THE ROLE OF TECHNICAL DOCUMENTATION IN ENABLING AUTOMATED GENERATION OF MACHINE CAPABILITIES *

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ABSTRACT

To meet the dynamic demands of Industry 4.0, manufacturing systems require enhanced adaptability and interoperability, particularly in light of the transition from *Machinery Directive 2006/42/EC* to *Machinery Regulation 2023/1230/EU*. This transition emphasizes the need for machine-readable and digital documentation standards. However, integrating these standards with capability modeling frameworks such as the Capability-Skill-Service model (CSS model), the Open Platform Communications Unified Architecture (OPC UA) and the Asset Administration Shell (AAS) remains challenging, which limits seamless interoperability and dynamic reconfiguration. This paper addresses these issues by presenting a methodology to automate capability generation using large language models. This approach standardizes technical documentation and bridges gaps through automation. Aligning the CSS model with the OPC UA and AAS frameworks enables integration into Manufacturing-as-a-Service platforms, driving innovation and efficiency in modern manufacturing ecosystems.

***K*eywords** Manufacturing-as-a-Service (MaaS) · Machine Capabilities · Onboarding · Standardization

1 Introduction

The accelerating digitalization of manufacturing has catalyzed the emergence of online marketplaces, such as Manufacturing-as-a-Service (MaaS), which provide manufacturers, particularly small and medium-sized enterprises (SMEs), with unprecedented opportunities to showcase their capabilities to a global audience and expand their customer base. To effectively engage with these platforms, manufacturers must adopt standardized formats for machine and service descriptions, such as the Asset Administration Shell (AAS). However, SMEs often face significant challenges in creating AAS-compliant models due to constraints in resources and technical expertise [1] [2].

A critical obstacle lies in extracting and structuring relevant information from various sources, including manuals, data sheets, technical drawings, and 3D models [3] [4]. These documents are mandated by the European Union (EU), which

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also provides guidance on the specific information that must be included in them. Manufacturing companies have the flexibility to determine how they describe their machines within the framework of these guidelines for human-readable technical documentation, beyond these requirements [5] [6]. To address this issue, this study introduces a tool leveraging large language models (LLMs) to automate the generation of AAS-compliant representations from machine-related documents. A feedback loop involving domain experts ensures the quality and completeness of these representations, aiming to lower entry barriers for SMEs and enhance their visibility and competitiveness in digital marketplaces [7] [8].

Additionally, the growing need for interoperability means technical documentation must support the automated understanding of machine capabilities. However, the adequacy of existing documentation for digital modeling remains uncertain [9] [10]. This study will evaluate whether current standards and regulatory frameworks enable effective capability extraction. It will also identify the requirements for future documentation practices that will promote automation, enhance interoperability and drive the digital transformation of the manufacturing sector.

2 Related Work

This section provides an overview of the regulations and standards necessary for selling machines in Europe, as well as the capabilities context within the Capability-Skill-Service model (CSS model).

2.1 Regulation and Standards for Machine Documentation

The *Machinery Directive 2006/42/EC* [5] will be updated by the *Machinery Regulation 2023/1230/EU* [6] from the EU, which provides manufacturers of new machines with guidelines on the documentation and tests required before a machine can be sold in the European Economic Area. The regulations provide a legal framework for machine safety and documentation within the EU. These regulations require manufacturers to provide clear, human-readable documentation to ensure safe operation and maintenance. From 2027, the *Machinery Regulation* will introduce instructions and manuals that are digitalized and expand the scope of covered products, adapting to technological advancements [6].

These regulations are complemented by standards such as *DIN EN ISO 12100* and *DIN EN ISO 20607*. The *DIN EN ISO 12100* standard, which emphasises risk assessment and reduction. It defines risk as a function of harm severity and likelihood. It also promotes clear communication of hazards and safety measures [11]. *DIN EN ISO 20607*, meanwhile, focuses on user manuals, ensuring they are comprehensive, understandable and tailored to the machine operator [12].

The EU directive and regulation are valid topics for standardizing new technical documentation, which would reduce the obstacles for SMEs participating in MaaS platforms and enhance their productivity.

2.2 CSS model with OPC UA and AAS

The CSS model is an extension of the product, process and resource paradigm, separating product design from production engineering. Within the CSS model, a service includes high-level functional descriptions and commercial information, as well as references to capabilities. A capability is a resource-independent description of a production function, including its properties and constraints. A skill is a resource-dependent implementation with inputs, outputs and a mechanism for executing and monitoring the production step. The key aspect of this model is the matching between the product requirements and the resources availability [13].

Integrating the CSS model with the Open Platform Communications Unified Architecture (OPC UA) and the AAS addresses critical modern manufacturing challenges such as interoperability, flexibility and scalability. OPC UA provides a standardised protocol for secure, interoperable communication, as well as a semantic, browsable interface for interacting with resources. AAS offers a structured framework for digital twins and enables the semantic description of assets. For instance, the AAS *Capability Description Submodel* template which is in the development by the Industrial Digital Twin Association (IDTA) enables the CSS model to describe capabilities in a machine-readable format, thereby facilitating the automated matching of required and offered capabilities [14] [13].

This combination enables the dynamic reconfiguration of production systems, real-time communication and the efficient allocation of resources, all of which are essential for Industry 4.0 scenarios such as shared production, MaaS and decentralized manufacturing [15] [13].

2.3 Determining Machine Capabilities

In [13], *Plattform Industrie 4.0* showed three methods to describe, assign and derive capabilities that are connected to method determining capability. The determination of machine capabilities is a fundamental aspect of capability-based engineering, as described in the CSS model. Describing capabilities focuses on creating formal semantic definitions, including properties, constraints, and hierarchical relationships, using standards like DIN 8580 and IEC CDD to ensure machine-readable formats for interoperability and reuse. Assigning capabilities links these formal descriptions to specific production resources, such as machines or tools, by identifying resource skills and their effects on products, ensuring alignment with functional attributes. Deriving capabilities extracts required capabilities from product specifications or process descriptions, matching them with existing formal descriptions and creating placeholders for undefined capabilities. Together, these methods provide a structured approach to capability modeling, enabling flexibility and adaptability in manufacturing systems [13]

2.4 RAASCEMAN

The Resilient and adaptive supply chains for capability-based Manufacturing-as-a-Service networks (RAASCEMAN) project incorporates the MaaS concept to effectively address supply chain disruptions. MaaS platforms enable the sharing of resources and collaboration between distributed manufacturing entities, using cloud-based technologies to optimize service matching and task decomposition. To be efficient and inclusive, the service matching process requires a standardized asset description to find suitable participants in a MaaS network and create a reliable supply chain. This approach enhances the flexibility and responsiveness of supply chain networks, enabling companies to adapt swiftly to unforeseen events.

For medium-term disruptions (lasting from a few days to four weeks), RAASCEMAN automates the quantification of disruption probabilities and impacts. It recommends alternative suppliers or manufacturing technologies, such as 3D printing. In the event of short-term disruptions (lasting under a day), RAASCEMAN employs dynamic production planning and scheduling based on upstream supply chain data to enable internal adjustments or outsourcing decisions. By integrating MaaS principles, the project supports the rapid preparation of quotations and verification of feasibility, thereby enhancing the efficiency of decision-making. Furthermore, RAASCEMAN contributes to the long-term design and management of supply chains, thereby improving the competitiveness of companies in the production of high-quality, customised products [16] [17].

RAASCEMAN features an interconnected pilot line that showcases various participants acting as factories within a MaaS platform. This helps to validate comparable real-world events and shows how factories can be connected and modelled to enable smooth exchange between customers and suppliers, and between suppliers.

3 Approach for Generating Capabilities From Technical Documentation

This section will show the two parts needed to reduce the effort required for SMEs to participate in MaaS.

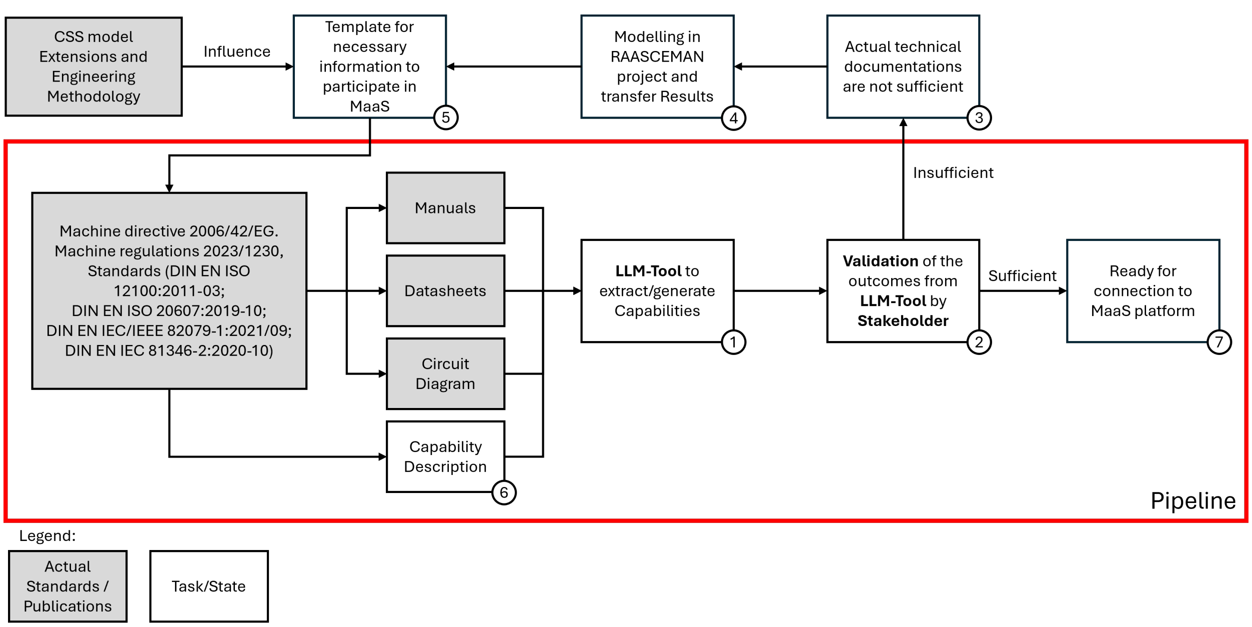

Figure 1: Pipeline for Automated Generation and Standardization of Machine Capabilities for MaaS Integration

3.1 Limitation of LLM-Tools to Generate Capabilities

Current standards prioritize human readability over machine readability, which limits their integration into automated systems. For example, standards are often distributed as PDFs, which are human-readable but not easily processed by machines. LLMs have exceptional capabilities when it comes to processing and generating textual information, they struggle to interpret domain-specific sketches. Sketches are often used as intuitive and efficient communication tools, and can convey complex ideas more effectively than text. However, the implicit and highly contextual nature of these visual representations poses challenges to current LLMs, which struggle to utilize domain-specific visual information effectively. This highlights the need for advances in AI that can bridge the gap between human-centric design practices and machine understanding [18].

[8] demonstrates that LLMs can generate AAS instances based on the input of the stakeholders. However, these instances are not aligned with a capability-based MaaS network, so they cannot be used with such a platform straight away.

To automate the creation of capability descriptions, a tool will be developed to assist factory stakeholders by describing capabilities for participation in a MaaS platform. This tool is based on LLMs that are pre-trained to describe capabilities and can also extract data from non-textual information. To validate the results of the tool by onboarding a new participant, the stakeholder must be involved in correcting or accepting the determined capabilities. This ensures that the information required for participation in a MaaS platform is correct and has been agreed by the stakeholder.

3.2 Pipeline for Automated Generation of Machine Capabilities

Current technical standards often lack the structural elements necessary for effective machine interpretation and integration into automated systems. Although these documents usually cover functions, parameters, and safety guidelines, they do not establish formal links between these elements and their operational contexts. Without contextual links, it is difficult to dynamically adapt functions to specific scenarios or requirements. Furthermore, most standards do not incorporate semantic descriptions, such as ontologies, which are essential for enabling machines to understand and reason about data. Ontologies provide a structured vocabulary and relationships that facilitate interoperability and automated decision making. Without these semantic annotations, the standards remain static and human-centric, which limits their utility in modern interconnected systems [19].

As illustrated in Figure 1, a methodology has been developed for the automation of machine capabilities within a MaaS platform. The gray boxes represent the current standards to generate technical documentation for new machines and publications within a capability-based manufacturing context. However, they are not inherently structured for machine-to-machine communication or for configuring connections in an automated MaaS environment.

The process begins with the identification of gaps in the existing technical documentation (3), which are often insufficient to generate the comprehensive capabilities necessary for MaaS integration. To address this issue, the preliminary concept involved the creation of a tool based on LLMs with the objective of extracting or generating capability descriptions from various heterogeneous sources. These sources could include manuals, datasheets, circuit diagrams, and other documentation (1). The outcomes of this LLM tool must be verified by the factory stakeholders against a sufficient description of the generated or extracted capabilities (2). A preliminary review of existing documentation revealed that it is often incomplete for the purpose of generating automated capabilities.

The extracted capabilities are aligned with the relevant standards and directives, including the *Machine Directive 2006/42/EG*, the *Machine Regulation 2023/1230*, and the applicable *DIN/ISO/IEC* standards, ensuring compliance (central grey box). The methodology under discussion here builds on the outcomes of the RAASCEMAN project (4), and identifies the requirements for enabling MaaS participation and demonstrating automated production handling. The RAASCEMAN project uses real demonstrators and collaborates with industry partners to evaluate these requirements. These results are then consolidated into a unified template designed for MaaS participation (5), which incorporates the generated capability descriptions (6). This process culminates in the machine being ready for integration into the MaaS platform (7).

The overall workflow is embedded within a broader engineering framework based on the CSS model, offering scalability and alignment with industry standards for digital manufacturing. The red-bordered section highlights the automated or semi-automated capability generation process powered by LLM tools, which forms the methodological core of this contribution. This paper demonstrate an approach to bring the capability description into the standardization for participation in a MaaS platform. These approach will be validated with RAASCEMAN project to find out the actual limitation and also the gap to standardize the machine-readable documentation.

4 Conlusion and Outlook

Integrating MaaS platforms with AAS standards offers SMEs a transformative opportunity to overcome barriers in digital marketplaces. This study addresses critical challenges in capability extraction and documentation structuring by leveraging LLMs to automate the generation of AAS-compliant representations, thereby enhancing interoperability and reducing entry barriers for SMEs.

The findings emphasize the importance of aligning technical documentation with machine-readable standards to enable seamless automation and interoperability. However, current standards prioritize human readability, which limits their utility in automated systems. Closing these gaps through semantic annotations and structured methodologies is essential for achieving Industry 4.0 objectives [15].

Looking to the future, the RAASCEMAN project will provide a robust framework for validating the proposed approach in real-world scenarios. Future research should focus on refining LLMs-based tools to enhance their accuracy and adaptability, as well as developing standardized templates for capability descriptions. Furthermore, integrating semantic technologies, such as ontologies, into AAS frameworks could enhance machine comprehension and interoperability even further, as discussed in [7].

In conclusion, this study contributes to the ongoing digital transformation of the manufacturing sector by proposing a scalable, standardized approach to capability modelling. By bridging the gap between human-readable documentation and machine-readable formats, it enables SMEs to participate actively in MaaS platforms, thereby fostering innovation, competitiveness and resilience in global supply chains [20].

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Conference

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