four layers describe the sequencing of the connected world. In doing so, the Supply Chain Structure Layer is oriented towards new legal requirements such as the Act on Corporate Due Diligence Obligations for the Prevention of Human Rights Violations in Supply Chains. Based on this, the Holistic Supply Chain Event Mapping Layer links the supply chain structure with asset-related supply chain events. These consist of the four core events specified in the GS1 standard – Object Event, Aggregation Event, Transaction Event, and Transformation Event. Subsequently, the Continuous Tracking Layer connects the intermittent supply chain events with a continuous data flow. The Digital Shadow forms the tip of the model. It summarizes the heterogeneous data structures into a holistic picture of the entire supply chain. Figure 2 shows the Model for holistic mapping of supply chains by means of tracking and tracing technologies.

4. Conclusion and Discussion

This paper proposes a first draft towards a new model for the holistic mapping of supply chains by means of tracking and tracing technologies. The model consists of five layers and aims at sequencing the complexity of the connected world in I4.0 supply chain networks firstly introduced in the RAM4.0 model. The proposed model considers new legal requirements, the involvement of supply chain event standards, and integrates new technological possibilities of emerging technologies such as the blockchain, cloud manufacturing, and 5G. This enables supply chain networks to address missing elements in order to enable a holistic mapping of their supply chains. Further research is being conducted to validate the model with regard to its completeness and to specify the impact of emerging technologies. Furthermore, a framework is being developed connecting the layers of the model with technological recommendations for action based on the objectives of industrial application scenarios.

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