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An Approach For Designing And Developing Microservices-enabled Manufacturing Operations Management In Greenfield Environments

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Abstract

Microservices are a special type of service-oriented architecture that promises flexibility through the encapsulation of functionality and loose coupling. With a growing need for responsiveness of manufacturing systems driven by customer expectation, competition, and regulatory changes, the microservices architecture is highly attractive for Manufacturing Operations Management (MOM) solutions. Manufacturing enterprises that have a traditional MOM solution as a monolithic system in place can transition to microservices architecture through reverse engineering their existing solution. This is not possible in a greenfield environment where the entire manufacturing system is built from scratch. In this paper, we present an approach for designing and developing a microservices-enabled MOM solution for greenfield environments. The approach is based on industry standards and incorporates a parallel design and development of the microservices addressing the functional needs of the MOM solution and equipment emulators, enabling early solution testing before the actual equipment is delivered. We evaluate the approach through a case study in which we developed a microservices-enabled MOM solution for a small-scale battery manufacturing line. We report that the ISA95 standard provides a good guideline for microservice MOM solutions, though the underlying data model needed to be modified to cover our case. The developed instantiation also shows that a microservices-enabled MOM can flexibly address new requirements. However, this does not come without a cost, as their integration and management require additional effort compared to monolithic architectures.

Keywords

Manufacturing Operations Management; Microservices; Manufacturing Execution System, MES; MOM; IIoT; Battery Cell Manufacturing

1. Introduction

The need for flexibility of manufacturing companies to adapt their operations to changes in the environment has become apparent in current crises such as COVID19 or the Ukraine crisis, in which the supply chains have been heavily disrupted. However, if even these crises would not exist, manufacturers need to be responsive to adapt to external changes [1]: Customers expect new product releases in a shorter timeframe, there is increasing global manufacturing competition, and governments impose new regulations to act on climate change. To deal with the challenges manufacturing companies must embrace flexibility throughout their manufacturing system, from the material over machinery to IT-Systems. With the increasing importance of data in manufacturing processes, the flexibility of the manufacturing IT-Systems that support the management of manufacturing operations (MOM) is crucial [2,3]. MOM solutions support through their underlying model a certain degree of flexibility to address changes in the manufacturing system, such as the addition of new products or production steps [4]. However, not all changes that occur later in practice can be foreseen. To dissolve this limitation, the adoption of microservices architecture, in which the MOM

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solution consists of several microservices, was proposed [5]. Microservices architectures will not necessarily avoid source code changes, but they should at least reduce these changes due to loose coupling. This capability makes a microservices-enabled MOM highly interesting for both established and new manufacturing sites. However, the methodology for designing and developing such a system substantially differs. Established manufacturers can reverse engineer their existing MOM solutions and gradually transition to the new architecture paradigm [6] [7]. New manufacturing sites are planned from scratch, and thus guidance for the MOM design and development endeavour is required. This paper presents an approach for designing and developing a microservices-enabled MOM that we evaluate by implementing a MOM solution in a case study. The remainder of the paper is structured as follows. In section 2, we discuss related work on MOM solutions and highlight the gap in research. Section 3 presents our approach for designing and developing a microservice MOM solution. We apply this approach in section 4 in a case study for a new small-scale battery manufacturing line. We evaluate our approach and our MOM solution in section 5. Finally, we conclude our paper with the key points in section 6.

2. Related work

For this section, we conduct a literature review on the design of MOM solutions. We searched Google Scholar with a focus on the last five years and extended our retrievals through cross-reference search. Among the literature, we identified three common themes in our review: the importance of standards for MOM solution development, the requirements of MES in the context of Industry 4.0, and the potential of microservices for increasing the flexibility of MOM solutions. Considering standards for MOM development, ISA95 is a well-known standard. [8] uses ISA95 as a guideline for developing an MES based on the open-source enterprise software platform odoo. [9] leverage the data model of ISA95 to implement an IIoT connected MOM system. Interestingly the model seems not to be applied in practice for system development, at least in some industries. A comparative study of different MES vendors [10] reports that only very few systems comply with the ISA95 standard. Other studies highlight integrating MES with IIoT platforms to align with Industry 4.0. [11] review relevant standards and ontologies of MES in the context of Industry 4.0. They highlight that an MES needs to be seamlessly integrated with all cyber-physical system components to enable highly automated solutions. Formal ontologies and models play an essential role in ensuring interoperability. [9] combine a quality function deployment and case studies to identify MOM's main requirements in smart factories. They also identify interoperability as the key requirement for MOM in a smart factory. This is also supported by [12], who identify interconnectedness as a crucial feature of system architectures for Industry 4.0. Several authors point out modularity as a desirable characteristic of next-generation MOM solutions. In particular, the microservices architecture is suggested as a suitable solution to address modularity [9,12, 5]. [13] point out that the functional scope of the service has an impact on the communication infrastructure and should be considered in the design of a solution but also argues that the benefits of flexibility are highly suitable for smart manufacturing. Aligned with this claim is a slowly growing interest in MOM solutions based on microservices. There is a small number of implementation attempts. These attempts are compared in table 1. Our literature review analysed the available approaches concerning the other two common themes. The available implementations do not follow any standard for their implementation but instead, seem to be built from intuition. In addition, with exception of [14], the connectedness to other systems as part of a smart factory was not considered. We further identify a gap in a missing methodology or approach for designing and developing a MOM solution in a greenfield environment. In our work, we aim to address this gap.

Table 1: Comparison with related work on MOM microservice architectures

Table	Li et al. 2019	Zhou et al. 2019	Wunck & Jonas 2019	Jin et al. 2021	Yi et al. 2019

Target	Greenfield	Greenfield	Brownfield	Conceptual	Conceptual
Model	Not specified	Not specified	Not specified	Not specified	Not specified
IIoT Integration	Yes	No	No	No	No
Case Domain	Production network	Not specified	Laser-Cutting	Tobacco manufacturing	None
Case Environment	Demonstrator	Not specified	CPS testbed	Conceptual	None

3. Approach for designing microservice-enabled MOM in a greenfield environment

This section presents our approach to designing a microservice MOM solution in a greenfield environment. The approach is visualised in Figure 1 including several steps and the associated vital roles involved. In contrast to the brownfield design of MOM solutions in which the design can orient on the existing boundaries, such as the equipment and software in place, the design for a greenfield does not have such strict constraints in place [15]. However, it is also evident that there must be a goal in place in which the principal purpose and scope of the manufacturing line are defined. There is a substantial difference in the design of the entire manufacturing line if the purpose of the manufacturing line is the production of high-volume goods compared to a manufacturing line for a small number of individualised products. For high-volume production, throughput is the key, and by contrast, flexibility is vital for the production of individualised products. The purpose impacts the entire manufacturing system, from equipment over processes to the MOM solution. For this reason, the first step in our approach is the definition of the manufacturing line goal and scope (0). This is the task of the executives overseeing the entire manufacturing site project. This definition serves as an input for the following steps concerned with the MOM solution's design. Our approach includes a parallel line to the steps for the actual MOM solution, which are targeted at creating equipment emulators. This is necessary in a greenfield environment where equipment is typically not present from the beginning. This defers gaining experience with the MOM solution, which could lead to severe flaws in the design. These are harder to fix the latter they are discovered [16]. The line for MOM solution design starts with the definition of operational procedures (1a). This step defines how operators on the shop floor interact with a MOM solution and the equipment of the shop floor. ISA95 part 1 defines a function model of manufacturing enterprises. Based on the defined goal and scope definition, the relevant functions can be selected and guide the characterization and modelling of the procedures. The result serves as the input for the segmentation of microservices of the MOM solution (2a). In this step, the functionalities of the microservices are determined, which defines the scope of each microservice. ISA95 part 3 provides activity models for operations management, production, maintenance, quality, and inventory. Each model activity is well-defined with clear boundaries and relationships to other activities. This property renders these models a viable template for segmenting a MOM solution in microservices. Each MOM microservice should have a clear functional scope [5]. Therefore, activities in the operational definition need to be mapped on these activity models. In the following step, the detailed design of the individual microservices takes place (3a). This involves designing the underlying semantics that determine the interactions of the microservices. ISA95 part 2 defines several common object models for all major entities involved on the shop floor, including personal, material, and equipment on which the data model design can be based. The parallel line of design of the equipment emulators begins with the manufacturing process characteristics (1b). The VDI 3682 standard provides a concept for describing processes in a standardized format. The format is solution neutral and allows the description of a process as the desired behaviour of a system by inputs and outputs in terms of product, energy, and information of the system. The latter is the most important for the emulator design.

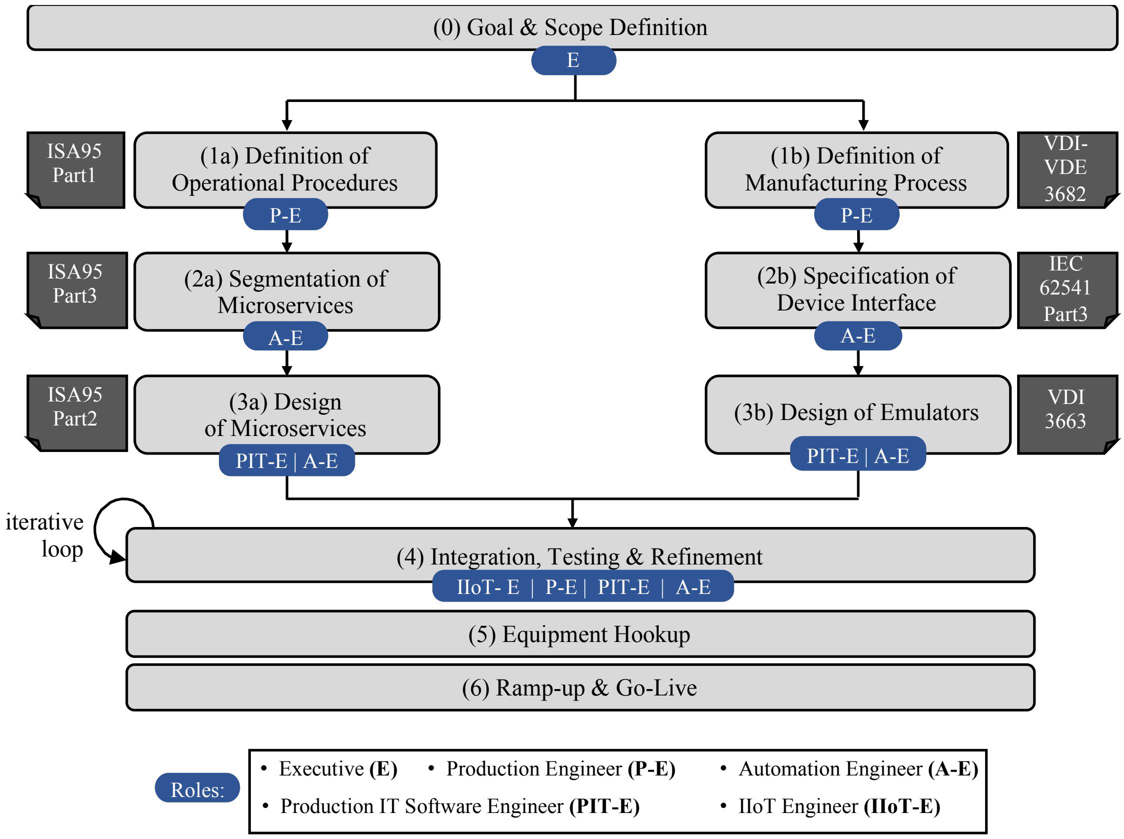

Figure 1: Approach for designing and developing a microservices-enabled MOM in a greenfield environment

Production engineers who design the manufacturing good's physical transformation process are the source of this information. Based on this specification, the information interface of the equipment can be defined in the following (2b). OPC-UA has been becoming a de-facto standard for the interoperability of equipment with MOM solutions in smart factories [17]. The IEC62541 standard specifies the protocol and provides the elements for constructing the information model from an IT perspective. These include different nodes such as objects, variables, and methods. An Automation Engineer needs to structure the IT interface based on the information inputs and outputs from the formal process description of the previous step. The emulator’s behaviour must be specified in the last step of the equipment emulator design (3c). The behaviour model can be implemented through simulation. VDI 3663 describes guidelines for the construction simulation models for material flow and production systems. Based on this standard and process, the automation engineer must specify the behaviour of the underlying model. After completing the design for the MOM microservices and the equipment emulators, the development begins [4]. Given the distributed nature and required interaction of microservices architectures [5] we propose an iterative approach that aims at an early end-to-end integration of all solution components to identify defects in design or implementation as soon as possible. State of the art microservices architectures are hosted on IoT platforms. For this reason, the development requires the collaboration between Production IT Software Engineers who possess the expertise to implement the functionality and IIoT Engineers who provide the know-how of integration and deploying the software. Automation and Production Engineers need to be involved in testing to provide recommendations for improvements to the MOM solution. The development iterations continue with the equipment emulators as long as the actual equipment is unavailable. As the implementation of the equipment interface might be itself subject to development defects on the side of the equipment supplier, it is essential to replace the equipment emulator during testing as soon as possible with the actual item of equipment (5). Testing with the actual equipment allows the development of a mature MOM solution that can be used early in the ramp-up to accelerate the final go-live of the manufacturing line (6).

4. Case Study: Small scale battery manufacturing line

Aligned with the Design Science Research Methodology [18] we applied the previously presented approach in a case study for designing a real microservices-enabled MOM solution to evaluate its utility. The battery manufacturing pilot line within the Center for Battery Manufacturing (ZDB) at Fraunhofer IPA served as the application environment. In 2019 the project for establishing a small-scale manufacturing line was initiated with the goal to produce small quantities of round li-ion cells, enabling research on new battery materials and manufacturing technologies. The entire manufacturing line was planned to cover all battery manufacturing steps, from slurry mixing over electrode coating to cell assembly and formation. The project focused on establishing the battery cell process steps from scratch in the past two years. This involved provisioning equipment for ten sub-processes. In the following, we report on our experience applying the previously described approach for designing and developing a microservice-enabled MOM in this specific greenfield case and present our developed artefact.

4.1 Application of the approach

For our MOM solution endeavour, the definition of goal and scope (step 0) was given through the ZDB project's previously described goal. Our work started with defining the operational procedures and the battery cell assembly processes that should be part of ZDB. We conducted these steps in collaboration with production engineers responsible for the battery cell assembly. To define the scope of the operational procedures, we analysed the functional model of ISA95 part 1 (step 1a). This includes ten functions for enterprise control of a manufacturing organization. Considering the goal of our manufacturing line, we identified that only order processing, production scheduling, production control, quality assurance, and product inventory control were relevant for our project. These are the core functions that are required to produce battery cells. At this stage and scale of the ZDB, the other functions are not (yet) relevant as the ZDB does not aim at manufacturing goods for commercial purposes. These functions themed the frame for the procedures we needed to consider in the operational procedure definition. The Production Engineers defined ten sub-processes for the battery cell assembly (Figure 2).

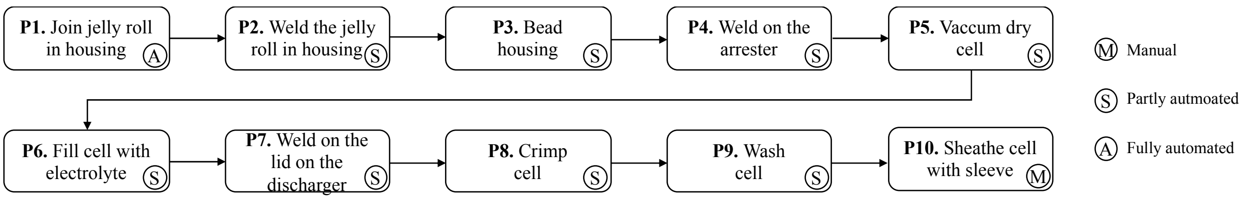

Figure 2: Battery Cell Assembly sub-processes

We jointly modelled the details of the planned operating procedures with UML activity diagrams for each of these sub-processes. These include swimlanes for the human actor (engineer or worker), the manufacturing equipment, and the MOM solution. For each item of equipment in the sub-processes P1 to P10, we conducted a specification of the process information inputs and outputs (step 1b), including units and measurement frequency. We sub-categorized thereby outputs to information available at the end of each sub-process, such as the result of the process or a particular measurement (e.g. height of groove) and information that characterizes the physical process during its execution (e.g. forces or temperatures). Based on the results from step 1a, we started the segmentation of the microservices (step 2a) by mapping the activities of the MOM solution in the UML activity diagrams to the activity model of production operations management in ISA95 part 3. Except for the detailed production scheduling activity and product resource management, which we decided should not be covered by the MOM solution due to the small production quantities, all activities were relevant. The activities related to production dispatching, product definition management, and production data collection determined the scope of single microservices. Due to the relatedness of production tracking and production execution, we decided to combine these activities in a single microservice. We also identified that most subprocesses (see Figure 2) required manual interaction of the worker. Therefore, there needed to be a way to convey recipe information. For this reason, we introduced another microservice, the operator guide that should cover this functionality. We specified the equipment interfaces (step 2b) using the results from step 1b as input. We used essential elements from the IEC62541 to construct a lightweight information model in cooperation with the Automation Engineer. This lightweight information model consisted of four central nodes: machine state, machine input, machine output, and process measurements. The latter directly reflects the categories of the process specification in step 1b. We introduced the respective variables in each corresponding node. For the detailed design of the microservices, we analyzed the production operations information model of ISA95 part 2 with a focus on the requirements of our case. We identified that the model itself has the most relevant entities, such as product definitions. However, it does not provide the flexibility for deriving product definition quickly from existing variants. Therefore we designed a new semantic model as a development foundation (see Figure 3).

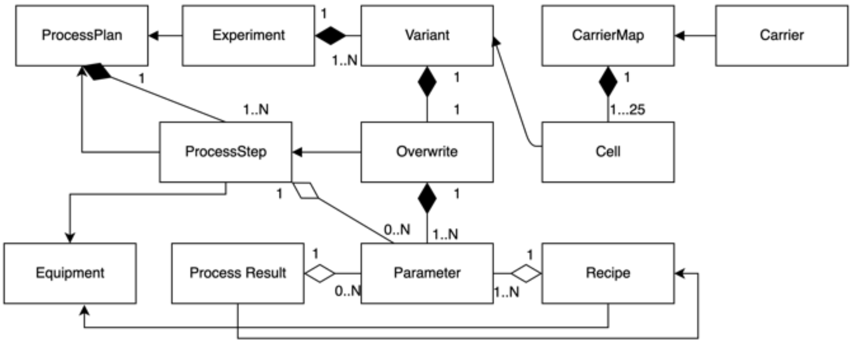

Figure 3: Semantic Data Model

We concluded the detailed design of the emulators (step 3b) by defining the behaviour of the equipment emulators. The VDI 3663 standard describes a detailed description of how simulations can be developed. Due to cost-benefit reasons, we decided against implementing a detailed physical simulation. Instead, we defined a range of reasonable values for each of the variables in the OPC-UA interface and a distribution function for statistically controlling value occurrences. We started the development activities by identifying artefacts that we already had available from previous projects and could be re-used to develop the MOM solution. These were the IIoT platform Virtual Fort Knox [19] including the integration middleware Manufacturing Service Bus (MSB) [20], a platform for creating emulators with OPC-UA and a lightweight MES from a partner organization. The MES could not cover all the required functionality for the defined operational procedures, particularly the management of experiments for single cells. However, it provides an API for controlling the functionalities for tracking and executing products through a manufacturing process which is why we used it as the solution for this microservice. We implemented the equipment emulators by transferring the equipment IT interface specification to an OPC-UA model using the SiOME modelling editor. The formal specification is the basis for instantiating an instance in the equipment emulation platform. The behaviour for each node was then specified by a separate configuration that includes the range, the distribution function, and the refresh rate. For the implementation of the MOM solution, we used an agile methodology defining a product backlog. We prioritized the implementation of a stub for each microservice that was able to be deployed on VFK. These stubs could communicate the most relevant information of the entities described in the semantic model via the MSB and were able to interact fundamentally with the equipment emulators. All microservices were further refined based on the feedback from the Production Engineers. As soon as an item of equipment arrived, we verified the integration of the equipment with the MOM solution. Apart from minor fixes, such as the OPC-UA security levels, we did not encounter issues. As one of the last steps, we integrated the workpiece carrier, for which we conducted three development sprints until no problems could be identified any longer. The final go-live of the battery cell assembly line is still pending at the date of writing due to the safety certification of the line, which was affected by the COVID pandemic.

4.2 Instantiation of the microservice-enabled MOM solution

The instantiation that resulted from applying the proposed approach is presented in Figure 4.

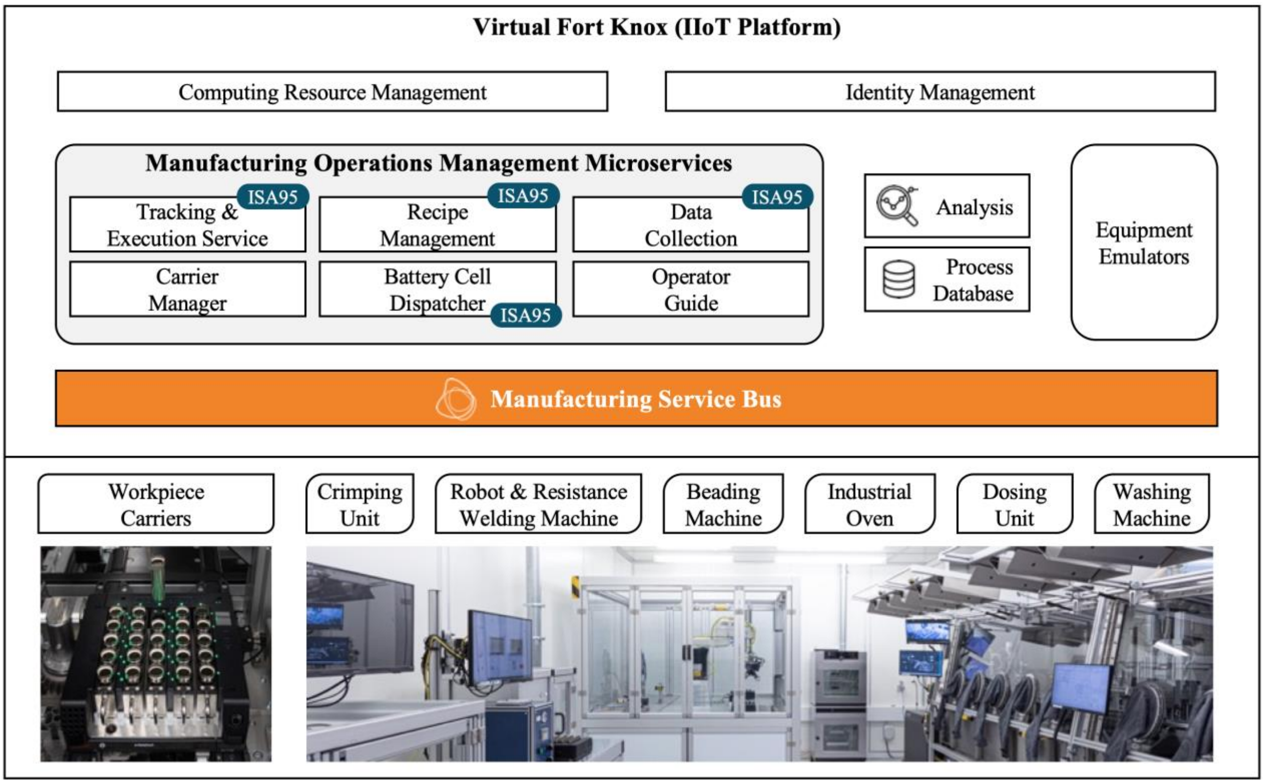

Figure 4: Overview of the MOM architecture

The VFK platform provides the provisioning of computing in the form of virtual machines. In our case, we include an additional layer of virtualization by embodying each artefact in a separate docker container to simplify the deployment. In addition, the platform provides the basic service of managing users' accounts for all microservices (identity management) and the MSB enabling the integration of microservices and shop floor equipment. The MSB also provides important security features. Only communication of registered and authorized microservices and equipment that passes over a secured connection channel is allowed. MOM is supported in our architecture through six microservices. The tracking and execution microservice allows the management of the process plans for battery cells. It tracks the progress of the cells through the individual manufacturing steps. The recipe management enables the definition of parameter variants for all individual process steps. Existing experiment setups can be used as templates. The battery cell dispatcher decides which cells are processed next. This is important as single cells can be extracted manually from the workpiece carrier. The carrier manager enables the placement of individual cells on the workpiece carrier. It allows the assignment of recipes to the single cells in the carrier. The operator guide conveys recipe information for processing the following cells to the worker. In addition, it allows the indication of process stops and starts. Data collection records all measurements during process execution (e.g. forces) with the context of the individual cell and recipe parameters. Our overall architecture also includes data storage and process analysis services, which are realized through pre-configured virtual machines for Grafana and InfluxDB provided by the VFK platform. Figure 5 presents the basic interaction sequence of our microservices-enabled MOM.

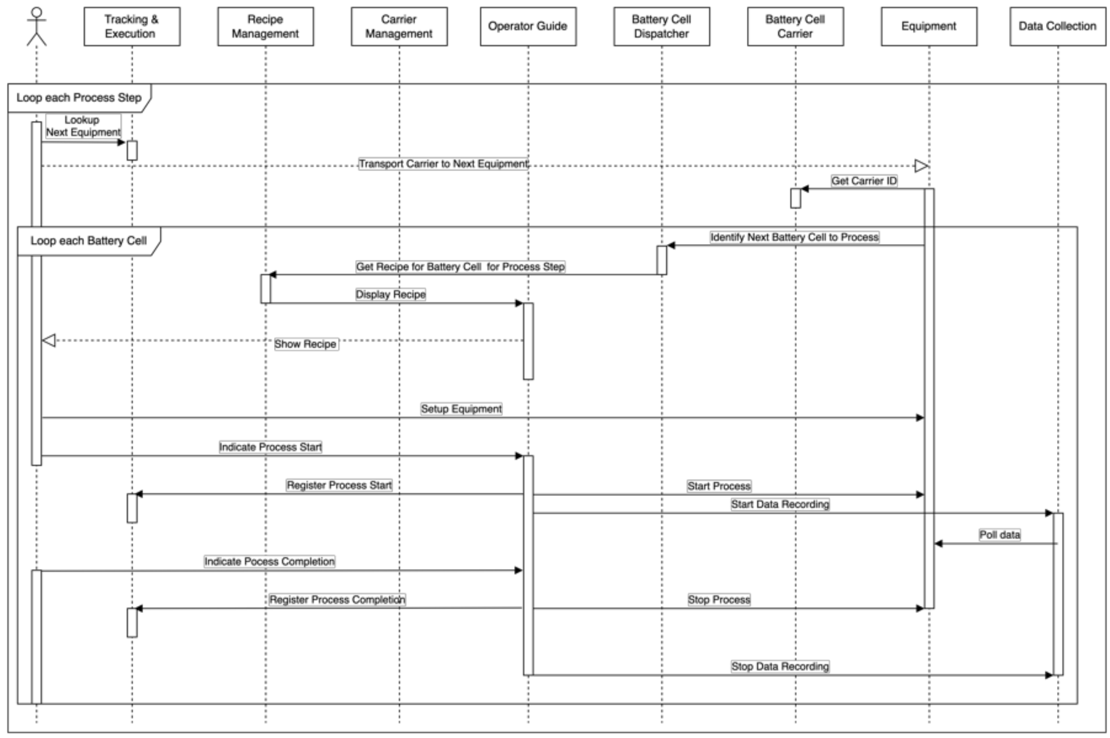

Figure 5: Interaction of microservices for experiment execution

5. Evaluation

In the following, we evaluate our approach and our instantiation by reflecting on our design and development experiences.

5.1 Approach

As our approach leads to an instantiation that, according to the feedback from the tests of our Production Engineers are covering the procedures adequately, we conclude that our approach can deliver effective MOM solutions on microservices. We see the merit of our approach on the one hand in the practical guidance by the incorporation of standards. ISA95 provided good advice for eliciting the functional requirements. On the other hand, the parallel use of emulators proved very valuable. Due to the global demand for battery manufacturing equipment, the delivery of our equipment was severely delayed. However, our emulators allowed us to verify our solution early. This showed during the integration of the workpiece carrier, for which we did not have an emulator but only interface specifications. In contrast to the actual manufacturing equipment in which only minor fixes were necessary, we needed three full days to integrate the workpiece carrier without any remaining issues. However, we also see the potential for improving our approach. The specification of the interface could benefit from OPC-UA companion specifications [21]. This would streamline the interface definition process and reduce the probability of issues even further.

5.2 Instantiation

Although the battery cell assembly line is not yet operational, we can already report from our experience regarding a necessary change for the MOM solution. In our design of the carrier management and the cell dispatcher microservice, the specification that we worked on with the Production Engineers only foresaw those stations would process the entire workpiece carrier as a whole or single cell. However, later during the project, it became clear that the workpiece carrier could not be placed in harsh environments like the washing machine or the oven. For this reason, trays on the workpiece carrier were introduced. The necessary change could be implemented by the carrier manager and cell dispatcher without affecting any other services. With a monolithic solution, this would have had a high probability of breaking changes affecting other modules. However, we also experienced drawbacks from the microservices architecture. Testing is far simpler for monolithic architectures as the test setup does not have to spawn multiple hosts and technologies, as it is the case for a microservices architecture. Another related issue is changes that might be necessary due to security vulnerabilities. When the log4j flaw [22] was discovered earlier this year, this meant investigating all microservices and their dependencies. In a monolithic architecture, such investigations are easier to handle.

6. Conclusion

Promising increased flexibility, microservice architectures are an attractive architecture style for MOM solutions. There are some attempts at implementing microservices production management solutions. Covering the lack of guidance for designing and developing such solutions for greenfield environments, we presented an approach building on industry standards. The approach incorporates a parallel design of equipment emulators and MOM microservices to be able to verify the solution as soon as possible, even when the equipment is not yet delivered. The ISA95 provides a valuable baseline for defining the operating procedures necessary for eliciting the functional requirements and segmenting the microservices. In a case study on a MOM solution for battery cell assembly, we could successfully develop a solution that covers the needs of the Production Engineers. Our experience with our instantiation indicates that flexibility can be achieved through a microservices-enabled MOM solution. However, there are also costs in managing complexity and testing that need to be addressed in future research.

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Biography

Michael Oberle (*1984) is a computer scientist and group leader at Fraunhofer IPA working in the field of smart manufacturing with a focus of data-driven and event-driven production control services.

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