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# Towards A Design Of A Software-Defined Manufacturing System Based On A Systematic Literature Review For Enabling A Decentralised High-Rate Electrolyser Production

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**Abstract**

Hydrogen is critical for the transition to an environmentally sound and reliable energy supply. This transition requires large capacities of performant and cost-effective electrolysers. Although performant electrolysers already exist, they cannot yet be manufactured at a high rate in series production. The project H2Giga-FRHY is researching a reference factory for large-scale production of electrolysers, developing new production and testing modules. As an essential building block of the reference factory, a research group at Fraunhofer IPA is designing and implementing a comprehensive software-defined manufacturing system (SDMS), which supports the decentralized high-rate production of electrolysers and allows for far-reaching insights regarding high-rate capability, quality, and cost of products, processes, and technologies involved. For the SDMS implementation, different enterprise architecture (EA) approaches are considered and evaluated in the scope of a structured literature review with respect to criteria arising from the project context and related research questions. In this paper, an approach to designing a software-defined manufacturing system is described, and its necessity is based on the use case-specific criteria discussed.

**Keywords**

Software-Defined Manufacturing; Enterprise IT Architecture; High-Rate Production; Decentralised Manufacturing; Greenfield; Electrolyser Production

## 1. Introduction

With the European Green Deal and the associated goal of climate neutrality for the EU by 2050, hydrogen is expected to play an important role [1]. The demand for hydrogen can only be estimated as of today, but many current estimations point to an increasing demand. In its hydrogen roadmap, Fraunhofer ISE forecasts a hydrogen demand in Europe of 800 TWh in a low scenario and 2,250 TWh in a high scenario. These hydrogen needs translate into a corresponding increase in electrolysers that can produce it [2]. To satisfy this upcoming market necessity, high-rate production is needed. In order to keep up with the changing demands that electrolysers need to meet in the current environment, PEM electrolysers are particularly well-suited [3]. The use of this clean electrolyser production is not widely prevalent in Europe. Furthermore, it will need a lot of efficient and affordable electrolysers with high capacities to meet Germany's demand for green hydrogen. Although efficient electrolysers are on the market now, they are often still made by hand in small quantities [4].

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In order to research high-rate production of high-performance electrolysers, the H2Giga-FRHY project brings together the expertise of various Fraunhofer institutes. The resulting distributed reference factory for large-scale production of electrolysers is to be linked using information and communication technologies to form a coherent virtual production line. This will be realized through a SDMS. SDMSs leverage Industry 4.0 technologies and paradigms such as the Industrial Internet of Things or cloud-based manufacturing to provide flexible, adaptive, and scalable manufacturing systems [5]. Rauch et al. describe distributed manufacturing systems as logical consequence of cooperating manufacturing companies and the resulting production networks, which further strengthen the characteristics of distributed manufacturing systems [6].To address the resulting challenges and its increasing complexity, we present an approach for the design and development of a SDMS for distributed high-rate electrolyser production in a greenfield environment.

H2Giga-FRHY is a Fraunhofer-overarching project funded by the German Federal Ministry of Education and Research. The aim of the project is to design a reference factory as a flexible, multidirectional, technologically advanced solution for the large-scale production of electrolysers. New types of production and testing modules are being developed. The production is distributed across five locations in addition to the main IT site. The envisioned SDMS in the Fraunhofer IPA subproject is based primarily on the three pillars of a digital representation concept, an edge cloud platform-based manufacturing operation management, and an evaluation system to support product improvement decision-making.

## 2. Method and data

This work aims to identify suitable architectures for a SDMS in the context of the H2Giga-FRHY project. A systematic literature review, following the guidelines of Kitchenham [7], was conducted to identify potentially suitable architectural approaches for a SDMS for distributed high-rate electrolyser production in a greenfield environment. Based on the use case of the H2Giga-FRHY project, criteria were defined to select and evaluate architectural approaches. The first research question (RQ) arises here:

- RQ1: Which architectures for distributed SDMSs do exist?

RQ1 aims to identify existing SDMS architectures. RQ2 - RQ6 evaluate the identified architectures against criteria, which are relevant in the context of the H2Giga-FRHY project. The criteria are derived from stakeholder requirements, elicited from stakeholders through expert interviews guided by predefined categories for functional and non-functional requirements. Phrase templates ensure that the requirements are well-structured, prioritized, uniform, and unambiguous [8]. As a result, 135 functional requirements, 25 non-functional requirements, and 7 constraints are elicited. In section 2.2, a criterion is established for each RQ. The papers are examined regarding the occurrence of the respective criterion in order to assess the extent to which they address dimensions that are relevant in the context of the H2Giga-FRHY project.

- RQ2: Which SDMS architectures are suitable for a scalable high-rate production?
- RQ3: Which SDMS architectures can give distributed production sites access to coherent digital production functionalities?
- RQ4: Which SDMS architectures are particularly suitable in a greenfield environment?
- RQ5: Which SDMS architectures are service-oriented architectures?
- RQ6: Which SDMS architectures enable a central provision of relevant information and functionalities of distributed production assets?

### 2.1 Search process and selection criteria

In the first stage of the literature search, the umbrella term "Enterprise Architecture" was searched in the five selected databases following the results as seen in Table 1. EA is a more common term than SDMS, since the latter is used domain-specific mostly and would decrease possible results. Therefore, the literature search

looked for EAs that can be used as SDMS. Due to their importance in scientific research, the chosen databases are frequently utilized for literature reviews. Despite their similarities, the databases are not entirely the same and can cover various literature [9–11].

Table 1: Results of the Literature Query, searching “Enterprise Architecture” in five databases (January 2023)

| | Scopus | Web of Science | ACM Digital Library | Dimensions AI | IEEE Explore |
|---|---|---|---|---|---|
| **Number of results** | 5,183 | 2,474 | 839 | 4,976 | 1,310 |

As these results are too broad and comprehensive, the search query has been specified as:

> (Distributed Manufacturing" OR "Value added network" OR "Distributed Manufacturing Systems" OR "cloud*manufacturing") AND ("Manufacturing" OR "Production") AND ("Architecture" OR "Enterprise Architecture" OR "Software defined" OR "enterprise architecture framework" OR "IT framework") AND ("Industr* 4.0" OR "Digital Manufacturing" OR "Digitali*ation" OR "Digital Twin") AND NOT ("logistic*").

The Query is divided into five parts. The first specifies the type of manufacturing that the architecture model should be created for, as the given use case addresses distributed manufacturing. The first search queries showed an overwhelming amount of education and governmental EA. Therefore, use case-specific criteria for production or manufacturing were added. The next criteria section shows the targeted information that are researched: an enterprise architecture framework. In order for the results to meet the current standards of a digital greenfield production, criteria on the topic of digitalisation are added. Since it is about production with its value-adding processes, logistic results were excluded. Due to the search terms, the resulting papers are all written in English. Therefore, there is no filtering by language necessary. Subsequently, the results are filtered as seen in Figure 1. Resulting in the following seven papers: Newman [12]; Guo [13]; Hung [14]; Roque Rolo [15]; Novak [16]; Shao [17]; and Sreedhanya [18].

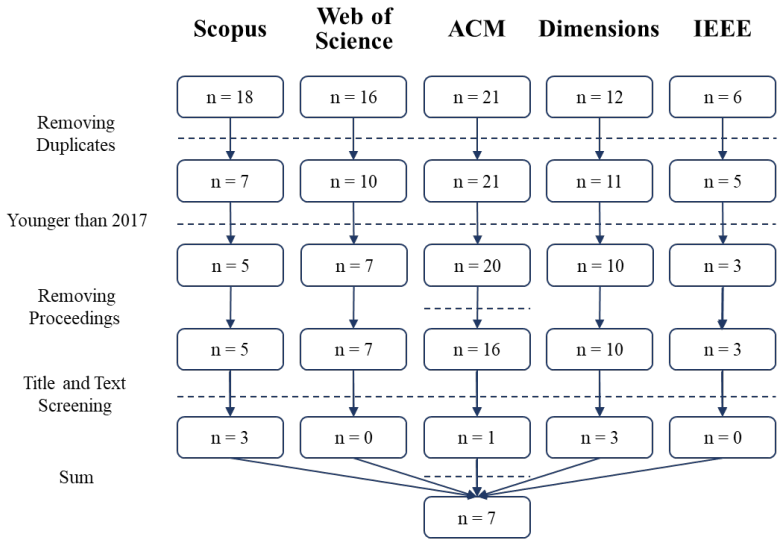


Figure 1: Filtering the papers through the criteria in the first column and the five selected databases (January 2023)

### 2.2 Quality assessment and data analysis

The resulting papers are evaluated according to the criteria extracted in chapter 2. This evaluation is shown in Table 2. The evaluating criteria answer the previously identified Research questions (RQ2 to RQ6) and arise from the requirements of the reference-factory. The rating of these criteria uses a system of circles, with empty circles (○) indicating that the criterion is not addressed, half-filled circles (◑) indicating partial coverage, and full circles (●) indicate that the criterion is comprehensively addressed in the proposed

architecture. All in all, the papers provide insights but do not provide a suitable SDMS architecture for high-rate production with distributed locations in a greenfield environment. Therefore, methods to create an appropriate EA are examined in the next chapter.

Table 2: Evaluation of the papers against the use case specific criteria. Evaluation in 3 levels

| Criteria | Newman | Guo | Hung | Roque Rolo | Novak | Shao | Sreedhanya |
|---|---|---|---|---|---|---|---|
| Domain suitable | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Central access for distributed locations | ○ | ◑ | ◑ | ● | ◑ | ◑ | ● |
| Greenfield suitable | ◑ | ◑ | ◑ | ○ | ○ | ◑ | ◑ |
| Service-oriented architecture | ○ | ● | ◑ | ○ | ● | ○ | ● |
| Provision of product and production data | ○ | ◑ | ◑ | ○ | ◑ | ● | ● |

### 2.3 Enterprise Architecture Methodologies

Yesilyurt's TOGAF ADM-based approach is used to create an EA design in a greenfield environment which is successful in battery cell manufacturing and recommended for electrolyser production but does not cover the challenges of distributed systems [19]. Other studies have found that agile EA in distributed environments faces obstacles, and have proposed lightweight TOGAF-based methodologies for digital transformation, but need to address production and manufacturing [20,21]. The systematic literature review of Ansyori [22] shows that most EA frameworks and methodologies are used in the public or educational sector outside of Europe [23–26] As the five most relevant Enterprise Architecture frameworks Zachman methodology, TOGAF, FEA(F), DoDAF, and Gartner Framework are listed [27–29]. Nonetheless, TOGAF is the only of these frameworks suitable for designing, planning, implementing and managing Software-Defined Manufacturing systems [22].

## 3. Solution Proposal

This chapter presents an approach for designing a SDMS using the TOGAF ADM cycle while addressing domain-specific challenges and proposing additional architecture assets. It focuses on the system design phases of the ADM, specifically the Architecture Vision, Business Architecture, Information Systems Architecture and Requirements Management phases (see Figure 2). The approach by Yesilyurt described in [19] is therefore adjusted. The Requirements Management phase is emphasized throughout the entire ADM cycle to ensure relevant requirements are continuously identified and managed. The proposed requirement engineering process is iterative and recursive [30,31].

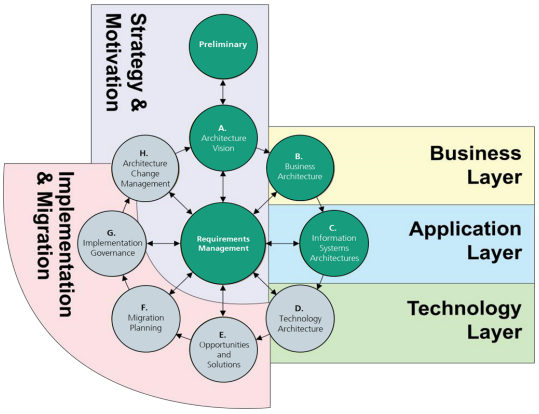


Figure 2: Simplified Mapping between ArchiMate and the TOGAF ADM, according to [32]

### 3.1 Architecture Vision

The Architecture Vision phase of TOGAF ADM aims to establish the scope and goals of an architecture, and create a high-level vision of the capabilities and business value it will deliver. This is demonstrated through the electrolyser reference factory use case of H2Giga-FRHY. The target architecture vision is presented in Figure 3. It illustrates shopfloors of different operating locations using a digital representation concept using the AAS standard to ensure continuous control and adaptation of products during manufacturing. This standard is currently under development in International Electrotechnical Commission project 63278-1, to ensure interoperability of heterogeneous production assets [36]. Shopfloor, testing sites, and IT headquarters have their own platform on local server hardware, connected through the digitalization platform and the AAS for cross-location communications and services. Suppliers, customers and partners can connect through a partner portal.

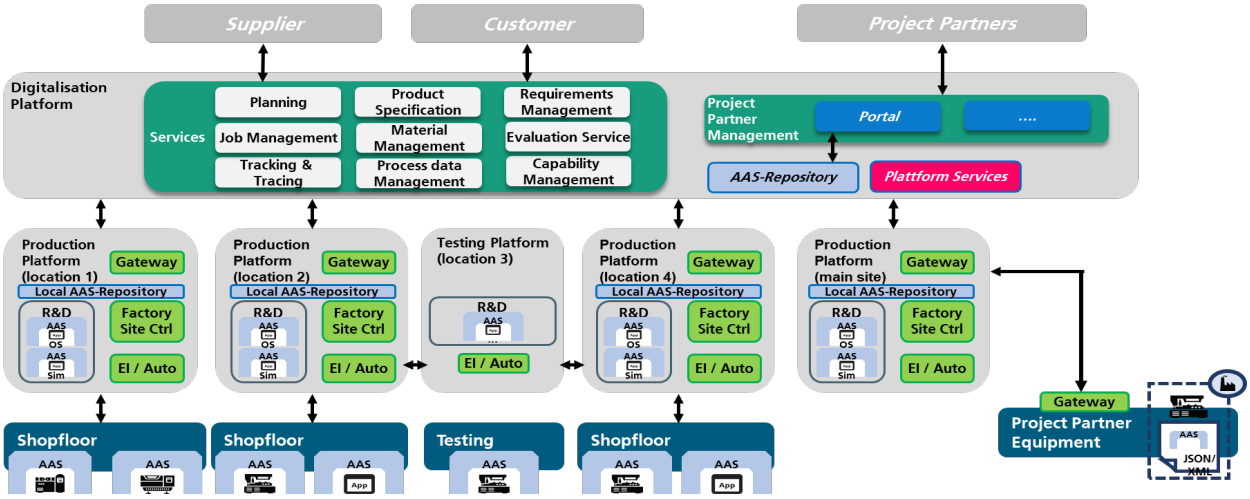


Figure 3: Architecture vision for the Software-Defined Manufacturing System based on the use case of a distributed electrolyser production

### 3.2 Business Architecture

This chapter describes the business architecture of the use case, including the value stream mapping and the gap analysis. It is divided into three steps: rough documentation; deepening per sub-product; and verification with review. The rough documentation includes important production processes sorted by sub-products and their relation. To design the business architecture the open and standardized modelling language ArchiMate based on the ISO/IEC/IEEE 42010:2011 standard [33] is used. Its modelling layers were used in the business architecture and the information systems architecture according to the mapping in Figure 3. The business architecture is developed through expert surveys by defining processes for each sub-product using a single business model and representing the relation between production and process through assignment relationships. The processes were described using EU harmonized terminology [34] to ensure uniform understanding and were reviewed by process experts. Interviews were held with experts in subpart-specific groups to obtain detailed process models, and with all experts to capture relationships and identify potential overall process failures.

The H2Giga-FRHY project includes six process steps for electrolyser production divided among five locations, with a focus on the subparts bipolar plate (BPP), porous transport layer (PTL), and catalyst-coated membrane (CCM) as it aims for a connected distributed production. Each process step is assigned to a production site and various design possibilities are presented as different processes are not completely clear at the beginning of greenfield manufacturing design.

### 3.3 Information Systems Architecture

The information system architecture aims to identify and describe data and application building blocks that support the business architecture and overall architecture vision, as well as identify gaps between the current and target architecture [31]. The previously elicited set of requirements is transformed into a high-level functional view of the SDMS. Requirements are grouped into application functions (AF) that represent automated behaviour and are clustered into cohesive, interrelated application components (AC), resulting in a high-level description of the target information system architecture, consisting of seven high-level ACs. This includes key ACs such as manufacturing operation management (MOM), digital twin (DT) and evaluation ACs.

#### 3.3.1 Manufacturing Operation Management Application Component

The IEC 62264 standard provides terminology as well as information and activity models for MOM [35]. This makes it a valuable architecture asset for the design of the MOM AC. Our approach is based on combining the TOGAF ADM and IEC 62264 [18]. The manufacturing operation models defined in [35] provide support in defining the scope of the MOM AC. The detailed activity models defined in [36] provide guidance and support for transforming and aggregating stakeholder requirements to well defined AFs in the area of MOM as well as identifying additional AFs. The information flows described in the activity models in [36] support the definition of the interaction between different AFs. We report that combining TOGAF ADM and IEC 62264 as proposed by [19] is an effective approach for identifying AFs for the design of a MOM in the context of distributed high-rate electrolyser production. However, this approach does not take into consideration the proposed target architecture, which allows for a holistic and integrated planning, scheduling and dispatching of the distributed manufacturing processes as well as a for an overarching tracking and tracing of the electrolysers. Moreover, each module must be able to function autonomously in case of errors or downtime of a single module. Therefore, multiple connected MOM ACs at each production module, with proper integration and synchronization are required. This aligns with the findings of current design challenges in MOM in [37].

#### 3.3.2 Digital Twin Application Component

The AAS provides uniform access to information and services of assets and forms the basis of our digital representation concept to ensure a continuous control and adaptation of relevant products during manufacturing. The AAS is based on the Reference Architecture Model Industry 4.0 (RAMI 4.0), whose hierarchy levels to classify assets within an Industry 4.0 environment are based on the models and terminology provided in IEC 62264 [38]. This common foundation enables the design of a coherent architecture with complementary MOM and DT ACs. A DT is a general concept that can be tailored for a particular problem and domain. This domain-dependence results in a huge variety of theoretical and practical models for designing and implementing DTs [39]. ISO 23247 series defines international standards for making and maintaining DT in manufacturing [40]. Consequently, the reference architecture defined in ISO 23247 provides guidance for implementing DT in manufacturing. Additionally, the guidelines for the digital representation of manufacturing elements provided in ISO 23247 are based on the information models defined in ISO 62264. Therefore, the combination of the AAS and ISO 23247 form the foundation of the future design and research activities regarding the DT AC throughout the subsequent TOGAF phases.

#### 3.3.3 Evaluation Application Component

The evaluation system shall support strategic decision-making in product improvement. It is based on the captured requirements and provides capabilities for product error evaluation, process evaluation, product performance evaluation, and cost evaluation. These align with use cases described in literature for data analysis in product planning. However, it does not include use cases that use product data to assess product performance or that support decision-making in development by assessing costs [41]. Moreover, Lindner's

doctoral thesis also focuses on improving products based on the analysis of usage data. It explicitly describes the lack of data models that enable the integrated management of data from product development and product usage [42]. This challenge is to be met with the DT based on the Asset Administration Shell (AAS) that covers and administrates product-related data over the entire lifecycle of an asset [38].

To support in product development, decision-making should be based on concrete values by specifying the extent to which a requirement is met. If descriptive statistics are not sufficient, key performance indicators (KPIs) must be defined. Here, one can fall back on already established KPIs that describe the economic productivity or the technical operation of a product. If there is a need for further measurement, a system of KPIs can be developed [42]. To provide decision support, digital services are being developed that make use of analytical methods. For this purpose, the use cases specific to the application are modelled at the beginning in order to derive the submodels of the AAS on the basis of the modelling. This is to ensure the provision of data for the evaluation services.

## 4. Discussion

Several SDMS architectures are described in the literature review above but they do not fulfill the defined criteria completely. As an alternative to these existing SDMS architectures (due to results reached the umbrella term EA), EA methods for developing new architectures were investigated. From both the partially matching EA and the partially matching methodologies, appropriate standards were put together to develop a proposal to fill the scientific gap. TOGAF combined with domain specific standards provides guidance to design a suitable SDMS architecture for the H2Giga-FRHY project. It is presumable that the method is transferable to use cases with similar domain specific challenges, including high-rate production, greenfield, and highly monitored manufacturing. A comprehensive verification of this statement is pending and would be desirable. However, in the project it shows that the proposed methodology can provide functioning subsystems of the SDMS. Including the architecture vision that provided a good foundation for the following TOGAF phases and it is recommended to have a similar detail-level in the strategy. Furthermore, ArchiMate functioned well as modelling language for its wide scope and conformance to TOGAF. As predicted in [19], IEC62264 worked well with the TOGAF steps. This corresponds with the authors of [37] who suggest that new design challenges for next generation MOM arise in the era of industry 4.0. This includes standardization, interoperability, software customization, modularity and an increasing need for decentralization of MOM solutions.

## 5. Conclusion and Future Work

This paper explored the design of a software-defined manufacturing system to enable the enterprise architecture of a benchmark factory for electrolysers. The H2Giga-FRHY project focuses on a greenfield, decentralised and digitalised high-rate production of electrolyses that concentrates on the technology sub-parts. A research gap in the area of design frameworks for distributed greenfield productions was identified through a systematic literature review.

The literature review showed missing potential for enterprise architecture and software-defined manufacturing systems for high-rate manufacturing that are highly monitored like the electrolyser production. A design method was developed to address the found research gap. The method uses TOGAF, requirements engineering standards, AAS, and IEC 62264 to identify and design the necessary services and submodels for the use case. It is based on ArchiMate's layer models. The design method used in the project works well as a software-defined manufacturing system in the use case, and it can be adopted by similar domains. Apart from these use cases, a verification of the methods used on the basis of further production use cases would be interesting and desirable.

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**Michael Oberle** (*1984) is a computer scientist and group leader working in the field of smart manufacturing with a focus of data-driven and event- driven production control services. One of his main achievements is the fully connected cloud-controlled battery manufacturing pilot line at Fraunhofer IPAs technical centre for battery manufacturing.