

Introduction to the OMP Manufacturing Reference Architecture

General Approach & Design Considerations

Published
May 17, 2021

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ACKNOWLEDGMENTS

This document is a work product of the Open Manufacturing Platform - Manufacturing Reference Architecture Working Group, chaired by Martina Pickhardt (Microsoft) and co-chaired by Nils Jensen (PwC).

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1. Introduction

Context

This whitepaper serves as an introduction to the Open Manufacturing Platform's (OMP) Manufacturing Reference Architecture (MRA) and will set the foundation for upcoming releases and new publications. It aims to give the reader the foundation to understand the general concept of the MRA within the OMP initiative, its benefits, approach, vision, goals, and scope.

Readers gain the foundation to benchmark their manufacturing architecture approach and design concept as well as further detail to support a planned architecture project.

While this document serves as an introduction, upcoming planned content from the MRA includes, but is not limited to:

- ◆ A collection of dedicated Use Case whitepapers that focuses on particular manufacturing challenges.
- ◆ Technical Architecture whitepapers and blueprints that discuss specific architecture templates, features, application ranges, and implementation aspects and guidance.

Intended Audience

This document is primarily interesting for readers who act in a function related to general IT topics, enterprise or solution architecture, Industry 4.0, or digital transformations regarding manufacturing or industrial production. The following descriptions provide examples of the roles and functions that will benefit the most of this whitepaper.

The white paper focuses on architect roles like **Enterprise Architects and Cloud/Solution/Software Architects** as they benefit from all content in this document. Respective architectures and approaches or principles can be benchmarked and adjusted if required.

Chief Technical Officer (CTO) / Chief Information Officer (CIO) can use the provided information as the starting point for their architecture strategy and approach or review a possible ongoing initiative. Of particular interest from a strategic point are considerations regarding the approach and the Use Case considerations. Especially the design principles and the Use Case considerations deliver insights into how to approach digital transformation projects for **Digitalization / Transformation / Industry 4.0 Manager**.

Although a basic understanding of IT/OT in manufacturing is certainly helpful, most roles within a manufacturing company will understand the content and gain valuable insights on manufacturing reference architectures.

2. Approach

The goal of the OMP MRA working group is to provide an open, based on industry standards, higher-level manufacturing reference architecture, enabling companies to align their shop floor infrastructure and systems while allowing industrial solutions to integrate faster. A technologically agnostic view is presented, which focuses on functionality over vendor specifications.

Key concepts the MRA will address are:

- ◆ Interoperability, flexibility & agility
(capacity flexibility with adaptive production building blocks)
- ◆ Innovation capabilities (state-of-the-art technologies, new business models)
- ◆ Integration capabilities (brownfield and greenfield) along with cybersecurity requirements
- ◆ Scalability for different industry environments

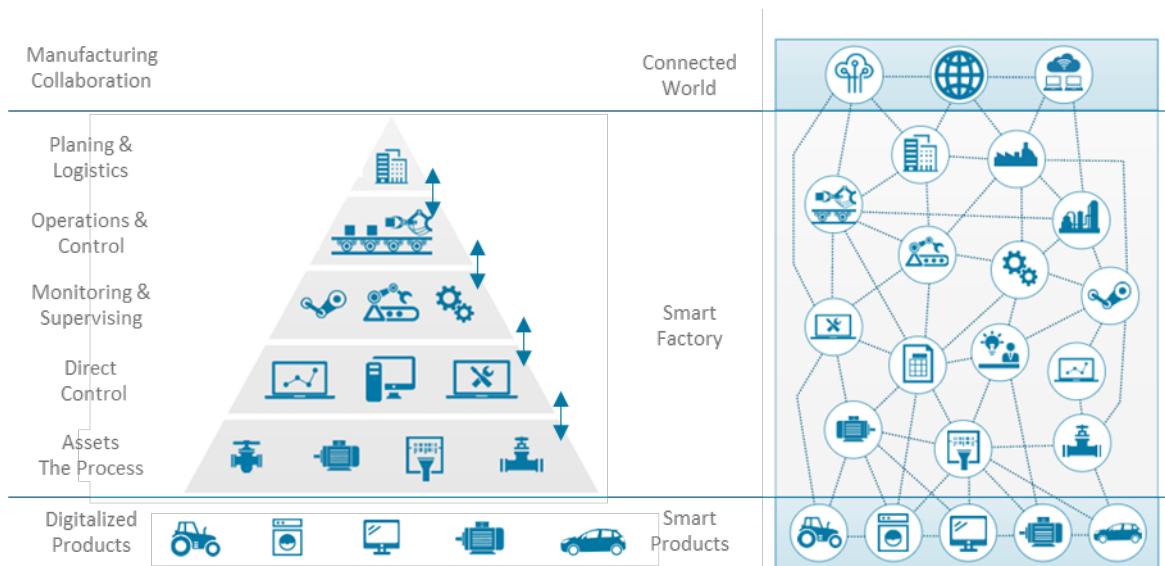
Practical guidance, blueprints, and architectural sketches are provided to help companies with their digital transformation.

Vision and Mission

When it comes to architecture design and approaches the complexity between IT and OT is already very high. The integration and connection efforts between shopfloor systems, machines, controls, sensors, other assets, and several existing IoT Platforms from different vendors are in a continuous improvement process. Very often these projects get stuck in singled-out proofs-of-concept because the holistic overall approach is missing.

Manufacturing processes require complex interactions of multiple, separate systems on different levels. In the past, these systems have often been systematically assembled into the well-known ISA-95 automation pyramid. This pyramid has its origins in the hierarchical enterprise structure of the Purdue Enterprise Reference Architecture (PERA) and current norms like IEC 62264 are still based upon it.

As described by the *Platform Industry 4.0 / RAMI 4.0 Model* (see Figure 1) the manufacturing ecosystem is moving from hardware-based structure and hierarchy-based communication to a more flexible system of machines and actors which can interact across hierarchy levels and communicate among all participants.



**Figure 1: RAMI 4.0 inherited and evolved the standard IEC:62264 hierarchy, (Platform Industrie 4.0, 2016a, pp. 11-12);
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New capabilities like discoverability, self-descriptiveness, and responsibility negotiation of assets up to data sharing across company boundaries, might help to overcome the rigid pyramid model and will create a more flexible network-driven architecture design.

The mission of the MRA working group is to provide hands-on guidance on how to define a reference architecture in this heterogeneous environment. This architecture serves the needs of concrete smart manufacturing use cases while taking new capabilities and new business models into account.

By designing such a smart manufacturing architecture there should be considered some main areas of concern:

- ◆ **Data Governance:** It is not just about connecting and collecting data, it extends into the transformation, collection, contextualization, and finally exposing it as actionable information. Building this contextualization and transformation from the beginning is important to enable the surfacing of primary constructs such as virtualized industrial assets and topologies. Further enablement of analytics and machine learning is supported through the publication of the context through a form of catalog and registry to support data scientists and process engineers to implement valuable solutions.
- ◆ **Cybersecurity:** By enabling shopfloor inbound and outbound communication, and enabling customers and partners access to production data, a secure, reliable communication flow should be established. Therefore, smart manufacturing solutions need a solid design of connectivity and communication protocols as well as sophisticated identity and access management systems.
- ◆ **Industrialization and Productization** The starting point of digital transformation might be data integration and reporting use cases, however, over time the need arises to create a pattern-based service catalog to enable reuse within the transformation. This might be a side-by-side activity by creating a smart manufacturing center of excellence.

- ◆ **Enterprise Deployment:** Implementing a digital platform utilized by optimization-orientated use cases will go through a life cycle or maturity process. It starts with experimenting, goes to incubate to prove its value in one site followed by deployment to multiple sites. Therefore, the platform needs to support enterprise deployment and management concepts and deployment techniques, at times differing between those utilized by IT and OT operations teams as it extends into edge environments. The techniques may differ from location to location based on software and hardware selection at each location.

Scope and System Structure

The collection of data, the transformation of data into information, and the various possibilities to make data and/or information actionable, and by this valuable, are the heartbeat of smart manufacturing. This is relevant in single plants and cross companies' boundaries covering whole value chains or to enable data sharing concepts.

Therefore, **use cases** based on **data flows** are the drivers defining the scope of the MRA.

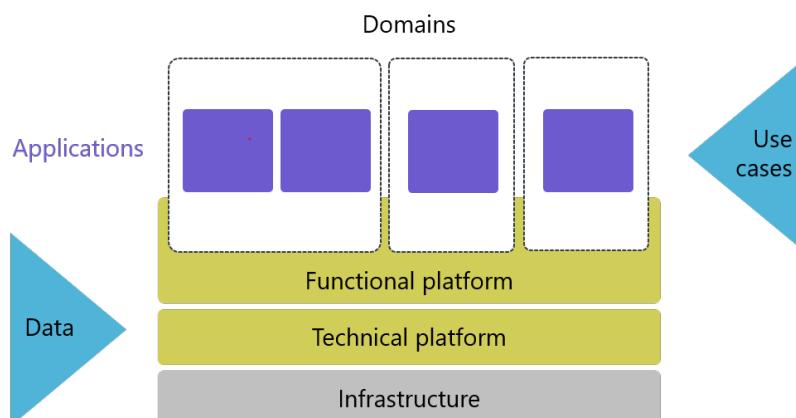


Figure 2: Data Flows and Use Cases are the main driver of the Manufacturing Reference Architecture

As data and information are driving smart manufacturing, a consistent definition of semantics is one of the primary challenges. These semantics are being addressed in the OMP Semantic Data Structuring (SDS) Working Group and are then aligned with the overall architecture.

Use Cases are scenarios of system behavior and express a business need. They are defined broadly in this context (e.g., predictive maintenance, production control tower) and consume information and data independently from each other.

Domain-specific **applications** are running on a platform, like maintenance apps for the shop floor or warehouse managing apps for the logistics department.

Due to the system complexity and to enable an “economy of scale” a **platform approach** is chosen. The platform can be divided into a functional and a technical part (*see Figure 2*).

The **functional platform** is business domain-dependent and contains services for the applications built on top of it. Examples are asset tracking, part traceability, or order data provisioning which are consumed by different applications for specific purposes. In contrast, the **technical platform** is independent of the business domain and the basic enabler for the functional platform. Examples are device management, virtual tenancy, logging, certificate management, IAM, etc.

Technical enablers like Integrated Developer Environments (IDE) or BI solutions can be part of both platform layers depending on the domain knowledge they incorporate: A dashboard solution can be rather abstract or already preconfigured with aspects like OEE measuring.

While sometimes the borders are blurry there is a rule of thumb to separate the functional and technical platform from one another: Business partners typically would only invest in the development of the functional platform. While the functional platform generates the direct business value together with the applications on top of it, the technical platform is the mandatory enabler and foundation for it. Examples of the “blurriness” are hierarchy service and virtual tenancy for the different plants and entities in the plants. They are spanning both platforms and therefore must be implemented in both layers.

Both platforms run on a defined **infrastructure**, that provides the actual compute power to execute any function, such as edge devices, servers, or other computers.

A central design principle for the smart factory will be the capability to scale agile and flexible production processes both vertically and horizontally.

In most manufacturing companies highly heterogeneous brownfield environments are in place, all using variations of the ISA-95 model, but with different technical implementations of comparable capabilities. This is very often because of historical processes and/or due to a broad variety of products manufactured.

The OMP MRA assumes exactly this heterogenous “brownfield” environment and targets a holistic IIoT platform, providing digital capabilities to enable manufacturers to connect or transfer their existing hierarchies to the requirements of Industry 4.0. As shown in *figure 3* the strict hierarchical structure can be extended with new elements: As introduced in RAMI the “connected world” is extending the architecture to a system outside the enterprise. They can be integrated down to lower levels. An example is a SaaS condition monitoring solution to monitor a given machine. As shown system connections can span multiple layers.

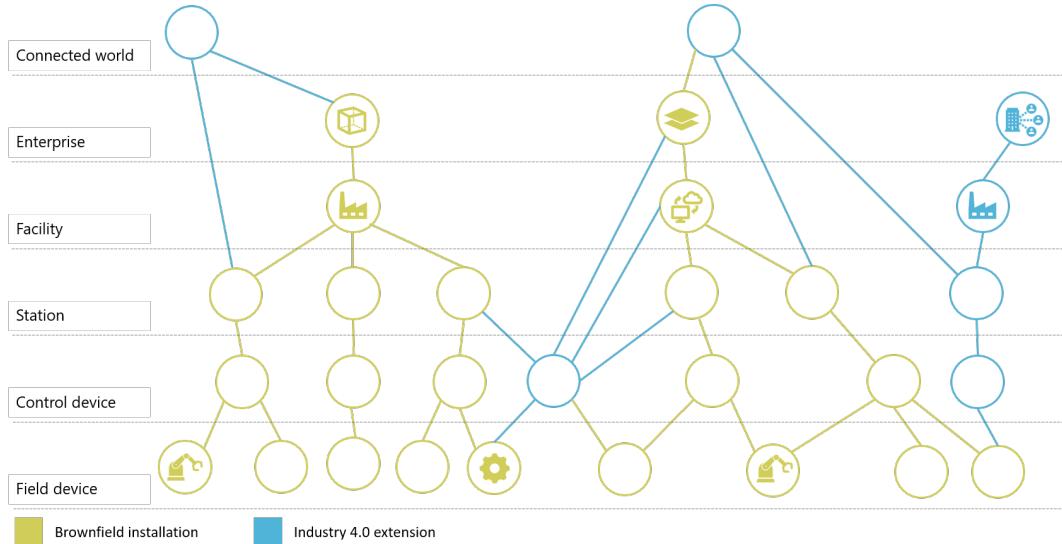


Figure 3: Scope of Manufacturing Reference Architecture

The MRA proposes to add to existing architectures, connecting to, and potentially cutting across, boundaries and layers of the existing infrastructure.

With all its limitations the automation pyramid at the same time answered a lot of questions. During the transformation indicated in *figure 3*, many strategic decisions must be made. Here are some examples:

- ◆ **Deployment:**
Where is the preferred installation and how should existing infrastructure be used?
- ◆ **Standardization:**
How much entropy should be granted on feature implementation for the plants? What is a realistic hardware standardization level?
- ◆ **Application integration:**
How can existing and new applications be integrated across the whole enterprise production system?
- ◆ **Asset Collaboration:**
How can existing assets and control systems interact with each other? How much collaboration should be targeted? Which discovery and negotiation procedures should be implemented? What amount of cross-plant collaboration is needed or granted?
- ◆ **Product lifecycle scope:**
What parts of the product lifecycle should be covered? Is R&D part of the scope? How many parts of the supply chain should be included?
- ◆ **Topology:**
What quality characteristics (performance, latency, security etc.) are needed?

3. Manufacturing Characteristics

Every company is unique, and manufacturing businesses are shaped by their history and product portfolio. But all manufacturing companies share the following characteristics to some extent.

Distributed Data Generation

Data in manufacturing is generated in diverse locations, systems, and devices. The data generation and collection processes are therefore highly heterogeneous. There is no easy way to comprehend the initial data gravity as the data generation stream has so many different sources and flow characteristics. High frequent vibration detection in machines is equally important as stock level changes from an ERP system.

Distributed Decision Making

Decisions in manufacturing are made across the production network. Centrally introduced orders are executed in plants that are typically in some kind of coopetition. Plants have a lot of decision power and therefore are driving many decisions to optimize the processes inside their own perimeter. This is an antagonist for standardization efforts. Inside plants decisions are made on different levels and by different actors from OT and IT. Data must be provided in different qualities to enable these decision processes. While in most cases these are made by humans there will be many more machine-driven decisions in the future.

Cyber-physical Processes

Manufacturing is the physical transformation of material to products. Familiar IT concepts like “undo” or “rollback” are therefore complicated. Reversing a physical transformation is challenging and usually requires a lot of effort and dedicated processes like rework. Therefore, architectures must be designed to allow alignment with physical transformation steps.

Extreme Asset Diversity

The most important elements on the shop floor are the assets, which can be broken down into machines and devices. In brownfield installations, there are typically many different product generations working side-by-side and some of them might be operational for many decades already. Connecting them for both data acquisition and command execution, therefore, is a challenging task and many generations of protocols (Profibus, Profinet, OPC UA, etc.) are examples of this. The missing standards in data semantics are adding to this complexity.

Extreme System Diversity

As with asset diversity, the manufacturing system landscape is typically a brownfield scenario with huge differences between the plants. The heterogeneity of the systems is typically growing with the overall company size. Often comparable capabilities are implemented differently from one plant to another. A broad variety of products being produced and company mergers in the past are fueling these differences.

Varying Response Time Requirements

Response time and network latency have highly deviating requirements, depending on the context of the specific use case and fit within the overall reference architecture. While PLC control loops may be measured in milliseconds and have the need for defined cycle times, for other contexts like interaction with an MES or alert acknowledgment seconds or even hours are sufficient. The architecture must be able to satisfy both extremes. Therefore, it is important that supporting operations and infrastructure can be placed accordingly. As an example, for low latency requirements on the shop floor a component will need to be able to run on the edge, while in more latency tolerant scenarios it may be well placed in a cloud environment.

There are specific requirements that are more typical to the operations side of the network that may require technologies such as time-sensitive networks (TSN) to be supported.

Heterogenous Ecosystem

Manufacturing is relying on a complex ecosystem of different partners within a company as well as external partners, suppliers, and customers.

They have different information needs and are granted individual data access. Cybersecurity and data privacy is, therefore, a huge challenge for balancing protection and open collaboration.

4. Key challenges

Manufacturing companies are facing the challenge to define their way forward in a very dynamic market. Unclear definitions like industry 4.0 and IIoT are adding to this. Successful digital transformations at scale are still lacking. The following topics describe the biggest challenges seen today.

From Initial Pilots to Scaled Adoption

A constant stream of innovation is hitting the shop floor. One can get the impression that computer vision, predictive maintenance, and many other buzzwords are standard technology elements of every shop floor. But they are mostly stuck in the pilot phase. Overcoming the roadblocks from local pilots to scaled adoption is one of if not the most important challenge. The following example showcases the typical challenges when considering the scale out of a use case scenario.

After a successful implementation of a specific Computer Vision use case there are three options for scaling: Do I want to use computer vision for other use cases? Do I want to adapt the use case to similar use cases in my plant? Do I want to replicate the use case in as many plants as possible? As every project requiring significant effort, priorities must be set.

Self-Funding Transformation

Huge transformation budgets for manufacturing are history. The current cost pressure on manufacturing companies mandates fast ROI. Saving money and reaping the benefits during the transformation journey is a

must. Simply collecting data, pushing them to a data lake, and then deciding how to gain insights at a later time is not a valid approach anymore. Gaining insights from data collected, transforming them into information, adding the appropriate semantics, and making them immediately actionable in the various use cases is paramount.

Lacking IT Skills

While OT knowledge in most companies is sufficiently covered by a company's own workforce or established suppliers, there is a shortage of skills combining IT and manufacturing knowledge. As IT is entering a lot of OT areas like software-defined PLCs this deficit is even increasing. People must be trained to apply existing knowledge and to replace some views of the past. The skill transformation can be covered with a well-balanced partner ecosystem, but this approach can be costly and risky.

Sidecar vs. Rip-and-Replace Approach

A fundamental challenge rests in the decision to build new applications side-by-side to the existing IT landscape vs. rearchitecting all applications into a new common architecture. The former is a targeted approach with a focus on short-term results. But it is adding additional complexity because existing applications are not replaced. The latter is going holistic and is including a clear execution path of replacing the existing application landscape.

Typical examples of a target sidecar approach are reporting applications. Quite often they have a well-defined functional focus like Overall Equipment Efficiency (OEE) reporting and are adding new technologies like data lakes or machine learning. Automated Guided Vehicle (AGV) fleet management and condition monitoring are additional examples.

The holistic approach usually follows a layered approach. Quite often it starts with general device and business application integration. The holistic approach requires a comprehensive technical, functional, and data architecture and usually results in a platform approach. The platform includes capabilities for cross-cutting aspects like asset registry, hierarchy service, and virtual tenancy for the different plants and entities in the plants.

Ambition Order of Magnitude

As explained in the preceding chapter manufacturing is characterized by distributed decision making. Enterprise-wide or cross-plant ambitions, therefore, are adding a major complexity to the well-established single plant decision processes. The plants in most companies decide autonomously on the budgets allocated to them. Trading shared spending versus individual benefits is quite often a time-consuming process.

5. Use Case Considerations for Architecture design

In the continuing work of MRA several representative use cases will be used to validate the design principles of the reference architecture, in conjunction with the Semantic Data Structuring (SDS) WG and the IoT Connectivity Working Group (IoT).

An architecture should not stand alone but must be designed in the context of delivering value to the manufacturing operations. This chapter introduces the core aspects of the use case themes considered during the design phase.

The reference architecture should enable manufacturers to leverage the newest digital and software technologies to e.g., improve KPIs within the production environment. Whilst manufacturers are broadly aligned in their desire to improve OEE and reduce costs, individual manufacturers have different priorities. Levels of automation on the shop floor, levels of analytical maturity, and end goals for digitalization programs also differ. Individual manufacturers will have a variety of priorities covering sustainability.

As such, the reference architecture must serve a variety of use case themes. The reference architecture should be relevant both as a feasible starting point and as a cost-effective end goal as manufacturers build towards their digitalization goals through a series of diverse but connected projects.

The definition of a company-specific reference architecture is an iterative process. Use cases drive the process of detailing the architecture. It is important that the data assets are continuously refined and unnecessary data duplication across use cases is avoided.

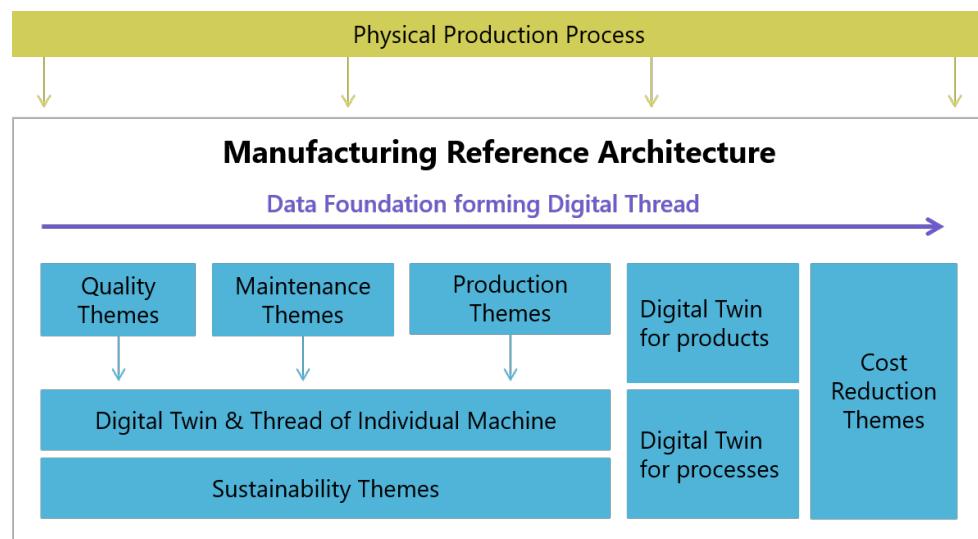


Figure 4: Example Use Case Themes supported by the Manufacturing Reference Architecture

The reference architecture must support the concept of a foundation of data, from which use cases can be built out. 'Starter' or 'Entry Point' use cases typically only require a small, defined set of data to implement, and can be aligned to three primary domains (*see figure 4*):

- ◆ **Quality:** Use cases will range from automated/digital quality inspection to root cause analytics.
- ◆ **Maintenance:** Use cases are focusing on reducing both planned and unplanned downtime.
- ◆ **Production:** This domain covers a broad range of use cases around increasing throughput either via better efficiency, or reducing stoppages and slowdowns not associated with machine availability. This

will cover improved process automation & materials handling, and increased digitization of the workforce through augmented reality and digital workflows.

As data from these domains is gathered and integrated from the factory floor, they start to form what is called “digital shadows”. From here more complex use cases, requiring a broader set of data, can be implemented with only a marginal cost.

Sustainability: In addition to reporting requirements these use cases will allow manufacturers to be more proactive around managing their carbon footprint, water & waste management, energy management, etc. while balancing environmental needs against cost, product quality, and production speed.

Virtualization: As the digital shadow grows for a particular machine to a complete set of sensor data coupled with its performance metrics it will form a digital twin of this machine. This digital twin will support use cases on current activities, in the production and quality domains.

Further collection and integration of data will form digital threads. Digital threads support use cases that look to implement use cases that consider a complete lifecycle – that of an asset, a production process, or of a product.

1. **Product Virtualization:** Capturing the exact circumstances of manufacture, including individual raw materials and sub-assemblies used in individual product creation. This can also be considered as supporting a ‘Lot Size of One’.
2. **Production Virtualization:** Enabling the optimization of the entire process, vs. individual machines or production steps.
3. **Digital Thread:** Whilst virtualization considers the current actions of a machine, process, or product; the digital thread will consider the behavior over a lifecycle. It is highly suited to supporting use cases in the maintenance domain.
4. **Topology:** Whilst the virtualized elements on their own have a great degree of value the understanding of their relationships to each other becomes critical in many scenarios. The knowledge of this topology allows for more advanced analytics and use cases.

Use cases around **cost reduction** will also be supported by the reference architecture. These could be top-down use cases, requiring a broad set of data such as supply chain configuration, work in progress, and safety stock optimization. Equally, they could be bottom-up use cases such as cost savings for specific operational steps or supporting functions.

Regardless of the intent of a specific use case, four **main personas** need to be considered. While all of them have a large set of commonalities, some of them require very specific platform capabilities, which could end in a large set of non-functional requirements for a platform.

The personas are:

- ◆ **Operator:** Operators are acting close to the actual production process. Tools (incl. the hardware) need to be designed to be used in challenging environments and display conditions and predictions near real-time. Latency requirements need to be considered – some use cases will require sub-second response times. Also, availability requirements are quite high.

- ◆ **Supervisor:** Foremen or supervisors are acting close to the production, focusing on a larger production area than an operator. They are frequently considered the process experts and as such their input in rating any output from AI and ML is highly valued. They will primarily use the same toolset as an operator, but with a richer reporting & analytics capability enabling them to take actions to improve OEE measures within their shift.
- ◆ **Plant Management:** Factory control tower use cases are mostly driven by reporting capabilities. However, this persona is aiming for yield optimization, which leads to capabilities on a high maturity level. Examples are factory maintenance shutdown planning, production flow optimization, etc.
- ◆ **Process or Industrial Engineers:** In general, the same as on plant management level. Solution examples are cross-site production optimization, end-to-end simulations, etc. Their personas will be supported by Data Scientists in their more complex analytical work. The core challenge is to establish a solid enterprise-wide data schema, to be able to analyze data across all sites.

As analytic maturity increases, customers, and suppliers (external or intercompany) can be considered as extended users. Required capabilities range from integrating demand and supply signals which would influence production sequencing through to simple status reporting.

6. Platform Capabilities

As introduced in chapter 2.2 the platform has a functional and a technical layer. Each Use Case is demanding different capabilities from these layers. By cross-referencing the capabilities required, manufacturers understand how to design the platform and the applications on top of it both in the initial phase and in the long term.

The following capabilities should be a priority:

- ◆ **Data Governance:** The orchestration of people, processes, and technology for democratization of data enable organizations to leverage their data as an enterprise-wide business asset as well as in cross-company data exchanges, becoming an important capability of a smart factory platform.
- ◆ **Data Integration:** Both sensor and other data captured from the machinery must be integrated with other data from applications such as ERP, MES, to form an analytical data set.
- ◆ **Data pre-processing:** Data can be pre-filtered or compressed on the edge to avoid massive data upload from unnecessary data: filtering and aggregation as examples.
- ◆ **Data Processing & Analytics:** Data processing occurs when data is collected and translated into usable information. It is important for the success to do it correctly as not to negatively affect the data output. The well-defined output will then be consumed for analytical workloads to find relevant relationships to transform information into actionable insights. In some cases (near real-time use cases) capabilities in this pillar need to be available close to the shop floor.
- ◆ **Data Transformation:** Data should be stored in its raw data format for the highest fidelity. However, to make data consumable and actionable, adding a) context to transform them into information and b) access layers for transformed and enriched data/information is required.

- ◆ **Data Accessibility:** It is critical to make data accessible in quality ensured and secure data pipelines to lead to informed decisions and actions. Data accessibility capability needs to be designed with the context of data ownership, data quality, data flexibility incl. centralized data schemas.
- ◆ **Data Reusability:** Data should be stored in their raw format to create a multi-purpose data foundation. It can be transformed as required by individual use cases through different zones. In general, a defined data schema across all factories needs to be applied.
 - Although there is a strong initial preference for creating this data foundation on the cloud, the reference architecture must support those cases where cloud connectivity is not reliable or desirable. This could be due to sub-standard connectivity SLAs in a particular location, the sheer volume of data required to be processed for a use case, or security concerns.
 - Ingested data, common data quality routines, and data preparation tasks need to be catalogued for easy use and reuse across several use cases ranging in complexity from AI to more simplistic dashboarding.
- ◆ **Support diverse personas:** As discussed above, the reference architecture will be designed to support multiple diverse personas. These personas have different IT backgrounds and skill levels. Applications could range from low-code applications using toolkits as well as custom-coded SQL-driven analytics, artificial intelligence, and machine learning for more complex use cases.
- ◆ **Control Loop Execution:** It is anticipated that manufacturers will increase their digital maturity over time, so the architecture cannot just propose an action, it must also support a control loop to bypass manual interaction with machines. The reference architecture will broadly support three levels of maturity:
 - Open-loop control: Analytic outputs are via a reporting tool or similar, and actions are taken by people.
 - Interactive control: Analytic outputs are fed back via the edge to the Human-Machine-Interface (HMI) for an operator to act on.
 - Closed-loop control: Analytic outputs directly drive a change in machine settings or behavior via the edge, without operator input.
- ◆ **Offline Support:** Some use cases will be rated as business-critical, so the application needs full offline support to enable production to continue if cloud links are down.

Besides the “functional” platform capabilities, the platform needs to provide functionality to manage and control the full solution space. Some important capabilities are:

- ◆ **Network and Communication:** Smart factory workloads increasing network requirements on the shop floor. For example, workloads with video streaming for safety or visual inspection use cases need a lot of bandwidth.
- ◆ **Edge Computing:** Like the network requirements, edge computing capabilities are required to enable “offline” scenarios as well as near real-time AI scenarios.
- ◆ **Operation Management:** In hybrid environments the importance of a harmonized operation management toolchain increases. Device and runtime management, as well as application telemetry and operations, should be considered from day 1.

- ◆ **Security and Authentication:** Depending on the scenarios, external access to resources might be required. For example, if you provide order status information, last-minute production changes, or sustainability data to your customers, you need to consider authentication capabilities for B2B or B2C scenarios in addition to the standard security requirements.
- ◆ **Front-End:** To increase the platform's value, it should support not only reporting and application frameworks, but with increased adoption of the platform, the need for a “low-code” solution environment is getting more and more important for process engineers or other officers providing applications.
- ◆ **24/7 DevOps:** Whilst data scientists are implementing AI-based solutions, the organization needs to be prepared for a “24/7” DevOps organization. Besides the organizational challenges, it is important to provide a toolchain that supports the full lifecycle for applications and machine learning workloads.

7. Architecture Design Principles

Successfully creating a reference architecture that is actionable by a large community of implementors requires a modular, extensible, adaptable, and flexible design, deferring implementation decisions until the last practical point (e.g., implementation platform selection and or toolchain). To support this a set of guiding principles have been defined to assist the implementor in aligning with current and future architecture concepts as well as supporting educated decision making. By understanding and - when in question - reflecting on these principles, the implementor will understand the intended concept and why certain decisions were made.

Platform Agnostic and Open

The reference architecture will not have an opinion on the platform or toolchain, leaving that to the implementor. To support this deferral and maintain flexibility services and components will maintain a separation of concerns, exposing clearly defined demarcation points, contracts, and interfaces for interoperability with other components in the architecture. When possible, any outward-facing exposed surfaces of the component will leverage industry and or open standards, vs. proprietary or bespoke ones.

While the reference architecture may have opinions on characteristics and locale of one or more components and services (e.g., the OT connectivity components should maintain affinity to the OT asset’s location) the contractual approach enables the services to be migrated between the enterprise locations and plants as appropriate.

The pluggable nature of the reference architecture supporting well-known contracts for integrations allows it to be platform-agnostic while choosing to implement platform-specific components and services as appropriate for cost, scale, or availability reasons.

Simplicity

As history has taught us simplicity tends to win out over complexity if the simple solution can deliver on the required business needs. Reasons for this include more comprehensive reasoning about the solution by its designers, lower chance of faults in operations, and easier support by the responsible teams. When options exist

and all solutions to the problem address the business solution select the simplest version with the assumption that adjustments can be made over time if required.

Security-by-Design

We have seen many architectures fail as cross-cutting aspects like security and compliance decisions have not been decided upon up front (“we don’t need this in our MVP”). But security, privacy, and compliance have severe implications that can’t be delayed for later decision making. If production data is not allowed to leave the data center located at the plant a public cloud solution might not viable.

Security must be integrated from the start, easy integration and adoption of additional security and compliance requirements is a must. Many of these principles require fast implementations and violations have a huge impact. Define features and components in a way that enables easy integration and adoption of the current security and compliance stances of the operator.

The Edge is an Extension of the Centralized Compute Power

Centralized information and compute power offer significant benefits when it is a viable choice. Cloud computing offers such centralization and is currently becoming the de facto approach for new IT developments. This introduces the need to encourage a cooperative solution that extends from the centralized compute power (e.g., Cloud) to the outer reaches of the edges. This will include the decision to make all information accessible from or in the cloud. This does not mean all information must be streamed or low latency, but it should be available centralized for enterprise-wide analytics and data mining.

Information is the Center of Gravity

Over the years there have been several movements associated with centralized and decentralized processing and storage, and it is currently in a centralized trend with the public cloud. As discussed before the goal of the solution should be to make all information discoverable, accessible, and actionable based regardless of its location.

Information can be moved to and from the edge and cloud as appropriate based upon different “temperatures” (*see Note*) representing latency and velocity requirements.

Common data access and analysis patterns have existed for many years with two higher-level solution domains that should inform the decisions when designing or implementing components and services:

- ◆ **High-Performance Computing (HPC)** is used when data is easier to move vs. coming up with enough processing power to perform the required operations. In this case, the data is moved to the compute resources and processed in many smaller sets, only later being reconstituted into the results.
- ◆ **Big Data** is leveraged when data is too large or too high velocity, so the compute resources are placed closer to the data to perform the operations.

The solution should borrow concepts and decisions from these two domains when solving problems to identify locations of execution and where data should be maintained and at what velocity (information temperature). In addition to this, as much data as reasonably possible should be moved to the cloud to take

advantage of the best AI/machine learning models and avoid the requirement to move massive amounts of data in the future. Options should still exist to perform distributed analytics at the edge.

Cost is a Factor

Due to the sheer volume of data, usage of resources, and the complexity of the analytical routines required to implement a solution, cost is always a factor. Individual projects under this larger umbrella term must return a net benefit. Thus, the reference architecture will be designed with principles that will help reduce overall cost. In particular:

- ◆ **Data reusability:** The foundation of many use cases is sensor data from machines. Capturing, preparing, and storing this data has an overhead cost. Sharing this overhead across multiple use cases will improve the ROI of individual projects. In addition, data reuse will reduce the cost of data quality.
- ◆ **Analytic reusability:** Like use cases, there are common analytic functions (for example in data quality and preparation) in addition to common analytic use cases. Analysts should be able to draw on pre-existing models, processes, and tools for either direct reuse or adaptation for new use cases.

These two factors combined imply a need for Governance. Both data governance and the governance of analytic routines – especially for common transformations. Governance covers a broad array of use cases, but at minimum, the reference architecture will consider:

- ◆ Data cataloging, including stewardship functionality
- ◆ Data quality
- ◆ Data retention policies
- ◆ Access and security, including consideration if data privacy regulation will apply
- ◆ Analytical Operations - systems and processes to automate and govern analytical routines from experimentation to production

An additional aspect of the cost considerations prescribes the need to balance scale vs. cost where that may be dynamically adjusted during operations. This is sometimes referred to as the elastic nature of the component, service, or solution.

Excursion:

- ◆ **Cold Information** is typically moved to and from the cloud or facility based on a timer or the arrival of a file allowing for large batches as required for performance and scale. This has a higher latency and is typically used for post-processing and analytics.
- ◆ **Hot Information** is typically moved to and from the cloud or facility through a streaming technique with a requirement of being to its endpoint with as low latency as reasonable. Examples of this may be tied to an alert on a piece of machinery that identifies a looming production outage.
- ◆ **Warm Information** is a combination of the Cold Information and Hot Information paths, where a condition that is transferred via the Hot Information path triggers a Cold Information transfer. For example, consider a rolling 2-minute window of vibrations that is being tracked for a generator. When a power spike occurs, it triggers a Hot Information data movement then immediately follows with a Cold Information movement of the vibrations file.

Design for Business Continuity, Disaster Recovery, and Compliance

Business continuity and disaster recovery are first-order concepts in all services and components. Each of these components, services, and/or capabilities will define a business continuity strategy from the start, along with confirmation and testing recommendations.

Compliance and or regulatory requirements must be inputs into the decision process for all aspects.

8. Conclusion

This whitepaper has laid out the most relevant architectural challenges in manufacturing brought on by the desire to transform to modern production.

Manufacturers face an ever-increasing number of partners whose digital touchpoints need to be integrated into production operations, whether they are solution providers for their own production or partners in the supply chain. On top of the old infrastructure more and more edge workloads are potentially being delivered and require flexible, open building blocks for scale and interoperability. Finally, there is a growing demand from manufacturers to assemble these building blocks as agilely as possible and thus also to build sequences of use cases to accelerate growth.

A modern manufacturing architecture should be therefore able to show how to integrate all these different data flows and pipelines through efficient data routing between edges and from the edge to the cloud in a closed loop and how to do this at scale, at the pace of the business.

The reality is that only a close collaboration between all players in the industrial space will help to gain value from Industrial Data. Doing this based on open standards and open-source building blocks will benefit all participants because it supports and enables the growth of this ecosystem.

In the end, the architecture must solve production needs. This in combination with the different requirements of companies in respect of customization, scalability, depth, and scope should still allow a generic architecture. Required elements and entities that arise from the semantic working group, the IoT connectivity working group, as well as working groups to come, will be reflected in the architectural picture. Of course, this also applies to the very specific use cases that are being worked on in the AGV Working Group.

The findings and recommendations of the Working Group are not exhaustive and will be extended in the course of future work. In our next publications, we will dive deeper into the different layers and aspects of the architecture and describe this very concretely by use cases.

9. Appendix

Definitions and Terms

List of all abbreviations used in the document:

AGV:	Automated Guided Vehicle
AI:	Artificial Intelligence
COTS:	Commercial Off the Shelf (product / solution)
ERP:	Enterprise Resource Planning
HMI:	Human-Machine-Interface
IIoT:	Industrial Internet of Things
ISA-95:	International standard from the International Society of Automation
KPI:	Key Performance Indicators
ML:	Machine Learning
MRA:	Manufacturing Reference Architecture
MVP:	Minimum Viable Product
OEE:	Overall Equipment Efficiency
OMP:	Open Manufacturing Platform
OPC-UA:	Unified architecture from the OPC foundation
OT:	Operation Technology
PLC:	Programmable Logic Controller
PLM:	Product Lifecycle Management
Profibus:	Device level industrial communication bus (Governed by Siemens)
Profinet:	Ethernet-based system level industrial communication protocol (Governed by Siemens)
Purdue Model:	Purdue Enterprise Reference Architecture (PERA) is a 1990s reference model for enterprise architecture
SaaS:	Software as a Service
SCADA	Supervisory Control and Data Acquisition
TSN:	Time Sensitive Networking