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Holarchy for line-less mobile assembly systems operation in the context of the internet of production

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Abstract

Assembly systems must provide maximum flexibility qualified by organization and technology to offer cost-compliant performance features to differentiate themselves from competitors in buyers' markets. By mobilization of multipurpose resources and dynamic planning, Line-less Mobile Assembly Systems (LMASs) offer organizational reconfigurability. By proposing a holarchy to combine LMASs with the concept of an Internet of Production (IoP), we enable LMASs to source valuable information from cross-level production networks, physical resources, software nodes, and data stores that are interconnected in an IoP. The presented holarchy provides a concept of how to address future challenges, meet the requirements of shorter lead times, and unique lifecycle support. The paper suggests an application of decision making, distributed sensor services, recommender-based data reduction, and in-network computing while considering safety and human usability alike.

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1. Introduction

Industrial assembly is the primary, value-adding activity in the value chain of production [1]. It comprises of all processes that join bodies, parts, and subassemblies, which, in turn, can be geometrically defined solid pieces or shapeless materials. It is generally characterized by a high degree of complexity caused by inherently cross-linked sub-processes, sophisticated material flows, and very short indivisible subtasks. Thus, there is a large parameter space regarding the assembly configuration, and optimizing the assembly processes is often a major priority. This priority is especially relevant when companies are confronted with increasing customer change requests, cost pressure, and technological progression. This market turbulence results from buyers' markets demanding individualized products with short lead times and product lifecycles. Considering that assembly accounts for up to 44% of overall cost and 70% of the time consumed for the entire chain of production [1], a central observation is that flexibility and optimality are key requirements for assembly systems. Future concepts, such as the Internet of Production (IoP) [2], also call for new assembly paradigms to make use of the developing advances in information technology, modeling and distributed sensing, and their application to production engineering. In this context, the recently introduced concept of Line-less Mobile Assembly Systems (LMAS) provides a suitable framework to incorporate the aforementioned economically driven requirements [3, 4].

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Contribution. In this paper, we introduce a cross-level service-based holarchy, ranging from the overall planning on the MES-level to operation execution on the field level, to enable a responsive production. Our framework is especially suitable for *LMAS*-driven assembly environments as it incorporates all relevant key enablers and data sources to also satisfy the requirements of tomorrow's smart factories.

Paper Organization. Sec. 2 summarizes assembly requirements and technological enablers before classifying them. Sec. 3 introduces our novel holarchy, which follows the principles of service orientation and Holonic Manufacturing Systems (HMSs). In Sec. 4, architectural prototypes highlight the feasibility of our holarchy. Sec. 5 concludes the paper.

2. Industrial Assembly in the Internet of Production

Terminology in the *IoP* context is introduced and requirements of assembly systems in turbulent environments are identified. The *LMAS* paradigm is explained, which offers novel possibilities to meet functionality, flexibility, and optimality requirements. To implement this paradigm in practice, the *IoP* provides enablers but simultaneously requires further research.

2.1. Preliminaries: CPPS & IoP

This work integrates into the framework of the *IoP*. Its vision is to create flexibility and cross-domain collaboration by providing contextual and semantic production, development, and user data in real-time and at adapted granularity [2]. It further describes a future information system architecture corresponding to the Industry 4.0 vision [5] for Cyber-Physical Production Systems (CPPSs) in smart factory networks. *CPPS*s intend to dissolve the traditional layer-to-layer communication found in pyramidal architectures [6]. They build upon the Industrial Internet of Things (IIoT), respecting the inherent production engineering challenges, i.e., wider parameter ranges, but limited available data compared to other domains. *CPPS*s are characterized by the duality of virtual models (cyber) and real-world (physical) assets as sensors and actuators combined with interoperable information technologies requiring no human intervention to generate and exchange, data in industrial contexts for analysis or operations reasons [7, 8]. Assets act as individual agents, which are arranged hierarchically. The virtual representation of these assets and the production data contribute to Digital Shadows in the *CPPS*, which are context-dependent data traces that answer to manufacturer needs. They are provided across life cycles, create data and knowledge bases for model extraction [9], and are used for data analytics [10] as well as decision and control tasks [11]. The assembly system represented by one or more Digital Shadows (DS) has general requirements, which are described in the next section.

2.2. Industrial Assembly System Requirements

When *CPPS* are created for assembly systems, the following general requirements must be met for a feasible and economical operation:

Functionality. For a functional assembly of products, the system must provide the required processes, operations, and activities in the intended quality within the specifications. In a system's design phase for developed and known products to be built on the system, the necessary functional scope is estimated and considered. However, ever-shorter product life cycles affect system cost amortization as functionalities for building so far unknown products have to be anticipated and may be adapted in the system's operation phase [12]. Further, functionality includes reliability and safety. A reliable and safe system is robust against external disturbances and impermissible operating conditions.

Flexibility. Flexibility is a non-trivial, multidimensional construct, which refers to the effortless and reversible change in system capabilities, respecting external and internal events [13]. It relates to capacities, functionalities, processes, or planning and control [14]: Flexibility in capacity (scalability) refers to shifting output quantities. Flexibility in functionality (adaptivity) allows for diverse requirements to be met, flexibility in processes (configuration) means similar results can be obtained in different ways, and flexibility in planning and control (agility) refers to changes in assignment and scheduling of the to-be-executed activities. Within those dimensions, range, resolution, and mobility are distinguishing features [15]: Range respects the upper and lower bounds of a flexibility interval, resolution denotes the granularity or intermediate states, and mobility refers to the speed and ease of change between states.

Optimality. Respecting the classic conflict of time, quality, and cost [16], an optimal operating point for the system needs to be determined. It has to be in accordance with strategic objectives resulting in temporary quantitative objectives (c.f. [12]). Economic viability is implied, which varies through the choice of the assembly system, considering existing strategic goals and production scenarios. For example, Dedicated Manufacturing Systems (DMS) produce large quantities of low-variant products with low unit costs. However, those are generally inflexible; scaling is achieved by increasing the number of labor shifts and lines. For commodity goods, such an approach is viable, but not for individualized products near a lot size of one.

2.3. Line-Less Mobile Assembly Systems (LMASs)

The Line-less Mobile Assembly System (LMAS) paradigm aims to fulfill the explicated assembly requirements exhibiting maximum flexibility and bases on three main principles [17, 18]: (1) a sufficiently obstacle-free space, without fixed machines or structural restrictions, has to be provided in the factory building, where assembly operations may be executed at any time and any place (**clean floor approach**); (2) Resources related to assembly move either actively as part of a mobile robot or passively with human or robot help (**mobilization**); (3) Production Planning and Control (PPC) has to be established to create suitable system configurations at factory-, station-, or resource-level as well as associated assignments, schedules, and routes (**dynamic cross-level planning & control**). *LMAS*s are hybrid systems respecting automated and manual operations. Humans exhibit similar or better mobility and flexibility features in comparison to multipurpose automation but behave less deterministically. In contrast to Flexible- (FAS), Reconfigurable- (RAS), or Evolvable Assembly Systems (EAS), the unique feature of *LMAS*s is that not only (sub-) assemblies and parts are transported, but also single- and multipurpose machines to constitute temporary stations. The repeated re-allocation of resources (*Flexibility*) is particularly attractive when assemblies' transport efforts are higher than cumulated resource transport efforts. Further, station capabilities have to be respected when assigning product operations to stations (*Optimality*) [4]. After processing, specific stations required for individual products are only dissolved, so that the involved resources can operate with a higher degree of capacity utilization in different stations. Consequently, station capabilities to perform operations are the result of resource emergence (*Functionality)*.

Flexibility is further achieved at different levels and in the dimensions mentioned. *LMAS* scalability is more fine-grained than in FAS and RAS paradigms, as assets can be added individually on resource level in contrast to FAS's and RAS's station level. Thus, capacity increase can be performed on a smaller scale. Adaptivity is implemented on the resource level using multipurpose automation and suitable algorithms to allow process parameters to be adjusted to the situation. System's configuration is executed repeatedly on all three abstraction-levels, as the resources are temporarily equipped with suitable tools or fixtures and combined to form processing stations. On factory level, the locations of these stations are only temporary, allowing to reduce total efforts and distance traveled. Agility is an inherent property of *LMAS*s' dynamic cross-level planning and control.

To operate this novel paradigm in production practice, further research is required concerning the assets of CPPS. Even though the automation pyramid is increasingly disintegrating, IT services for operations are required that handle Manufacturing Execution Systems' (MES) tasks. Three models are important constituting this functionality: (1) An overarching regulatory framework is needed respecting the *LMAS* characteristics. (2) An information model (asset model) is necessary to facilitate communication, data exchange, and interpretation. (3) An interaction model allows for the execution or implementation of process flows involving multipurpose automation.

In general, planning and control architectures for the *overarching framework* can be distinguished in hierarchical, semi-heterarchical, and heterarchical approaches [19]. While resources within *CPPS* in general follow a heterarchical architecture flexibility, optimality, modeling, and operation must be able to consider a semantically global scope. Thus, *LMAS*s are inherently semi-heterarchical as resources are required to reach their predetermined targets autonomously. Implementations of semi-heterarchical approaches in manufacturing are found in so-called Holonic Manufacturing Systems (HMSs), denoted as holarchies integrating necessary operations activities in production into self-organizing but co-dependent hierarchies of subsystems [20]. Its entities are called holons and can be part of superordinate entities while simultaneously representing the comprehensive whole of subordinate entities when viewed from an internal perspective. Their relationships can change over time.

The required information model provides a structure for the multilateral communication between the participants and the overall PPC; Resources are logically organized at the *LMAS* inherent resource-, station- and factory-levels.

The necessary interaction model involves resource-specific functional models and state machines of the agent nodes corresponding to physical hardware. According to the *IoP*, resources shall be enabled to interpret and fulfill the given targets autonomously. Vendor specifics must be respected.

Status and location of the mobile resources on the shop floor are crucial planning and control information. Thus, metrology for both, direct and continuous measurements, as well as indirect and discrete measurements, have to be considered in framework compilation.

2.4. Internet of Production Enabler and Research Gap

The current focus of research is the transition of *LMAS*s from an organizational concept to a technical materialization as *CPPS*s. Previous efforts in the *IoP* context produced results, which are a starting point for *LMAS* implementation:

Computational Power. Advances in information technology have led to scalable provision of computational power via cloud-, edge-, and embedded-computing [21]. Additionally, hardware-level virtualization allows for a separation of concerns cross-hardware with low management and transfer efforts [22]. *LMAS*s require computational power locally on resources to execute operations and globally to realize NP-hard optimization [17]. The implementation of (local) physical control loops poses further requirements in terms of reaction time and guaranteed (real-time) availability.

Algorithms. Artificial Intelligence (AI) and Machine Learning (ML) algorithms allow systems to react appropriately to new, previously unknown situations, increasing autonomy and reliability in the sense of functionality. Performance improvements in algorithms come at a higher computational complexity and thus benefit from the available computing power [23]. In *LMAS*, algorithms enable local and global decision making for agents and nodes.

Interoperability. Interoperability is the ability of independent, heterogeneous systems to work together to exchange information in an efficient and reusable way or to make it available to the user without the need for separate agreements between the systems. It is thus integral to the communication between the different components of an *LMAS* and must be integrated into the information model. Industrial protocols have been established; however, further research is needed to incorporate the domain knowledge [24].

Networks. While fundamental interconnectivity is trivial, the capabilities of a network connection in terms of bandwidth, latency, and reliability exhibits a conflict of aims, especially for wireless technologies. Although still subject to research, novel technologies, such as 5G, and paradigms, such as in-networking processing [25], are expected to be beneficial to *LMAS* system designs in the near future.

Human Factor. Employees in smart factories are not to be rationalized but rather integrated using two ways. Firstly, certain decisions shall remain a human responsibility, that requires data preparation for decision support. Secondly, operators shall execute assembly operations. For both, information provision can be enhanced by augmented reality. As human-robot collaboration is expected, safety must be guaranteed. For *LMAS* and operator safety, only the relevant areas of the network, where collaboration takes place, must be stopped in case of an emergency. Further, for PPC in *LMAS,* predicting human behavior remains a challenge [18].

Autonomous Robots. Multipurpose automation is indispensable for the presented approach. Higher degrees of resource autonomy are required. In unstructured or volatile environments, behavior can be adapted by incorporating additional sensor information. Autonomous guided vehicles (AGVs) and integrated solutions combining 6-DoF-kinematics with AGVs exhibit the desired mobility. Collision-free dynamic motion planning, collaborative path accuracies, and distributed control require further research to satisfy the functional requirements of *LMAS*s.

Distributed Sensing. The availability of sensors and metrology systems, which are indispensable to achieve the desired autonomy, is constantly increasing. They are the most prominent representatives of the need for novel data contextualization methods, i.e., reduction, distribution, and audience-oriented preparation of information as well as the transition between local and global scope. Metrology and systems providing precise and real-time location information are a general scientific problem, but a priority for *LMAS*. Especially as resource location is a novel but primary input variable for overall production planning and control.

The key research gap is the integration of the individual enablers and functional blocks to a holistic system. This gap motivates the proposed holarchy in the following section and is complemented by a need for functional models describing data and behavior of components on all semantic levels with the challenge of interoperability.

3. Concept

The development of a framework to integrate individual enablers and functional blocks into an overall *LMAS* must respect industrial assembly requirements (Sec. 2.2) as well as specific requirements for *LMAS*s (Sec. 2.3). Based on prior *IoP* results and utilizing corresponding technological advances (Sec. 2.4), we propose a holarchy that can provide and use data to describe the functionality and behavior of the different system components. As illustrated in Figure 1, our *LMAS* holarchy exhibits different semantic layers and consists of holons, which correspond to different tasks in production.

In general, a holon either represents a physical component, e.g., the robot to which it is connected, or it exists as a logical asset in which case it can be generated or dissolved at runtime. Each holon consists of a set of functional blocks, directly corresponding to its assigned tasks. The *planning holon* (top right), for example, holds three of these blocks. The *communication* block connects the holon to the others via a general *pub-sub-communication layer*. The *control node* block manages the holon-specific state machine and provides time-dependent services via the interface to the outside world or responds to asynchronous requests via the *pub-sub-communication layer*. The *model* block provides the understanding of holon-specific problems; the *planning holon*, e.g., holds a linear mixed-integer model to minimize the system's total costs [4, 17]. These blocks are individually interchangeable so updates can be deployed. Subsequently, we present the layers and holon types in more detail, presenting Figure 1 from right to left.

Planning Layer. The *planning layer* holds the *planning holon* and the *enterprise holon*. The *planning holon* performs global decision-making and defines local goals for the underlying assets which are realized autonomously according to the current situation. Input is retrieved from the *pub-sub-comm layer*. The *enterprise holon* provides information on customer needs and management specifications.

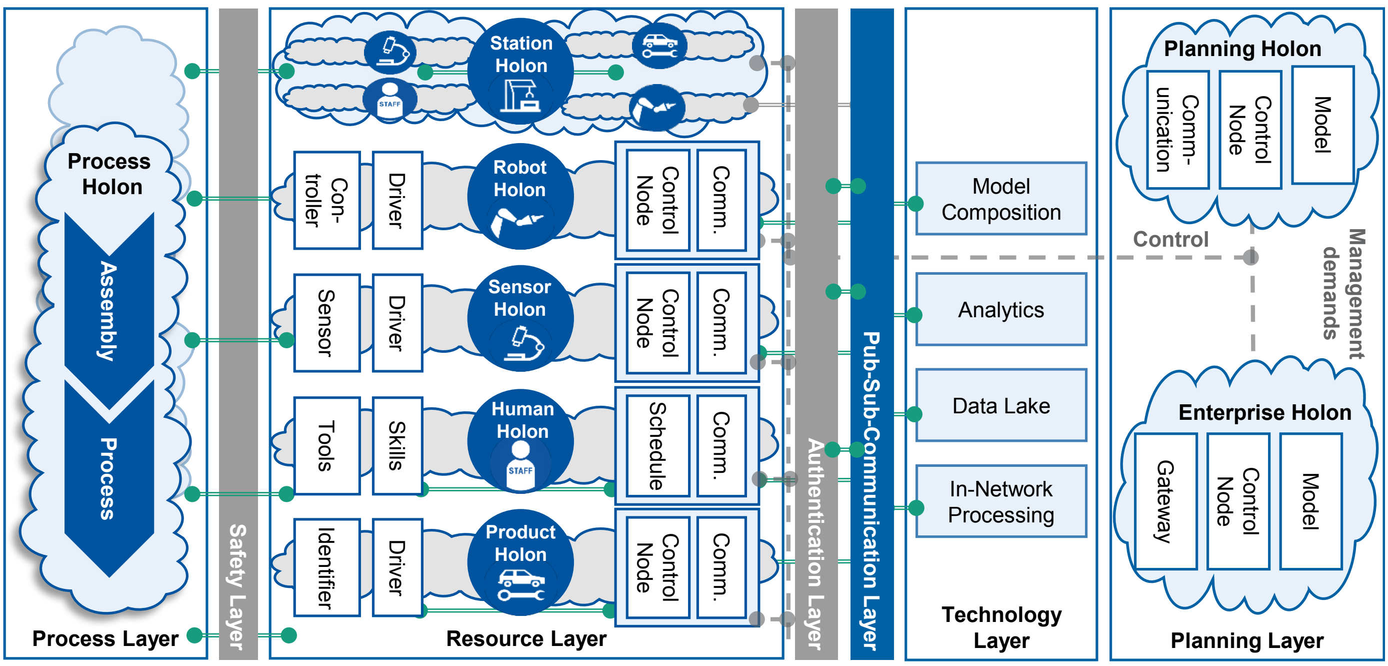

Figure 1: LMAS Holarchy. Holons are semantic cyber-physical entities representing processes, resources, and planning. They hold state models and communication interfaces and are organized according to their abstraction level, organizational purpose, and temporal variability. Levels of abstraction range from factory to local sensors. Layers connect holons and provide technologies as safety, authentication, and Pub-Sub-Communication.

Technology Layer. This layer encapsulates services that only exist in the cyber world and are aggregated logically. Elements of this layer do not execute individual goals but react to requests of connected holons. For instance, simultaneous requests of different holons to the same sensors could overload the network infrastructure; the technology layer provides required information by composing and aggregating information (*model composition*). Available unstructured information is stored in the *data lake* [26]. *Analytics* are deployed to extract meaningful knowledge for requesting holons. To serve time-critical requests with information from multiple assets, we make use of *in-network processing* [25], i.e., small pieces of functionality deployed on networking equipment.

Pub-Sub-Comm-layer. The holons work on drastically different time scales and, thus, have different understandings of when messages need to be received. To ensure robust communication, we consequently deploy a publish-subscribe architecture which detaches senders and receivers and provides asynchronous service. This layer is platform-independent to unify the requirements of the different entities ranging from simple sensors to high-end computation servers.

Authentication Layer. The *authentication layer* provides reliable authentication of the different communicating entities, independent of device-specific capabilities. The consequent identification of the entities further allows for a-priori data scoping and reduction, e.g., for human-machine interaction. It also builds the basis for authorization: While product information shall be accessible cross-suppliers [27], robot control should be limited to the narrowest possible scope to ensure security and resilience. Other aspects involve data privacy and traceability, such that authentication and authorization interests are assumed for all holons and users.

Resource Layer. On the shop-floor level, all resources have a holonic representation entailing the communication (*Comm.*) and functional blocks (*Control Node/Schedule)*. The different physical resources are hereby represented by dedicated holon types (*robot*, *sensor*, *human*, and *product*), which can also be temporarily combined into logical *station holons* to allow for higher-level abstractions that are needed for the planning and control of assembly processes.

Robot Holon. This holon type represents stationary and mobile robots to execute transport or assembly operations. Their *control node* implements AI or ML algorithms to autonomously realize shifting planning goals. The *communication* block retrieves relevant location information from the *pub-sub layer*, either in uncontextualized form or with additional aggregation by the *technology layer*.

Sensor Holon. Sensor information is indispensable to provide real-world feedback to control loops. Most illustrative is the need for a spatial reference frame for assembly operations if fixed monuments are omitted owing to the clean floor approach. Distribution, heterogeneity, and station-overarching of the individual sensors systems motivate the equitable holon definition: Resource abstraction (using system-specific drivers) is fostered by a measurand-oriented, model-based approach to sensor communication and control including a concise set of metrology-related metadata, e.g., timestamp, and unit. Mechanisms for global contextualization of local measurements, historical data access, and stream-based processing are part of the *technology layer*.

Human Holon. Ergonomic working conditions and data privacy need to be respected in *LMAS*s. The *human holon* is attached to the communication layer, so that working instructions are displayed on assistance systems at manual working stations. Information level of detail and frequency of occurrence respect individual skills and are adjusted based on the current (task status, strain, fatigue).

Safety Layer. The reliability of each machine and each data exchange, which could change or adapt the machine behavior, is a key factor when judging whether the system can be deployed in the production environment. Therefore, a *safety layer* has to supervise all system boundaries and interactions and has to provide functionalities for reliable communication in wireless or non-wireless *CPPS*s.

Process Layer. The different stakeholders or physical/ sensor holons have to be controlled to fulfill a certain process step concerning a certain product. Therefore, the process layer aggregates the states of all stakeholders and decides whether all requirements are fulfilled to trigger the next process step in a sequence of steps. Furthermore, sensor data can be used to adapt and optimize the process during runtime.

The proposed concept describes the basic structure, a *LMAS* can be built on. To show that this concept describes a feasible structure, it has to be challenged in real production environments. Therefore, first use case applications implementing this holarchy are introduced in the next section.

4. Towards Future Assembly

To demonstrate the architectural advantages, we present three applications focusing on different layers and holons of the architecture. Those are part of ongoing research in the *IoP* and target different *LMAS* aspects. We illustrate the relation of each use case in the context of the LMAS holarchy.

(i) Human working time prediction. To include the capabilities of human operators in *LMAS*, a prediction of the duration of assigned tasks is required. The analysis of scheduled times for process step execution and captured real processing times show operator-dependent variations that can be captured in distribution functions. Generally, on a planning level, time prediction algorithms are based on Methods-Time-Measurement (MTM). The *data lake* provides the basis for predictions of task durations that have not been performed by the respective operator. By considering predetermined time measurements of task execution, uncertainty in prediction can be reduced. The prediction functionality is provided as a service in the *technology layer*, while the utilities to determine the individual performance of a person is captured in the *human holon*. The prediction is not limited to single working steps; it can be extended to whole tasks and task queues, if the operations in those tasks can be modeled with MTM. By updating the prediction for execution times for the task in real-time, the *human holon* is respected as a multipurpose asset by the *planning holon.* If considered beneficial regarding KPIs, human holons are re-assigned to other tasks.

(ii) Car window assembly process. A full automation scenario is the car window assembly presented in [11]. The process is characterized by numerous variants and product deviations. The process itself is not changing frequently, but robots' trajectories must be adapted to react to part surface deviations. Trajectory adaption is executed during runtime using force-control. The *robot* and *sensor holons* involved in the *process holon* share state information and sensor measurements for trajectory planning and control tasks. The *pub-sub layer* is explicated using MQTT. In future research, safety aspects for a safe interaction in human-machine and machine-machine interfaces need to be examined more closely, addressing *safety layer* relevant demands.

(iii) Global spatial referencing. The *sensor holon* principle is prototyped for the domain of Large-Scale Metrology (LSM) instruments as they are a crucial part of an *LMAS* infrastructure, making a global localization of assets on the shop floor possible. The available prototype comprises of three laser trackers, an iGPS system, and an ultra-wideband localization setup providing a metrological reference frame of the entire shop floor. Communication is abstracted using a technology- and protocol-agnostic model for LSM instruments centered around the mobile assets as core functional elements of the systems [28] and further realized as microservices supporting the Pub/Sub pattern in MQTT. For global information contextualization, a method for automatable coordinate registration is called from the *technology layer* [29]. Its results serve as a source for a set of microservices in the *planning layer* dedicated to resource management. In its entirety, the prototype is subsumed under the term of Coordinates as a Service following the Sensor Information as a Service concept presented by [30].

These use cases, alongside other numerous applications embedded in the Internet of Production, present evidence of how the research and problem statements of the well-known *future assembly* can be abstracted in the layers and holons of the proposed holarchy for *LMAS*.

5. Conclusion and Outlook

Ever shorter lead times and unique product lifecycles pose increasingly high requirements for production. Consequently, flexibility, functionality, and optimality are essential characteristics that assembly systems must satisfy. The *LMAS* paradigm addresses these needs by mobilizing resources to configure the factory based on current orders situation. This requires an elaborate information system infrastructure, so all involved entities get the right information at the right time.

In this paper, we presented a holarchy, which provides a structure of how an *LMAS* must be implemented and how different holons must interact to meet the stated requirements. In essence, all different assembly resources are represented by dedicated holons, which can be established on demand. Exemplary implementations highlighting different aspects of the concept show the general feasibility of our approach. For future work, we plan to extend our partial implementations into an integrated demonstrator to provide a scalable and flexible assembly infrastructure.

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