Putting 5G into Production: Realizing a Smart Manufacturing Vertical Scenario

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***Abstract*—As 5G and network function virtualization (NFV) are maturing, it becomes crucial to demonstrate their feasibility and benefits by means of vertical scenarios. While 5GPPP has identified smart manufacturing as one of the most important vertical industries, there is still a lack of specific, practical use cases.**

Using the experience from a large-scale manufacturing company, Weidmüller Group, we present a detailed use case that reflects the needs of real-world manufacturers. We also propose an architecture with specific network services and virtual network functions (VNFs) that realize the use case in practice. As a proof of concept, we implement the required services and deploy them on an emulation-based prototyping platform. Our experimental results indicate that a fully virtualized smart manufacturing use case is not only feasible but also reduces machine interconnection and configuration time and thus improves productivity by orders of magnitude.

I. Introduction

To realize 5G, huge efforts have been invested in research, standardization, and innovation actions in recent years. One of the key aspects of 5G is network function virtualization (NFV), where network services consist of multiple interconnected virtual network functions (VNFs), which can be executed on commodity servers. Compared to previous networking generations, 5G and NFV promise new levels of management flexibility and automation with on-demand provisioning of network services, short delays and high data rates for unmet Quality of Service (QoS), improved reliability, lower costs, and new business opportunities and use cases through novel services [1].

As work is ongoing to put these promises into practice, a main focus now is the alignment of 5G with the requirements of various vertical industries. These verticals represent different sectors with a variety of envisioned use cases that are driven by 5G and NFV. Hence, both the development as well as the final assessment and evaluation of 5G are based on the requirements and success within each of these vertical use cases. To this end, 5GPPP identified smart manufacturing (also called “factories of the future”) as one of the five key vertical sectors that are most important for 5G [2].

In the envisioned smart manufacturing scenario, the introduction of 5G significantly transforms traditional manufacturing processes by enabling higher degrees of flexibility, automation as well as the introduction of completely new services such as remote maintenance. With the rise of industry 4.0 and industrial Internet of things (IIoT), more and more machines, sensors, and actuators will be interconnected, allowing fine-grained monitoring and control to further optimize manufacturing processes. While this generally envisioned smart manufacturing scenario has been described by 5GPPP and others [2], [3], their outlined use cases remain at a high level. Although they are a good starting point, more specifics are needed to actually realize a smart manufacturing scenario.

Our contribution is to evolve these high-level scenarios building on the longstanding manufacturing experience of Weidmüller, a real manufacturer with globally distributed factories, offering a variety of different products ranging from electrical terminal blocks to complex automation solutions. We focus on a practical use case that simplifies and accelerates the interconnection and setup of new manufacturing machines or entire machine parks and enables real-time machine data analytics. By introducing flexible and scalable network services, running on a co-located server acting as NFV infrastructure point of presence (NFVI-PoP), much of the complicated, time-consuming manual configuration can be automated.

After reviewing related work in Sec. II and describing the specifics of the smart manufacturing use case in Sec. III, we detail the envisioned architecture and involved components to actually realize the use case in Sec. IV. Finally, we describe our developed and deployed proof of concept, presenting first results that indicate the feasibility and usefulness of NFV-based services for smart manufacturing (Sec. V).

II. Related work

Multiple authors highlight the importance of aligning vertical requirements and use cases with ongoing work in slicing and multi-tenancy [4], [5]. In their white paper [2], 5GPPP identifies five key vertical sectors where 5G can drive social or industrial progress: Energy, e-health, media and entertainment, automotive, and factories of the future (or smart manufacturing). Blanco et al. provide a survey splitting the aforementioned five vertical industries into smaller use cases as well as introducing additional use cases – again many of which related to smart manufacturing (e.g., machine-to-machine communication or remote computing and industrial control) [3]. While other vertical scenarios, i.e., smart cities/energy [6]–[8], e-health [9], media and entertainment [10], and automotive [11], already receive considerable attention, there is only little work related to smart manufacturing.

Wollschlaeger et al. review technology trends in industrial communication [12]. They identify 5G as potential disruptive technology but also discuss the challenge of managing complexity and heterogeneity through NFV. We tackle this challenge, by developing modular NFV-based services that can easily be deployed as Docker containers. Twamely et al. [13] provide a brief overview of a smart manufacturing scenario but focus on automatic validation and verification of network services to achieve high quality. Similarly, Backman et al. [14] use smart manufacturing as an example for their proposed blockchain-assisted slicing but do not go into the practical details of the use case. While our envisioned smart manufacturing network services could also be isolated from other services using slices, we focus on providing practical details and an actual realization of the vertical use case.

In previous work, Behnke et al. [15] propose a first concept for a practical smart manufacturing use case. Similar to our envisioned use case, they consider flexible network services to facilitate the interconnection of new manufacturing machines. We build on and significantly evolve this first concept by providing further use case details and completely revising the architecture and involved network services to achieve the use case. While Behnke et al. focus on general-purpose VNFs like firewalls or IDSs, we also design manufacturing-specific VNFs that are necessary to actually realize the use case. In contrast to this previous work, we now provide a proof-of-concept implementation and first results by really implementing and deploying our described smart manufacturing network services.

III. Smart Manufacturing Use Case

With smart manufacturing, many manufacturers hope to improve their productivity and efficiency, reduce manual, error-prone human intervention, and introduce novel services. Building on Weidmüller's experience as a real manufacturer being active in over 80 countries and with a over 160 years-old history, we identified and designed a practical smart manufacturing use case, reflecting actual needs of today's manufacturers. Even though today's factories are already highly automated, there are still various tasks that have to be performed manually by human professionals. An example is the rearrangement or connection of new manufacturing machines in a factory's machine park (at Weidmüller, these are typically molding machines). By connecting the different machines, their machine data (e.g., sensor values or settings) can be monitored, analyzed, and potentially readjusted quickly and easily from a single (remote) location. Today, connecting all machines requires considerable manual configuration, which is time-consuming and error-prone. The manual effort is especially high when creating a new machine park where many new machines have to be integrated into the factory network to transmit status information and allow machine control.

In this use case, we therefore use 5G and NFV to improve automation and flexibility when connecting new machines as well as easily monitor data coming from the different machines directly at the edge. To this end, we envision three network services consisting of multiple VNFs that are running on a close-by NFVI-PoP and are orchestrated by a service platform like OSM [16] or 5GTANGO [17]. Specifically, we consider the following three network services (details are discussed in Sec. IV):

- NS1: Factory edge service, typically deployed once per machine park (or, for large parks, multiple times) to collect and monitor machine data in real time and forward it to the cloud
- NS2: Machine interconnection service, deployed once per machine and connects it to the machine park's network
- NS3: Management portal, deployed once per machine park for graphical, interactive service configuration

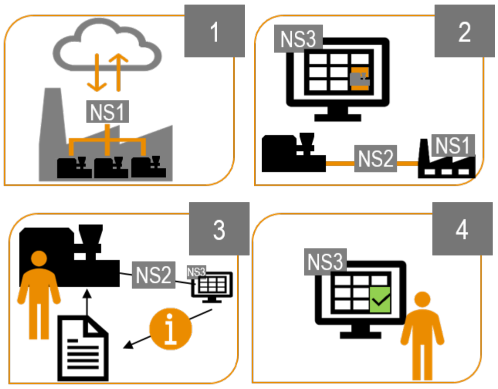


Fig. 1: Steps for connecting machines within a machine park using flexible network services (NS1–NS3)

These network services facilitate the process of connecting a new machine by (at least partly) automating the involved steps. They also enable real-time analytics of machine data at the edge of the machine park and connection to the manufacturer's cloud system for further analysis. While analysis in the cloud allows correlation with machine data from other machine parks and factories, the real-time analysis at the edge is crucial to quickly react to undesired changes in machine data. A common assumption that is in line with the situation of typical machine parks, is that an NFVI-PoP is available (or can be installed) in the machine park's server room. On this NFVI-PoP, a service platform can be installed and the network services can be executed. Here, we assume NS3 is already deployed, while NS1 and NS2 are deployed as follows (also see visualization in Fig. 1):

1) When creating a new machine park, a new instance of NS1 is started using the service platform to perform local processing of machine data and connect the machine park to the manufacturer's cloud system.
2) After physically connecting a new machine to the machine park and switching it on, the machine awaits initial configuration via its configuration screen. To this end, technical staff creates a new machine in the management portal (NS3), which then generates all required information for configuration of the physical machine. As current machines often cannot be configured remotely but only

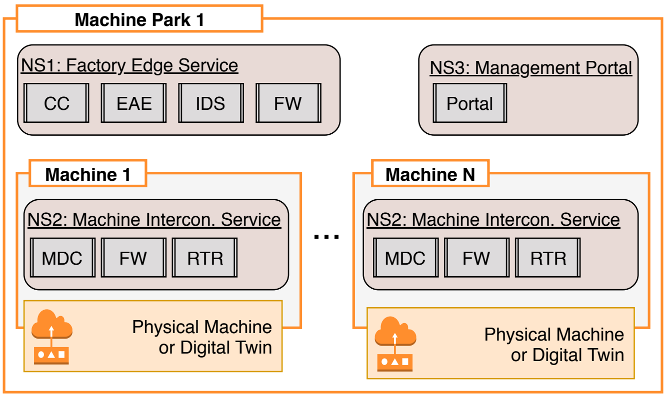


Fig. 2: Smart manufacturing architecture (single machine park)

via their configuration screen, NS3 selects and presents all relevant configuration settings to the technical staff (e.g., to print or display in an augmented reality headset and enter it at the physical machine's configuration screen). At the same time, the service platform instantiates NS2 to connect the new machine.
Here, there is room for future developments and research to automatically and remotely configure manufacturing machines and IIoT devices, e.g., via a custom dynamic host configuration protocol (DHCP).

3) Technical staff goes to the machine and enters all information given by NS3: IP, DNS, gateway to be used, session folder path for any file-based data exchange, corresponding credentials, etc. The machine then connects via NS2 and NS1 to the machine park's network. As it is being used, the machine uses standardized machine control protocols such as Euromap 63 [18] inside NS2 to send data to the edge analytics service and the cloud as illustrated in Fig. 3 (detailed in Sec. IV).
4) Finally, technical staff confirms the successful deployment using NS3.

IV. Architecture and Involved Components

In this section, we first present an overview of the architecture (Sec. IV-A) and then discuss the involved components (Sec. IV-B) to implement and realize the smart manufacturing use case described in Sec. III.

A. Smart manufacturing architecture overview

Fig. 2 shows the envisioned architecture with the three identified network services (NS1 to NS3) with their involved VNFs that are required to realize the described use case in a machine park (or factory site). We choose the architecture level of a machine park since we assume that each machine park comes with its own (small) NFVI-PoP on which all required services are deployed. This ensures that a factory could continue its production even if a machine park is temporarily disconnected from the rest of the (global) factory network. Of course, the described architecture can also be applied to other abstraction levels, e.g., for the whole factory.

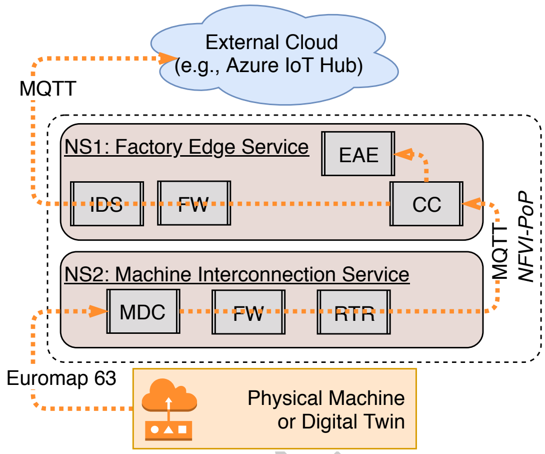


Fig. 3: Logical data flow from a machine through NS2 and NS1 to the factory-wide cloud backend.

The figure shows that NS1 and NS3 are deployed once per machine park, while NS2 is instantiated once per machine, enabling separate, isolated connections per machine. In large machine parks, NS1 could also be scaled out to multiple instances for load balancing.

With these network services being deployed, Fig. 3 shows the logical data flow from a machine through NS2 and NS1 to the cloud (e.g., Microsoft Azure IoT Hub[1]). It starts from the machine, which generates data, e.g., sensor values. Alternatively, a digital twin can be used for testing purposes, i.e., a virtualized copy of the physical machine with the same interfaces and producing similar data. NS2 collects this data and translates it to an MQTT-based messaging format [19], which is widely used in IoT. It then sends the data to NS1, which aggregates the data of all machines and temporarily stores it for further local processing. Finally, NS1 forwards the collected data to the external, factory-wide cloud backend for in-depth analysis and long-term storage.

B. Smart manufacturing network services and VNFs

We designed the following three network services to realize the smart manufacturing use case in practice:

1) NS1: Factory edge service: The factory edge service (NS1) is deployed once per machine park. It has two main purposes: First, it connects the machine park with the rest of the (global) factory network and with the factory-wide cloud backend, which collects monitoring information from all production sites of the entire company. Second, it provides edge analytics capabilities to monitor and analyze the data produced by the machines directly at the edge of the machine park. This allows quick reaction, e.g., when machine metrics exceed thresholds.

NS1 contains two use case-specific VNFs for machine data aggregation, local storage, forwarding, and data analysis: The cloud connector (CC) and the edge analytics engine (EAE).

[1]Azure IoT Hub: https://azure.microsoft.com/en-us/services/iot-hub/ (accessed Jan 21, 2019)

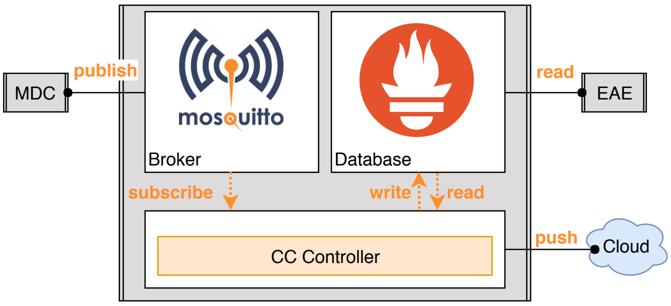


Fig. 4: Cloud connector (CC) VNF (part of NS1)

The CC consists of three deployment units, each realized as either a virtual machine (VM) or lightweight container (Fig. 4). The first deployment unit is an MQTT message broker (e.g., Eclipse Mosquitto[2]), which enables the messaging between NS1, NS2, and the cloud backend. The second one constitutes a time-series database (e.g., Prometheus[3]) for aggregating and storing incoming data from the machines of the machine park. Finally, the third unit controls and processes the entire workflow by writing the machine data to the local database as well as pushing it to the external cloud backend.

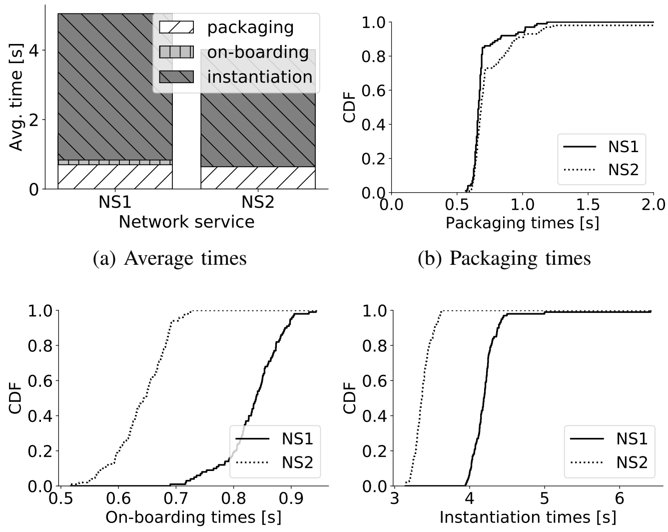
The EAE connects to the CC's database to access data of the machines within the machine park. This local database contains both incoming real-time data as well as a short history of recorded data. For visualization and easy interpretation of this data, the EAE can provide a graphical dashboard (e.g., using Grafana[4]). It can also send alerts if any machine data (e.g., temperature) reaches a pre-defined threshold to ensure quick reactions by technical staff.

Furthermore, NS1 contains a number of general-purpose VNFs such as a firewall (FW) and an intrusion detection system (IDS) to ensure that no malicious traffic enters the machine park's network. Optionally, it may include additional supporting VNFs like WAN optimizers or routers depending on the requirements of the machine park's uplink to the rest of the company's network.

2) NS2: Machine interconnection service: The machine interconnection service (NS2) is deployed once per machine within the machine park. Its purpose is to interconnect a single machine, e.g., a molding machine or a 3D printer, to the machine park's network, which is used to control all machines and to collect machine data (e.g., machine state or sensor data).

One challenge of a real-world manufacturing scenario is the connection of NFV network services to existing production machines (or their digital twins). A widely-adopted standard for interconnecting manufacturing machines, e.g., molding machines, is Euromap 63. Euromap 63 is a file-based exchange format that uses a shared session folder to exchange small text files containing machine data or parameter settings. To support such data exchange formats, we introduced and implemented a machine data connector (MDC) within NS2 that interacts with

[2]Eclipse Mosquitto: https://mosquitto.org/ (accessed Jan 21, 2019)
[3]Prometheus: https://prometheus.io/ (accessed Jan 21, 2019)
[4]Grafana: https://grafana.com/ (accessed Jan 21, 2019)



(a) Average times
(b) Packaging times
(c) On-boarding times
(d) Instantiation times

Fig. 5: Service startup times (100 independent repetitions): Much faster than manual configuration of machines.

the connected machine using Euromap 63, translates the data into MQTT messages, and sends them to NS1. The benefit of MQTT is its support for publish/subscribe communication patterns, allowing a wide set of analytic functions to subscribe to the data produced by the machines. We designed the MDC to be exchange format-agnostic, consisting of modular plugins for supporting different exchange formats such as Euromap 63. In doing so, different variations of the MDC can easily be created and used to communicate with machines using different formats.

In addition to the MDC, NS2 also includes a firewall for security and a router (RTR). The router creates an own subnet per machine to which all components (e.g., controllers and sensors of the machine) are connected. This one-subnet-per-machine policy is based on our experience and reflects real-world factory deployments, which are organized exactly like this. However, in today's manufacturing networks those subnets are set up, configured, and maintained manually by the factory's IT staff. Such manual configuration and maintenance is error-prone and very time-consuming, especially if machines are moved between machine parks or production lines. Here, smart manufacturing with our described architecture and network services can greatly improve productivity and avoid errors.

3) NS3: Management Service: The manager service (NS3) plays a supporting role and is deployed once per machine park. While it is not crucial for the actual machine operations, it offers management functionalities (e.g., a graphical factory portal) to support the technical staff. This simplifies and accelerates adding new machines and monitoring their states. For simplicity, it may also integrate the EAE's dashboard in one consistent, powerful user interface.

V. Deployment and first results using 5GTANGO

To demonstrate the feasibility and usefulness of our proposed smart manufacturing use case, we developed the required network services, NS1 and NS2, and their involved necessary, use case-specific VNFs. We implemented all VNFs as Docker containers, which can be quickly started and stopped. The entire implemented prototype with all custom-built VNFs is available as an open-source project [20].

We used the framework of the 5GPPP phase 2 project 5GTANGO with its rich service development and prototyping toolchain to implement and deploy our prototype. Specifically, we used the SDK and 5GTANGO's lightweight NFV prototyping platform [21].

One benefit of introducing flexible network services in a smart manufacturing scenario, is the quick, automated machine interconnection and configuration using these network services. To better understand and quantify this benefit, we measured the startup times for the involved network services NS1 and NS2. To start these services, they need to be first packaged into modular NFV packages, which are then onboarded and finally instantiated using the 5GTANGO NFV prototyping platform [21].

Fig. 5 shows the results of measured startup times of both network services over 100 independent repetitions performed on a machine with an Intel Xeon E5-1660 CPU and 32 GB RAM. The average times in Fig. 5a illustrate that the packaging and on-boarding times for both services are negligible (well below 1 s). Also the instantiation only takes a few seconds. Here, NS1 has a slightly higher instantiation time than NS2 (around 1 s) because it involves more containers that need to be started (the CC alone consists of three containers). The cumulative distribution functions (CDF) in Fig. 5b–5d show that the measured times are distributed closely around the mean, indicating that the services start quickly and reliably. Comparing the startup times of NS2 (around 4 s), which is started for connecting a new machine, with the time and effort of manually connecting machines, configuring routers, etc. in traditional factories (minutes to hours) illustrates the huge increase in efficiency that flexible network services and smart manufacturing can provide.

VI. Conclusions and Future Work

The results of our developed and deployed smart manufacturing use case indicate that through the introduction of flexible network services, adding new machines to a machine park and configuring their connections is magnitudes faster than in today's traditional factory networks. This use case clearly illustrates the feasibility and benefits of introducing smart manufacturing: Increased productivity and flexibility as well as novel services such as runtime analytics at the edge. We will further evolve the work presented in this paper and use it as vertical pilot in the 5GTANGO project to validate the 5G and NFV concept.

Acknowledgments

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