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Ontology-based matchmaking and scheduling for Manufacturing as a Service

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Abstract

The pressure to develop a resilient value chain is currently a significant challenge due to a wide range of influences and disruptive factors. In achieving resilience, Manufacturing as a Service (MaaS) is a new approach with the potential to increase the responsiveness, flexibility, and scalability of manufacturing industries. The manufacturing services offered must match the specific requirements of the companies requesting them. Based on the analysis of the current state of knowledge, a three-stage ontology-based matchmaking approach is proposed to support human decision-makers in satisfying on-demand needs through the use of shared manufacturing resources offered as services. The capability of the proposed approach to semantically connect MaaS users is demonstrated for a MaaS scheduling service, which coordinates the execution of a set of on-demand manufacturing jobs by shared resources. Despite the constraints associated with the technical and organizational dimensions of industrial sectors, as well as with the complexity of supply chain dynamics, several key levers for expanding the adoption of MaaS are discussed throughout this paper.

Keywords: Manufacturing as a Service; Ontology; Matchmaking; Scheduling as a Service

1. Introduction

Manufacturers are increasingly empowered by digital capabilities (including IoT, cloud computing, automation, and big data), which enable them to improve performance at the facility (or fab for short) level. The ongoing industrial revolutions, Industry 4.0 and Industry 5.0, change the production environments and the way in which performance is evaluated [3]. This alone is not enough in our realities marked by complex, multifaceted challenges that can be described as **B**rittle, **A**nxious, **N**on-linear, and **I**ncomprehensible (BANI[1]) settings as a new normal, sustainability imperatives, etc. Expanding integration and the collaborative scope between manufacturing stakeholders becomes thus essential [6]. Along with other technologies (e.g., information technology, inter-organizational information systems, digital product passports, and cloud-based collaborative platforms), Manufacturing as a Service (MaaS) emerges as an enabler to further enhance the responsiveness, flexibility, and scalability of manufacturing industries, fostering the development of resilient, sustainable, and circular industrial practices.

To support the unlocking of MaaS's potential, this paper addresses the following relevant questions of current importance: **(i)** *Concept perspective* (Section 2): What impedes the widespread adoption of MaaS despite its clear benefits, and how its broader implementation can be supported?, **(ii)** *Bare essentials*: Data exchange is required to enable MaaS[2]. What are the fundamental features of an ontology-based matchmaking for MaaS? (see Section 3) How can matchmaking be leveraged to enable interaction with other subsequent services, such as MaaS scheduling service to efficiently coordinate the execution of a set of on-demand manufacturing jobs by shared resources? (see Section 3).

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2. MaaS: *Definition, motivations, barriers*

Definition. Manufacturing as a Service (MaaS) has the potential to transform supply chain models, from dyadic to complex and networked ones, by leveraging manufacturing capabilities to provide cost-effective, scalable, and fast solutions, not only under normal operating conditions but also in abnormal ones such as disruptions happening in different segments of supply chains (from supply to distribution). The transformation from production-oriented manufacturing to service-oriented manufacturing is enabled by cloud manufacturing [16, 8, 2]. Various definitions of MaaS coexist in the related literature. In this paper, the following compounded definition is adopted:

Definition ([17], the European Commission[2]). *MaaS represents a service-based manufacturing concept that is enabled by cloud manufacturing and managed in a centralized way for responsive, flexible, and scalable manufacturing industries.*

In a previous work, [17] characterized the key features of MaaS, as follows (slightly expanded). MaaS can disperse manufacturing services across both geographical and logical boundaries. Primarily demand-oriented, MaaS is characterized by short-term collaboration as frequently as needed. MaaS provides both individual manufacturing services and combinations of such services (i.e., service bundles) within and across industry boundaries.

Motivations. The servitization of manufacturing had a strong push in our current BANI[1] realities due to its capability to mitigate various disruptions along supply chains caused by lack of workers, limitation of shipment, or breakdowns of suppliers [9, 18]. The disruptions showed the fragility of the global supply chains with just-in-time approaches, as smaller delays may lead to huge problems later in the supply chain [12, 10]. Generating the possibility of creating new purpose-oriented, more regional-orientated value networks may increase the supply chain resilience and the circularity of our economy, and make the manufacturing sector more sustainable:

- *Resilience:* The most crucial type is increasing resilience, which means addressing a crisis. In this study, this would mean the disruption of a supply chain node/link (transportation of supplied goods/materials supplier's facility itself). MaaS can be applied to recover as quickly as possible.
- *Circularity:* As a key player in the circular economy, manufacturers are well placed to create and exploit new circular business opportunities together with upstream and downstream stakeholders. Supported by cloud manufacturing, the MaaS mechanism supports stakeholders to play collectively across their value chains (business models and value creation) to allow them to narrow (use less and more efficiently), slow down (use longer), and cycle (use again).
- *Sustainable manufacturing: (Economy, society)* MaaS allows manufacturers to scale production up and down without cost based on demand. MaaS can thus contribute to increasing the Overall Equipment Efficiency (OEE) and make full use of qualified personnel. This implies the generation of business models around manufacturing services that are demand-oriented. *(Environment)* Optimized equipment utilization leads to better resource consumption and less environmental damage.

On the widespread adoption of MaaS. One of the most important differentiation characteristics of MaaS from contract manufacturing is the high level of digitalization/connectivity of stakeholders[3]. The vision of a networked production with a high level of vertical connectivity and consistent data flow has been defined by the principles of *smart manufacturing*. Despite the anticipation of enhanced productivity with simultaneous flexibilization, current surveys indicate that the complete implementation of this vision remains elusive [5]. In particular, small and medium-sized companies with a great variety of product variants are falling behind in the interconnection of field-level (physical assets) and management-level (fab-wide control) [1]. This indicates that not all data gathered in production and associated internal processes can be accessed in real-time and used for data-driven services. Consequently, the seamless integration of Manufacturing Services (MfgS) into established value-creation chains represents a significant challenge for manufacturing enterprises.

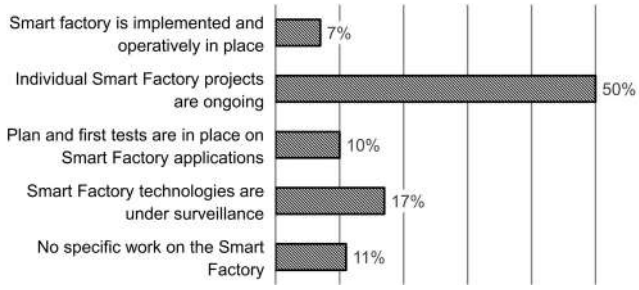

Fig. 1. Degree of implementation of smart factories in Germany based on the work of Feldmeth [5]

As figures about the degree of vertical connectivity are missing, an indication can be derived from other numbers. Therefore, as illustrated in Fig. 1, more than 40% of manufacturing companies lack a connection between field devices (machines, equipment, and tools) and management systems at the enterprise level, which can facilitate system-based access to data. Consequently, today only a few companies can take advantage of a comprehensive data processing system to identify suitable matches between demand and supply in the manufacturing sector. As data sharing is crucial, but companies classify data as sensitive, this is a large hurdle for implementation.

At a supply chain level, collaborative Inter-Organizational Information Systems (IOIS) have been implemented in numerous supply chains over the past two decades to improve integration and coordination (e.g., SupplyOn[4]). Despite their potential benefits, widespread adoption has been limited mainly by the small number of proactive industry participants and the complexity of integrating autonomous business processes [6]. Having a larger scope, MaaS inherits the necessary conditions of IOIS, including technical and organizational alignment between

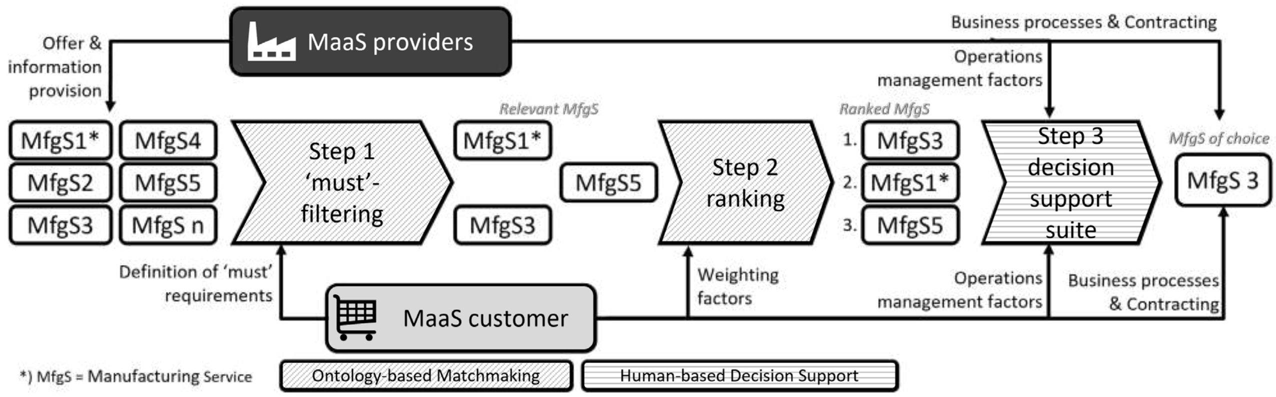

Fig. 2. Step-wise orchestrated matchmaking with human as final decision maker supported by a decision support suite

companies/industry sectors and the orchestration of spatial and temporal dynamics of distributed systems of production.

Barrier mitigation strategy for MaaS adoption. In light of the facts discussed previously, it is essential to consider the different degrees of connectivity/digitalization of potential users to facilitate the expansion of MaaS. However, if data is classified as sensitive, this complicates the necessary transactions between users, making it challenging to enable subsequent services. Deep diving into the different industries offers a new understanding of relevant characteristics (see e.g., the casebook provided by the MASTT2024 project[3].): **(i)** *On the importance of semantic interoperability:* Free capacity can have different meanings depending on the industry or technology in focus. For instance, in sheet metal processing, free capacity refers not only to a machine that is not occupied but also to free space on the raw sheet metal plane, which could be addressed by an efficient nesting of parts to be cut out. **(ii)** *"The devil is in the detail":* This example shows that additional details could be considered depending on the process step and the applied technology. **(iii)** *Towards the multi-instantiation of MaaS:* Besides digitalization and connectivity, the capability to share/use production resources can be constrained by multiple barriers: lengthy and costly homologations/qualifications of industrial processes (e.g., aerospace), manual manufacturing (e.g., electronics), and quality control requirements (e.g., automotive), etc. An immediate step towards MaaS would be to share accurate and timely information to allow upstream or downstream operators, followers of MaaS, to adapt their production capacities swiftly or to use/share qualification-free machinery. Even for this first step, the relevant data must be automatically derived from the existing information systems of the MfgS provider and customer. **(iv)** *Towards the management of MaaS production workflow:* Conventional enterprise software (e.g., enterprise resource planning, manufacturing execution systems) designed for traditional manufacturing processes lack the capabilities to manage the particular features of service-oriented manufacturing systems.

In Section 3, we present the fundamental data requirements and minimal transactional data that allow for the establishment of an effective matching system for MfgS and collaborative decision support. Easy-to-use, real-time data exchange/monitoring, and automation of processes are among the main MaaS specifications[3]. During the transition to MaaS, we propose to relax the real-time specifications in favor of event-based ones. We argue that this strategy does not violate the definition of MaaS as long as the relative advantage is applied to measure and demonstrate the responsiveness, scalability, and flexibility of manufacturing ecosystems, as done for the adoption of IOIS [6]. The approach dedicated to connecting semantically MaaS users to support better decision-making within collaborative manufacturing networks is illustrated via a MaaS scheduling service.

3. MaaS: *From matchmaking to other services*

With the rise of a platform economy, multiple stakeholders in Europe pointed out that large platforms in the USA and China can harm the sovereignty of the European industry [11]. In this sense, Gaia-X[5], a European initiative, was started with the objective of creating a federated data infrastructure that ensures secure and sovereign data sharing across cloud services [19]. The main elements are interoperability, data portability, and compliance with European regulations, which foster the stakeholders' willingness to collaborate. Besides a clear governance framework, a focus lies on transparency and security in data transactions, reinforcing Europe's digital autonomy and driving the development of a competitive digital economy [13].

Ontology-based matchmaking approach. Semantic product requirements and process attributes are crucial for an accurate and efficient matchmaking of manufacturing capabilities. The matchmaking process involves comparing the product requirements with the capabilities of available MfgS, ensuring compatibility and optimal resource utilization.

A fundamental feature of the Ontology-Based Matchmaking (OBMm) is the ability to define must-requirements for the selection of services and to weigh these requirements at least in clusters, therefore enabling the users to prioritize certain requirements or requirement clusters such as sustainability or resilience depending on the situation. Consequently, to represent requirements, the ontology concept has attributes to describe its must-characteristics and its importance for the decision situation by associating a weight, which is a sharp numerical value. In future work, these sharp values for the weighting may be advanced towards a linguistic variable in the sense of fuzzy-set theory or related. In addition, requirements have a Boolean attribute *isNegated* to realize logical not-operations.

The OBMm is divided into three steps, as illustrated in Fig. 2: **(i)** The available services are filtered by the must-requirements based on their characteristics. **(ii)** The remaining services are ranked in accordance with their fulfillment of the requirements to support the decision-maker. **(iii)** Humans, as decision makers, are therefore not patronized by the approach for OBMm but supported by a ranking of applicable available manufacturing services, which they can choose based on their preferences or the specific decision situation, respectively. The decision support suite can include various MaaS services dedicated to making feasible the resource exchange from an operations management point of view, ranging from concurrent supply chain planning capabilities (scheduling, production planning, etc.) to coordination support (pricing). For illustration purposes, we examine how must-filtering and ranking steps support the scheduling service in the next paragraph.

For the OBMm, requirements refer to characteristics of manufacturing services. Both requirements and characteristics may not be quantifiable, but they have reference values for comparison. If they are quantifiable, they refer to a quantity that has at least a value and a unit of measurement and can be derived, e.g., from the National Aeronautics and Space Administration (NASA) ontology for Quantities, Units, Dimension, and Types (QUDT) [15]. Alternatively, other ontologies for quantities may be used. If requirements and characteristics are not quantifiable, they refer to an arbitrary instance of a class of ontology. For quantified comparisons, requirements can request equality but may be based on a minimum or maximum condition with included or excluded boundary values (so they can be closed or opened as intervals). Thus, to define quantified requirements based on an interval, users must define two requirements, one for the minimum and one for the maximum condition. Non-quantifiable requirements are fulfilled if the characteristic ”has” an arbitrary instance of the ontology class, which is defined by the reference value of the requirement.

Manufacturing service and resource scheduling. Scheduling problems emerged in the 1950s as a decision-making problem aiming to ensure the execution of manufacturing steps (i.e., operations) by a set of resources while meeting production Key Performance Indicators (KPIs) of a given fab efficiently [3]. Much research has focused on this problem since then, given the straightforward and critical impact of scheduling decisions (including assignment of operations on machines, sequencing of operations on machines, and operation timing) on production efficiency (such as cycle time, throughput, and on-time delivery). Even if scheduling problems have been addressed mainly in centralized scheduling frameworks, problems are organized in a distributed and hierarchically (temporally and spatially) manner. Powered by physical systems, the IoT and cloud computing, automation, and big data in the manufacturing industries have tremendously pushed forward the scheduling landscape by unlocking horizontal and vertical integration as well as decentralized and autonomous scheduling [14]. This allows for integrating hierarchical decision levels in the scheduling process by considering supply chain information. Scheduling full fabs is generally a highly complex problem. Global-local scheduling approaches gain momentum. Global scheduling operates at a fab-wide level and prescribes targets for sets of tools. Local (or toolset) scheduling considers the work-in-progress to identify the best current dispatching decisions [4].

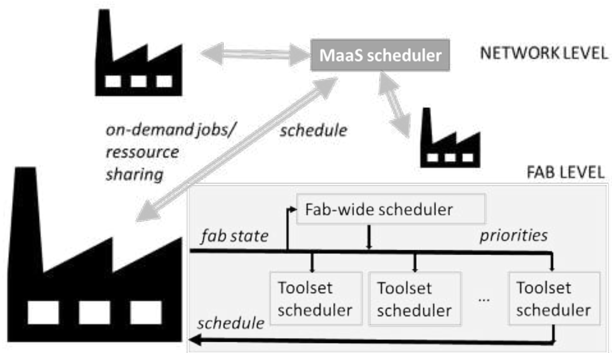

Fig. 3. Vertical and horizontal integration of scheduling decisions: *From toolset to MaaS and vice versa* (extension from [4])

MaaS scheduling can be seen as a natural extension of scheduling in shop floors, as illustrated in Fig. 3. To support distributed manufacturers in sharing and using manufacturing resources, consider a MaaS framework that manages the scheduling of requested jobs on shared unrelated parallel machines in a centralized way. Following the pipeline applied for production planning developed within the SC3 EU project[6], let us define the minimal set of requirements to be met by the ontology for supporting scheduling decisions within MaaS:

- *Data representation for centralized MaaS scheduling of a distributed set of jobs on a distributed set of resources:* Let $j \in \mathcal{J}$ be a set of on-demand jobs specified by the resource consumers jointly with a due date, denoted by d_j, of job j. Let $k \in \mathcal{M}$ be a set of unrelated parallel shared machines (i.e., production capacity) proposed by a number of MfgS providers jointly with a set of available time slots $\mathcal{A}_k = \left\{[s_1, e_1], [s_2, e_2], \dots\right\}$.

  Minimal master data and transactional data for MaaS scheduling are provided in Table 1. To support the generation of scheduling problem instances, at least three linking parameters must be constructed by OBMm (Step 1): **(i)** Subset of machines $\mathcal{M}_{ij}$ capable of executing operation i of job j. **(ii)** The time operation i of job j takes to be processed by machine k, denoted by p^k_{ij}, and **(iii)** Eligibility score e_{jk} of performing job j on resource k.

- *Automated generation of instances of scheduling models*: Scheduling problems are generally classified formally by a conventional three-field notation α, β, γ proposed by [7] and widely adopted by the scheduling community, where: α refers to extensions introducing new types of decision, β refers to problem constraints, γ specifies criterion/criteria to be optimized.

To instantiate the model of the MaaS scheduling problem, it is necessary: **(i)** to consolidate the specifications of resource consumers $< \alpha_c, \beta_c, \gamma_c >$ and providers $< \alpha_p, \beta_p, \gamma_p >$, and **(ii)** to aggregate and align γ_p and γ_c to apply the best γ_{cp}.

Note that, by virtue of the MaaS definition, the scope and domain of MaaS performance criteria (at the network level) can be larger than the union of fab-level performance criteria:

$$\bigcup_{c\in C, p\in P} \gamma_{cp} \supseteq \bigcup_{c\in C} \gamma_c \cup \bigcup_{p\in P} \gamma_p$$

With the network-wide visibility of cross-industry fabs enabled by MaaS, the set $\bigcup_{c\in C, p\in P} \gamma_{cp}$ can serve multiple purposes achievable only at the network level, including enhancing resilience/robustness (schedule stability, job slacks, and machine workload, etc.), sustainability (machine idle time, machine speed, production during the off-peak periods, time-of-use tariffs, etc.), and competitiveness (OEE, time to market, etc.).

- *Automated generation of instances for a given scheduling problem:* In a MaaS framework, schedulers can be called in a rolling setting. This leads to a series of scheduling instances, which are created considering the current state of production environments. The structure of a scheduling instance must be represented using the proposed ontology based on the three-field notation of [7].

- *Representation of the MaaS scheduling process:* The resource sharing occurs between two or more fabs (related or autonomous), requiring alignment of scheduling decisions among all involved stakeholders. To deal with this joint scheduling problem, MaaS must specify the synchronization of manufacturing activities to support the sharing of common gains and framing of partnerships within a network involving at least one MfgS provider and one consumer.

  Operating in a dynamic environment, a critical question in a MaaS framework is the scheduling process itself. Let us distinguish different classes of approaches [20]: **(i)** *Proactive approaches*: All jobs and machine availability and associated parameters are known in advance, either in a deterministic or probability-based format. Typically, the goal of these approaches is to determine a sequence that optimizes scheduling criteria of interest. **(ii)** *Completely reactive approaches*: No schedule is generated in advance. Decisions are taken locally in real time by considering the current set of available jobs. These approaches typically rely on simple policies such as shortest processing times and earliest due dates. **(iii)** *Predictive-reactive scheduling*: A schedule is generated beforehand by considering the available information. When the predictive schedule is subject to updates due to new events, reactive alternatives modify the schedule.

- *Representation of scheduling decisions:* After an instance of a scheduling model is solved, the associated decisions must be represented using the ontology. MaaS schedule decisions serve as input for fab-internal scheduling decisions/schedulers.

Table 1. Minimal set of master data and transactional data for MaaS scheduling

Production resource consumers $c \in C$	
$\mathcal{J}$	Set of jobs
$O = \cup_{j\in J} O_j$	Set of operations partitioned into a set of jobs J
d_j	Due date of job j
β_c	Constraints imposed by consumer c
γ_c	KPIs of consumer c
Production resource provider $p \in P$	
$\mathcal{M}$	Set of available production resource k
$\mathcal{A}_k = \{[s_1, e_1], [s_2, e_2], \dots\}$	Set of available time slots $[s_\bullet, e_\bullet]$ of resource k
β_p	Constraints imposed by resource provider p
γ_p	KPIs of provider p
MaaS framework	
$\mathcal{M}_{ij}$	Subset of machines capable of executing operation i of job j
e_{jk}	Eligibility score of performing job j on resource k
p^k_{ij}	Processing time of operation i of job j on resource k (net processing time)
α	Set of decisions for resource consumer c and provider p
γ_{cp}	MaaS optimization criteria conciliating KPIs of resource consumer c and provider p

Connecting matchmaking scheduling services in a MaaS framework. Based on a service-oriented design, it is necessary to create interfaces between MaaS functions. Matchmaking aligns technical, organizational, and certain temporal framework conditions with requirements. Scheduling focuses on optimizing the assignment of operations on machines, sequencing of operations on machines, and operation timing. Thus, there are certain overlaps in the properties and characteristics to be analyzed.

As a linking time-related parameter in a distributed system, modeling processing times is critical. They can be: **(i)** *Known* by virtue of fabs' connectivity. This is the case for most practical use cases and corresponds to high levels of fab connectivity and information sharing. **(ii)** *Instanciable* by MaaS based on the characteristics specified by the resource providers and consumers. This corresponds to high/low fab connectivity and medium information sharing. **(iii)** *Unknown:* Modeled in an implicit way for low levels of fab connectivity or information sharing. To do this, let us assume a low level of connectivity and a significantly low amount of information available. The temporal fit can only be insufficiently optimized in Step 1 of the OBMm (see Fig. 2). To assign on-demand jobs j to available resources A_k while respecting due dates j, one can consider the net processing times. The net processing time can be calculated by subtracting the transport times (i.e., the time for transportation to/from) from the gross processing times (i.e., maximal time available before delivery, not violating due dates). Transport times should not exceed a fixed percentage of the gross processing times.

4. Concluding remarks and perspectives

The widespread adoption of MaaS is impeded by heterogeneous information systems and the lack of frameworks within which quantitative operations can be managed concurrently. Therefore, the availability of data, as well as the connection of the data flows of the different actors in MaaS-ecosystems, have to be improved. For this, technical means in the sense of IT networks, as well as a common language for the communication between the actors, are needed. Upcoming open digital ecosystems (e.g., Gaia-X[5], Catena-X:[7]) as IT-linkage between actors are essential for increasing the number of potential users. To support this, ontologies as "lingua franca" for the communication are a promising approach to advance the interoperability between supply chain actors, and even between industrial sectors, consequently making viable MaaS. This paper proposes a three-stage ontology-based matchmaking approach and illustrates its capability to semantically connect MaaS users to support a scheduling service that manages the execution of a set of on-demand manufacturing jobs by a set of shared resources, thereby ensuring the economic application of MaaS at service provider side.

Future work will address the programmatic realization of MaaS ecosystems and their quantitative justification with regard to economics, resilience, and sustainability.

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Notes

1. The BANI World, for IRSM 2022: https://www.youtube.com/watch?v=stBdyNBwfpU&ab_channel=JamaisCascio
2. Manufacturing as a Service: Technologies for customized, flexible, and decentralized production on demand: https://www.horizon-europe.gouv.fr/manufacturing-service-technologies-customised-flexible-and-decentralised-production-demand-made
3. Manufacturing as a service for the EU'S twin transition until 2040 (MASTT2040): https://www.mastt2040.eu/
4. SupplyOn platform: https://www.supplyon.com
5. Gaia-X: A Federated Secure Data Infrastructure: https://gaia-x.eu/
6. Semantically Connected Semiconductor Supply Chains (SC3): https://cordis.europa.eu/project/id/101007312
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