

Rethinking Interoperable CPS as Interactive Behavior Designs

Christian Stary^a

^a Johannes Kepler University, Business Informatics-Communications Engineering, Altenbergerstraße 69, 4040 Linz, Austria

Abstract

This paper considers the design of interoperable CPS as socio-technical development task, as CPS represent evolving interactive systems. Pathways from level I to 6 are provided suggesting structuring the development of a design language for modeling and architecting interoperable CPS as Systems-of-Systems. The pathways address various levels of complexity of architectural designs as well as language requirements for stakeholder-centered behavior modeling.

Keywords 1

CPS, Interoperability Engineering, socio-technical system design, System-of-Systems, Complex Adaptive Systems, Interaction Science, behavior modeling

1. Introduction

Interoperability Engineering is increasingly getting a design task requiring interactive access to design representation in a stakeholder-centered way. According to Gartner's forecasts 2019, over the next several years, the workforce's ability to exploit business-relevant technologies such as Internet-of-Things (IoT) systems, will decide whether many organizations can build up or keep competitive advantage (cf. <https://www.gartner.com/smarterwithgartner/top-10-technologies-driving-the-digital-workplace>). Individual activities will be bound to digital actions creating an "Internet of Behavior" in public communities and business settings (<https://www.gartner.com/smarterwithgartner/gartner-top-strategic-predictions-for-2020-and-beyond/>). Consequently, Cyber-Physical Systems (CPS) will be affected by continuous interactive change, requiring the (dynamic) adjustment of their components ensuring interoperability.

Since such a pragmatic view on Interoperability Engineering is of prime concern for seamless CPS operation in volatile environments, behavior data direct activities of CPS in real time, and encourage or discourage a particular (human) behavior. For instance, shop floor or home management systems could adapt their features to the status of available sensor systems and the behavior of the currently present people. The understanding of the situation and specific needs of stakeholders grounds the design of CPS systems and handling their interoperability. Behavior specifications abstract from the origin of actors (machines, humans) and allow subsuming components to more complex systems.

Behavior specifications result in modeling CPS and the interplay of components as an immanent and pervasive task. Both, developers, and users adapting behavior dynamically require proper language and tool support for design. It is expected by 2023, that '40% of professional workers will orchestrate their business application experiences and capabilities like they do their music streaming services' (<https://www.gartner.com/smarterwithgartner/gartner-top-strategic-predictions-for-2020-and-beyond/>). It is not sufficient for organizations or communities of practice to work with static designs or monolithic applications. They need flexible schemes when technology or model adoption and task restructuring become part of their work (cf. [10]). Otherwise they will fail to arrange, customize, and exploit CPS technologies for interoperable service and production developments.

The paper develops pathways based on a refined system understanding to reflect the connectivity and dynamic modularity of CPS. Recognizing the interactive and socio-technical nature of evolvment,



the pathways differentiate architecture concerns from behavior representations, as the latter address tool requirements for modeling interoperable CPS.

2. Evolving CPS as Interactive Systems-of-Systems

CPS-architectures are traditionally run decentralized, being linked to communication and modular (e.g., agent-based) structures. Some parts need to co-operate through exchanging information and adapting to environmental changes, others deliver or process data on demand. Overall, CPS allow large-scale interconnected processes as reconfigurable networks of locally autonomous actors, including IoT-enabled sensory system [7]. Thereby, CPS link “cyber” (virtual, computational) and “physical” components. Their openness and socio-technical character stem from interconnecting physical, social, and virtual worlds.

CPS are heterogeneous systems, including distributed physical devices and computational components. As flexibility and re-configurability matter for operation due to changes in environment, the granularity of the system, the access to components, and the way information is exchanged are crucial design parameters. Any CPS architecture encompasses physical objects, sensors, actuators, computing devices, controllers and communication network(s) that are represented as digital twin in a model of the actual system. As such, it has to be capable to represent and support human-device interaction and device-to-device communication. According to Interaction Science, the ‘interaction is considered as the exchange of material or immaterial goods between acting parties (biological or technical entities) embodied in a certain context. Overtime, these interactions establish behavioral and cognitive schemas that transfer as patterns and expectations to further activities and in this way influence the acting stakeholders. Stakeholders are identified as the persons that are involved in system- and interaction-relevant processes, either operating, (re-)design, monitoring or controlling a system. As they interact in a certain environment, they create specific patterns in the system representing the environment.’ [1]

These system-wide patterns shape the behavior of each actor (humans, robots, applications, etc..) resulting in a Complex Adaptive Systems and thus, creating challenges of interoperability in systems (cf. [8] for production). A System-of-System perspective on these kind of ecologies helps coping with complexity, taking into account emergent behavior and transformations (cf. [2]). Thereby, components (sub systems) are linked in a way their internal structure can handle their interaction to form a unified whole (cf. [5]), albeit their often physical and functional heterogeneity. As System-of-System they are organized hierarchically, with each component contributing to an overarching system function. Allowing for autonomous behavior of each component constitutes a federated system architecture. In this way, CPS can evolve from autonomous sub systems towards a network of interacting components (cf. [9]). In the course of interoperability engineering the protocol of interacting with the network actors is decisive for dynamic alignment to contribute to a common objective of a CPS. It needs to be considered part of the CPS architecture and as design enabler.

3. Pathways to a Design and Architecture Language

Engineering interoperable CPS supported by a design and architecture language requires not only a specific system perspective, as already indicated in the previous section, but development paths that take into account CPS architecting and design as an interactive process. Although being intertwined, they need to meet different requirements due to the interactive and socio-technical nature of evolvement processes.

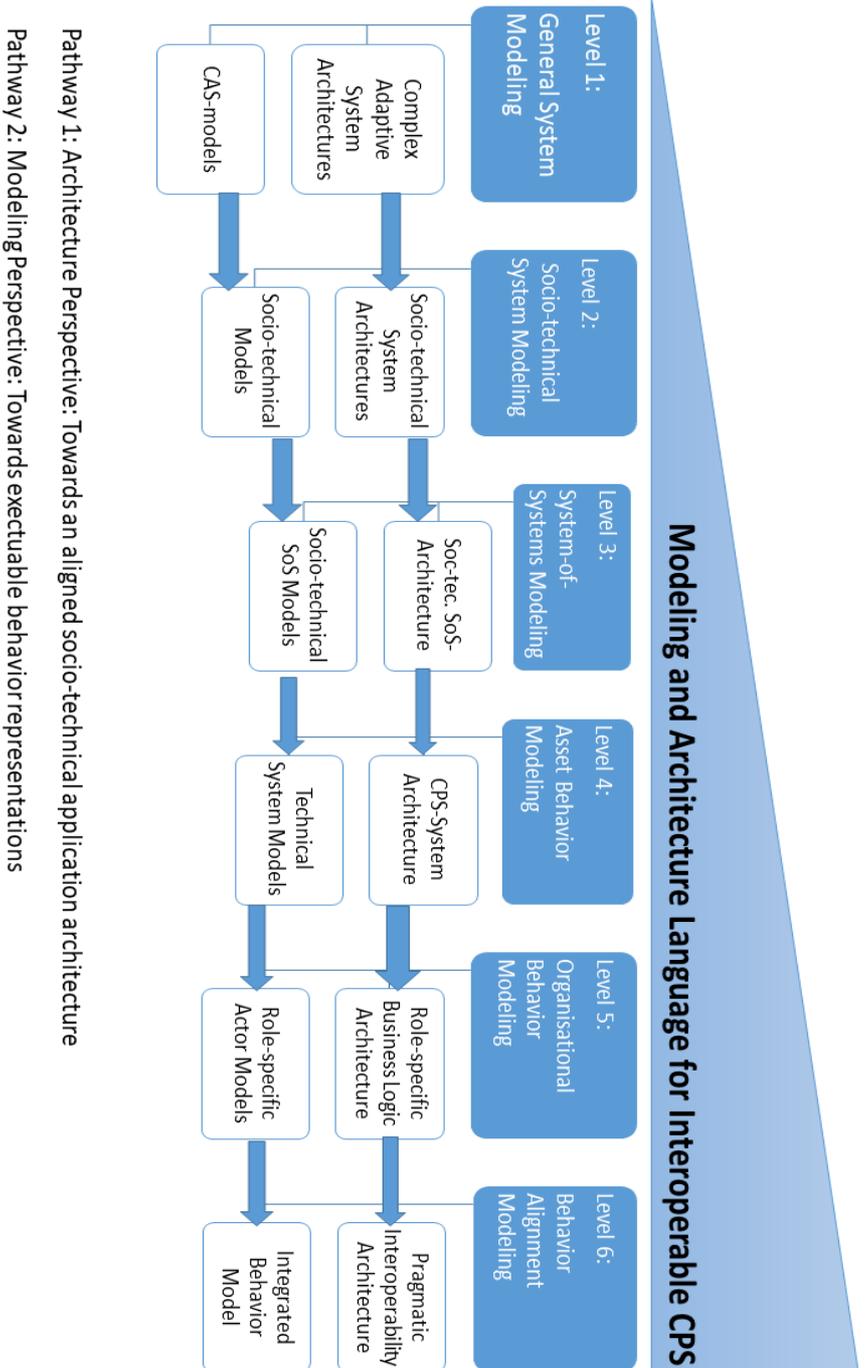


Figure 1: Pathways

Figure 1 details for each of the milestones (development level) the architecture and language perspective. The pathways towards an interoperability design and architecture language reflect how alignment of architecture modeling and the deployment of interoperable CPS can bring value taking into account a system perspective on modeling that accounts for the context of CPS operation. Each pathway enhances the design space for CPS technologies in a domain-independent way due to encapsulating actor behavior and standardized interaction. As such the migration from existing architectures and systems towards interoperable CPS can be facilitated.

Level 1 addresses the dynamic nature of a system when designing CPS. Stakeholders and CPS components constitute a Complex Adaptive System. In level 2, the 2 components establishing CPS as socio-technical system are in the focus of development. Level 3 captures the federated system aspect – sub systems can operate on their own while being part of a larger system. Level 4 tackles the technological CPS constituents and their behavior representation. On level 5 the business logic and thus, user and usage-relevant behavior is addressed. Level 6 explicitly refers to interoperability issues, namely in terms of aligning behavior designs of the sub systems of CPS, ensuring operational connectivity.

SoS development should lead to architectures allowing dynamic changes. Situation-sensitive behavior is a key issue in CPS engineering support. A situation is analyzed in terms of how the different complex adaptive system parts influence and relate to each other rather than decomposing it into parts that are studied in isolation. The resulting system behavior focuses on actors of different kinds, e.g., designers tackling interoperability issues on the model that needs to be propagated to operation. The designer can be the users of the CPS at hand. As such they play a dual role and need to work together on several levels even when following complex paths of behavior.

Designers need to be able to keeping the whole in mind when working on CPS designs [4]. Besides the CPS components designers need to set links and interconnections which influence the behavior. Subject-oriented design (cf. [3]) can help due to its simple interaction structure and behavior centeredness. It allows encapsulation of behavior and addressing actor behavior through data-driven message exchange. A language providing simple mechanisms for modeling enables stakeholders to be engaged more effectively into component alignment as they are relieved from transformation tasks.

In case behavior models are represented in a semantically precise language they can be executed for probing. Such a feature supports stakeholders testing pragmatic interoperability of CPS. In this way fundamental System-of-Systems factors (cf. [6]) are addressed: (i) *autonomy*, where components within the CPS can operate and function independently; (ii) *belonging* (integration), which implies that the constituent CPS components can integrate for System-of-Systems capabilities; (iii) *connectivity* between components and their environment; (iv) *diversity* addressing different perspectives and functions; and (v) *emergence* (foreseen or unexpected). As the latter addresses all types or levels of interoperability, it is key to CPS evolvement. Hence, an effective design language needs features for mapping emerging structures to an existing model and architecture, as well as alignment functions for interoperability engineering.

4. References

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