Knowledge Graph Modularization for Cyber-Physical Production Systems*

Stefan Bachhofner[1] [0000-0001-7785-2090], Elmar Kiesling[1,2] [0000-0002-7856-2113], Kabul Kurniawan[1] [0000-0002-5353-7376], Emanuel Sallinger[3,4] [0000-0001-7441-129X], and Philipp Waibel[1] [0000-0002-5562-4430]

[1] WU Wien, Institute for Data, Process and Knowledge Management,
[2] Austrian Center for Digital Production, Vienna, Austria
[3] TU Wien, Databases and Artificial Intelligence Group, Vienna, Austria
[4] University of Oxford, Oxford, UK

Abstract. Knowledge Graphs (KGs) have a large potential to support analytics and AI applications in the manufacturing domain, which in the age of Industry 4.0 is increasingly driven by data. Compared to other domains, however, KG techniques have seen limited adoption in this field so far. We argue that the construction of KGs in the context of Cyber-physical Production Systems (CPPSs) requires a systematic methodology grounded in domain-specific abstractions. Consequently, we introduce a KG modularization framework based on the well-established RAMI 4.0 architecture model. A key benefit of the proposed approach is that the resulting KGs support navigation across abstraction hierarchies, enabling bottom-up contextualization of raw data on the one hand, and top-down explanations by linking to lower levels of granularity on the other hand. We motivate the proposed approach and illustrate its application with a real-world use case from the automotive sector.

Keywords: Poster · Cyber-physical Production Systems · Knowledge Graph Modeling · Modularization

1 Introduction

Industrial production is currently undergoing a major paradigm shift that is often described as Industry 4.0 (I4.0). This development at the confluence of advances in digital and manufacturing technologies [8] is strongly driven by data as a key enabler, creating opportunities beyond classic monitoring and improvement

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applications [9]. In this context, Knowledge Graphs (KGs) have strong application potential as a means to, e.g., create an integrated, multi-perspective machine data space from heterogeneous data silos, lift and contextualize machine-generated data, and facilitate cooperation between various domain experts and Artificial Intelligence (AI) agents based on shared concepts.

Motivation and challenges. Our motivation stems from industrial applications such as the ones within the H2020 Teaming.ai project[5]. In particular, our real-world motivating scenario focuses on human-AI cooperation in quality management and optimization of injection molding processes in the automotive industry, with a KG at its core. This production process is composed of the following steps: *(i)* initial parameter setup: setup of the injection molding machine and production of trial parts; iterative parameter adjustment until quality issues are resolved; *(ii)* production start; *(iii)* automated quality inspections during production, i.e., a computer vision system inspects each produced part; *(iv)* parameter optimization is triggered when faults are detected. This scenario raises a number of more general archetypal challenges for CPPSs:

- **(C1)** It requires collaboration of AI agents and human stakeholders, such as *quality controllers* and *process engineers*, across **multiple organizational, functional, and temporal levels of granularity**.
- **(C2)** Reliable quality control and parameter optimization requires **contextualization**, e.g. of sensor data with higher-level operational information and quality requirements ("navigating upwards").
- **(C3)** Diagnosis (e.g., of increased NOK rates for a particular part), by contrast, requires **explanations**, which necessitates the ability to navigate to lower levels of granularity ("navigating downwards").
- **(C4)** Finally, a key challenge is to **link** decisions and goals on the production (e.g., line control) and operational levels (e.g., classification of defects) to higher-level business goals (e.g., increase Overall Labor Effectiveness (OLE) and guarantee the fulfillment of quality requirements).

To address these challenges, we propose a KG layering approach that facilitates purpose-driven, agile construction of reusable KGs across multiple layers of abstraction and perspectives.

Opportunities and Impact. KGs have countless demonstrated applications across industries including finance, technology, and many other sectors. However, this potential of KG-based systems is still largely unrealized in manufacturing, where the concept has seen limited adoption and integration into real-world manufacturing systems so far [4].

With the approach demonstrated in this paper, we are building KGs for manufacturing companies in the injection molding and milling sectors, but also for higher-level applications such as manufacturing and use of replacement parts. The most important concrete impact of KGs in these use cases are *(i)* delivering a trustworthy, auditable, integrated datastore that preserves the inherent heterogeneity of manufacturing data, *(ii)* the combination of different types of AI and

[5] `http://teamingai-project.eu`

human reasoning in an integrated platform, and *(iii)* improved decision-quality in the manufacturing and selection of parts by taking all available information into account.

2 Related Work

Domain-specific layering models are prevalent in the manufacturing domain. The ANSI-ISA-95 standard [1], for instance, has been widely adopted to partition activities in manufacturing enterprises into five layers, i.e., *(i)* production process, *(ii)* sensing and manipulation, *(iii)* monitoring and supervision, *(iv)* manufacturing operations management, and *(v)* business planning and logistics. More recently, the Reference Architectural Model Industrie 4.0 (RAMI 4.0) [5] has been introduced as a three-dimensional conceptual framework that represents the I4.0 space along three axes: *(i)* life cycle and value stream (IEC 62890), *(ii)* hierarchy levels (IEC 62264), and *(iii)* layers. Lee et al. [10] propose a similar framework for implementing CPPSs based on five levels: connection, conversion, cyber, cognition, and configuration.

Efforts to formalize some aspects of these models have focused either on specific subsets, such as the semantic description of CPPS components' asset administration shell [3,11], or the integration of the wealth of available layering models and guidelines. For the latter, Bader et al. [2] introduce a KG that annotates and classifies existing I4.0 standards and norms to lower the entry barrier for I4.0. Overall, these contributions can help CPPSs development, but they do not tackle the specific challenge of constructing modular KGs in production systems applications.

Apart from using KGs to relate different layering models to each other, the semantic web community also put effort into **making KGs more modular**. This can, e.g., be accomplished by organizing ontologies based on their abstraction or by proposing proven design principles. For the former, Guarino [7] proposes to categorize ontologies hierarchically based on their generality. The higher an ontology is in this hierarchy, the higher its re-usability. For the latter, Gangemi et al. [6] proposes building blocks for ontology design. They argue that accessibility for experts and non-experts is key for re-usability, which can be achieved with simple and modular ontologies, in combination with tool support.

3 Layered CPPS Knowledge Graph Construction

As a foundation to organize industrial KG conceptualization and implementation, addressing challenge (C1) raised in the introduction, we focus on the **vertical *layer axis* in RAMI 4.0** [5]. This axis decomposes complex I4.0 manufacturing systems into loosely coupled layers, adopting principles from information systems and software engineering. In our proposed KG development and modularization approach, illustrated in Figure 1, layers have multiple roles:

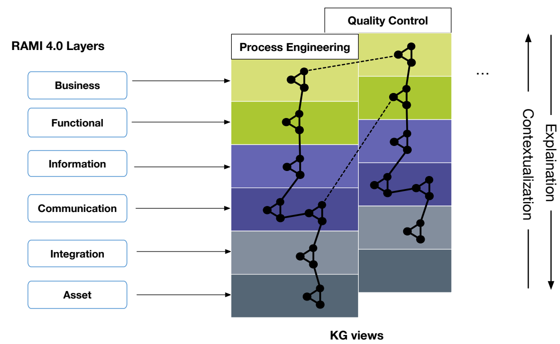

Fig. 1: Layered CPPS Knowledge Graph Approach

- In the **conceptualization phase**, they support the scoping of vocabularies and ontologies used to represent various aspects in the KG; Mapping concepts to layers facilitates a modularization of the KG that is consistent with the layering of the manufacturing system.

Example. As discussed before, the injection molding use case is composed of the steps: (i) setup of the injection process, (ii) production, and (iii) quality inspection. The layering allows to interface with the domain experts appropriately: the process engineer, e.g., acts at the communication and integration layers (typically represented by Supervisory Control and Data Acquisition (SCADA) and/or Programmable Logic Controller (PLC) systems).

- At **production run time**, the layers serve as a guideline to structure the interactions between components and stakeholders with the KG, based on the modularization principles of the framework.

Example. For instance, classifications made by automated visual quality inspection components are assigned to the integration layer and may be propagated from there through higher-level events to the upper layers. In this context, the KG is a digital twin of the real-world system that links relevant aspects for a given perspective. This allows to overcome challenge (C4) from the introduction.

- Methodologically, we propose a **modular and incremental** approach to develop KG-based applications in I4.0; rather than developing a single, monolithic KG, which requires a large up-front investment and bears considerable risk, our approach aims to incrementally build a CPPS-wide KG as an aggregation of more granular per-use case views, while ensuring their conceptual alignment through a set of shared core concepts. This also enables cross-view linking and navigation across multiple perspectives (dotted lines in Figure 1).

Example. In our use case we have discussed (i) setup of the injection process, as well as (iii) quality inspection. In Figure 1, we see the foreground view "Process Engineering" corresponding to (i) and "Quality Control" corresponding to (iii). This however, can be the results of an incremental construction.

– Critical to our approach are **contextualization** (C2) and **explanation** (C3), illustrated by the "upwards" and "downwards" arrows illustrated on the right side of Figure 1. The proposed modularized KG approach allows one to naturally addresses these challenges.

Example. A process engineer sets a number of initial parameters for the injection molding machine, e.g., injection speed. The number of parameters vary based on machine type (20+); choosing appropriate values requires substantial expert knowledge From the view of the process engineer, <u>contextualization</u> is of utmost importance - what effect these adjustments have on the overall outcome of production (presented at higher RAMI 4.0 levels). From the view of the factory manager (typically at the three top-most layers), <u>explaining</u> why the production outcome is how it is, e.g., based on parameter settings on the injection molding machines (presented at lower RAMI 4.0 levels) is key. A modularized KG approach is a natural fit for this.

Conclusions. In this paper, we introduce a KG modularization framework in the context of CPPSs and illustrate it in a real-world industrial use case. Our layered CPPS KG provides navigation across different abstraction hierarchies (i.e., bottom-up contextualization and top-down explanation) but also linking across multiple views. For future work, we plan to demonstrate the application of the framework to a wide set of use cases. Our goal is both to demonstrate the concrete impact of the KG platform across our manufacturing use cases, including our industrial partners in automotive injection molding, milling, aircraft manufacturing, and consumer appliance manufacturing.

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