On Combining Domain Modeling and Organizational Modeling for Developing Adaptive Cyber-Physical Systems

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Abstract: Cyber-physical Systems (CPS) integrate physical and computational entities into coherent Systems of Systems. Since CPS are typically both socio-technical and embedded in a physical environment, these systems require adaptive properties, e.g. in order to respond to environmental changes. The integration of Multi-Agent Systems (MAS) in industrial and CPS is an active research topic. In this paper, we outline our work in progress on utilizing, combining and supplementing established modeling approaches, i.e. domain specific (reference) architecture models and organizational MAS models for the development of decentralized, adaptive CPS.

1 INTRODUCTION

Developing Cyber-physical Systems (CPS) requires interdisciplinary collaboration, where physical components and digital services are constructed, aligned and integrated into coherent Systems of Systems (SoS). Multi-paradigm modeling (Carreira et al., 2020) and Model-Driven Development approaches, e.g. (Uslar et al., 2019), have consequently been proposed to enable these efforts. Since these systems have to influence and respond to their physical environment, agent-oriented modeling and development approaches have been proposed as well (Leitao et al., 2016; Challenger and Vangheluwe, 2020).

A trend towards decentralized coordination and adaptation schemes can be observed. It is necessary to develop a *cyber-physical and human system* (CPHS) (Wasa et al., 2020), where human stakeholders are integral parts. When regulatory, operational or possessory circumstances prohibit direct control of system elements, incentive-based coordination schemes are often applied, e.g. market-based coordination as *Transactive Energy* approaches in the power grid (Abrishambaf et al., 2019; Huang et al., 2021). Also decentralized coordination mechanisms are investigated (Frey et al., 2015).

In this paper, we outline work in progress on combining agent-based and CPS-oriented development approaches, in order to facilitate the development of these next generation CPS. We intend a framework for documenting best practices and supporting principled development procedures. Domain models, e.g. (CEN-CENELEC-ETSI, 2014), facilitate a use case decomposition where each interoperability level is gradually concretized from the abstract conception to the implementation level. The proposed decomposition is straightforward for hierarchical, control-oriented structures, but it is challenging to devise decentralized interaction schemes, e.g. (Huang et al., 2021), and coaction in CPS (see Section 2). Successful designs require a coherent alignment of multidisciplinary system elements.

Here Multi-Agent Systems (MAS) come into play: MAS provide a rich set of concepts and tools for developing ensembes of autonomous possibly self-interested software entitites which adapt to their environment. A major design effort for CPS development is to bridge the micro-macro-link (Köhler et al., 2005; Sudeikat et al., 2012), i.e. enforce coherence of the system by adjusting microscopic activities and interactions on the basis of *organization-centered multi-agent systems* (OCMAS). Augmenting CPS-oriented designs with organizational structures facilitates designing and analyzing applications. Thus, we identify possible extensions and supplements for integrating organization-centred approaches on MAS (Dignum, 2009) with current approaches for designing CPS.

This paper is structured as follows. In the next section, we outline related work. In Section 3, the integration of OCMAS with reference architectures is discussed. We identify research challenges in Section 4, before we conclude Section 5.

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2 RELATED WORK

The construction of CPS requires interdisciplinary development teams that combine modeling and engineering approaches from different disciplines. Thus multi-paradigm modeling (Carreira et al., 2020) is applied for the development of these systems. In this context, the integration of agent-based modeling and engineering techniques with model based development approaches has been proposed in (Challenger and Vangheluwe, 2020). While the development approach proposed here details the proposed integration, it is agnostic towards specific implementation approaches.

Based on multi-paradigm modeling (Carreira et al., 2020), the interdisciplinary nature of the development of CPS leads to a mulit-paradigm development efforts where different implementation approaches have to be integrated. A combining meta-model has been proposed to facilitate integrating software agents, actors and organizational models in a coherent application (Cossentino et al., 2019). Building on these efforts, we aim at coherent modeling and development procedures that facilitate coherent application designs in the context of CPS.

The integration of Agent Oriented Software Engineering (AOSE) in industrial applications poses several conceptial challenges. For example, the applicability of AOSE-Methodologies has been examined (Cruz and Vogel-Heuser, 2017). There remains a conceptual gap between the engineering of automation systems and their seamless integration in MAS-based system architectures and development procedures. We address this by combining established modeling approaches, but seamless integration remains a conceptual challenge.

We surveyed the utilization of SGAM in the development of smart grid applications. Prominent examples comprise model-driven application development (Uslar et al., 2019), the preparation of co-simulations (Barbierato et al., 2020) as well as the analysis of security aspects (Henze et al., 2020). Also the description of self-organizing properties and non-functional requirements (Lehnhoff et al., 2014) has been proposed. The integration of software agents in these designs found limited applications yet. Examples are (Babar and Nguyen, 2018; Dethlefs et al., 2014). Specific extensions, e.g. (Szekeres and Snekkenes, 2020) have been proposed to provide a more comprehensive models of CPS. In the remainder of this work we focus on the established SGAM model as is is most widely excepted. We do not alter the model itself but provide an optional extension which prepares agent-oriented development practices.

3 INTEGRATING SGAM AND OCMAS

Here, we advocate for integrating the SGAM-approach with an organization-centred approach on multi-agent systems (OCMAS) (Dignum, 2009) in order to support the design of adaptive collectives. Therefore, our models contain *micro* elements (agents, goal directed behavior, learning etc.) as well as *macro* elements (roles, positions etc.) (Köhler-Bußmeier and Wester-Ebbinghaus, 2013).

3.1 Architecture Models of Cyber-Physical Domains

CPS development usually addresses systems in a complex application domain with established domain elements i.a. technical / organizational entities and communication protocols. The influencial *Smart Grid Architecture Model* (SGAM) provides a reference architecture for the Smart Grid domain. This approach has also been adopted for other domains, e.g. for maritime logistics & Industry 4.0, where corresponding architecture models have been developed (Gottschalk et al., 2017). These models provide a conceptual framework where the system context as is and the system-to-be can be expressed.

Following the SGAM-approach (see Figure 1, left), *Domains* are used to categorize the topology of the physical space. E.g. for the Smart Grid, Domains describe the power generation value chain (i. a. generation, transmission levels, consumption). *Zones* describe the automation levels for enabling remote controlling of physical entities. These range from low-level abstractions (*Field*- and *Process*-zones) up to *Enterprises* and/or *Markets*. On top of this plane, *interoperability* levels allow to describe controlling software systems. These levels range from physical elements populating the *Component* layer to the overall *Business* objectives. The accessing of low-level elements is described in the *Communication* layer. The *Information* layer describes the semantic information that are exchanged with elements in the *Function* layer. On top the *Business* layer defines the enterprise and/or market interactions that influences and motivates the manipulation of the physical entities in the first place. Applications of this modeling approach include, among others, the location of patterns of industrial agents (Salazar et al., 2019).

A corresponding methodology guides the elaboration of Use Cases for applications in this domain (CEN-CENELEC-ETSI, 2014), where each interoperability level is gradually concretized from the abstract conception to the implementation level.

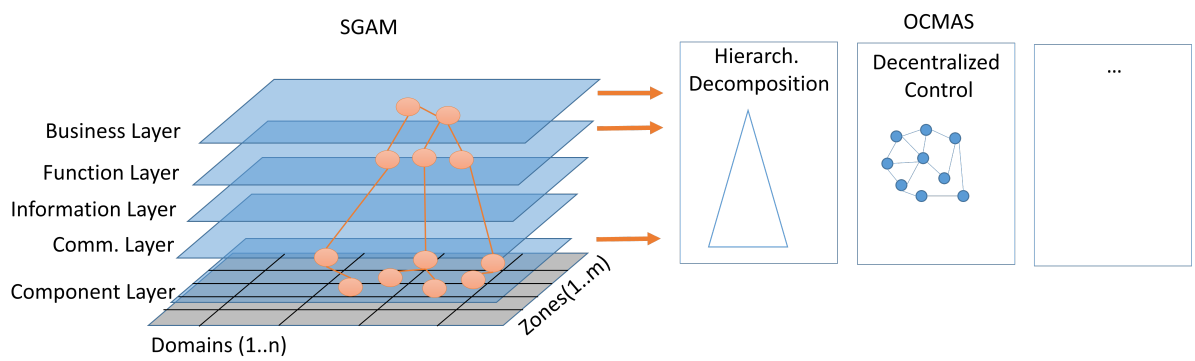

Figure 1: Left: Generalized view on Architecture Models (adapted from e.g. (CEN-CENELEC-ETSI, 2014)). An organization contains elements on the Business, Function and Component Layers. Right: Besides hierarchical decomposition, we aim to support decentralized organizational structures in CPS.

3.2 Organization-Centered Multi-Agent Systems

From a conceptual viewpoint, MAS have a bottom-up tendency; organization centered MAS (OCMAS) complement this with a more top-down view introducing concepts like positions, norms, roles etc. Therefore, OCMAS are a good candidate to capture central architectural aspects used to specify the overall behavior of a system at-large.

Concerning the design of adaptive CPS, we consider three dimensions (see Figure 2): the *administrative* dimension (i.e. the spectrum from systems ruled by one central authority vs autonomous systems), the *architectural* dimension (i.e. monolithic architectures vs peer-to-peer systems), and the degree of *self-organization* capabilities (i.e. ranging from feedback loops over emergent self-forming to autopoetic self-building systems). Of course, there are well established means describing each dimension in isolation: e.g. choreography of autonomous workflows, e.g. cloud systems for distributed architectures, and e.g. agent based simulation for self-organization. However, we see an increased demand for an integrated approach, which has to take care of the interplay of the three dimensions, to support the various tasks of engineering CPS.

3.3 Combining Perspective: Layered Desing of Adaptive CPS

An outline of the elements of a decentralized, adaptive cyber-physical system, based on the generic, 6-layered desing approach for adaptive CPS from (Musil et al., 2017), is given in Figure 3. We adopted this layered system structure particularly to distinguish between and locate purely reactive as well as deliberative control elements, e.g. (Cossentino et al.,

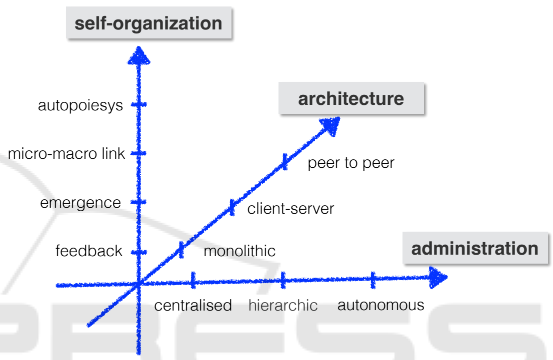

Figure 2: Model Dimensions in OCMAS.

2019) and to indicate high-level coordination mechanisms, e.g. markets (Wasa et al., 2020).

The utilization of physical components is to be orchestrated (*Physical Layer*). These units provide functions and services on a purely reactive fashion, based on the local programming, i.e. using PLCs or IECs. The adoption of recent M2M-protocols, e.g. OPC UA (Schleipen, 2020), allows augmenting these units with information and service models. Typically these elements are controlled via computational elements on site (*Proxy Layer*). These elements are interconnected (*Communication Layer*). *Services* are building blocks for distributed applications (*Application Layer*). The top-most layer describes the socio-technical integration of applications e.g. in markets or social networks. A fully fledged CPS will require a comprehensive integration of third-party services and socio-technical elements. For example, a comprehensive mobility solution that provides a.o. parking services and provides additional, supplemental means for the onward journey to users may require weather forecasts, billing services, and a platform for communication with the human users. The computational elements may range from traditional service providers to actors (Hewitt, 2015) and reactive/deliberative agents. In fact it is a design effort to decide for the appropriate implementation approach.

This framework can be directly mapped to the interoperability layers of SGAM-based reference architectures. The Proxy layer is implicitly present in the SGAM-based Component layer. The Applicattion and Service layers can be expressed in SGAM by the interplay of Busniess and Function layers. While the Socio-technial aspects are typically extended as a top-most zone (e.g. Markets), related extensions to the SGAM model have been proposed as well (Szekeres and Snekkenes, 2020).

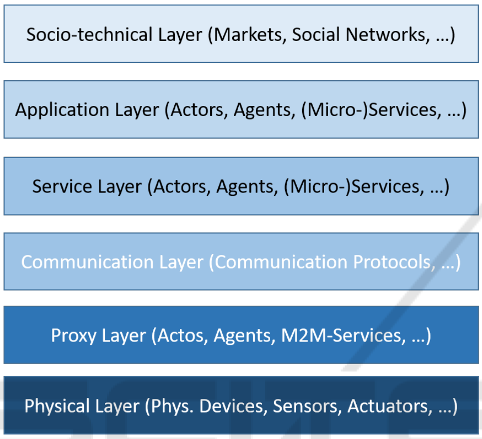

Figure 3: Conceptual Model of a decentralized adaptive system, adapted and adjusted from (Musil et al., 2017).

3.4 Integration

Architecture models, like SGAM, provide valuable information about the context of a CPS. The layers of Figure 3 can naturally be modeled by SGAM-compliant models (see Section 3.3). However these layers possibly contain agent societies which prescribe collective decision making, e.g. when a market zone comprises localized markets (Wasa et al., 2020; Mahesh et al., 2019) or system elements are arranged in holarchies (Frey et al., 2015).

Organizational models can supplement the SGAM-based description of a use case with an agent organization which allows to realize the intended system behavior. Abstracting from the behaviors of individual agents, the interplay of agents is modeled explicitly. When an application is extended reasoning about the existing, possibly implicit, organization and how to supplement it is an additional modeling concern.

The use case methodology (Gottschalk et al., 2017) prescribes an abstract, 4-step process, where every layer in the SGAM-model is gradually refined till the implementation is prespecified. Correspondingly, agent societies in the SGAM Layers can be prescribed as well (see Figure 4). The resulting organizational model is a crosscutting concern, because individual agents can be located within a single layer (e.g. see (Salazar et al., 2019)). It will comprise deliberative and reactive participants on multiple layers which collaborate for realizing system requirements.

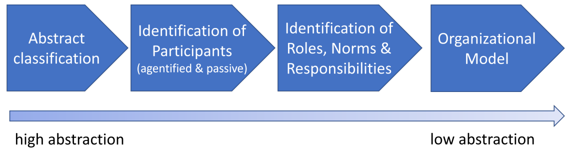

Figure 4: Organization development for SGAM models.

It is to note that a system design is based on a number of Use Cases. For each Use Case, the corresponding, appropriate organizational sub-model or organizational supplement has to be identified. This analysis has to consider the organizational structures that are already present and the implications of the related Use Cases.

The described combination of models also fit in generic development methodologies for CPS. E.g. in (Leitao et al., 2016), based on (Farid and Ribeiro, 2015), CPS development is approached by detailing high-level design principles to MAS which are then to be integrated in other hardware and software systems. Architecture reference architectures and system specific architectures serve as intermediate design artifacts in in this development approach. High-level design principles, e.g. bionic, self-organizing, market-based, can be expressed as organizational alternatives in CPS development and thus supplement the refinement of CPS designs.

We particularly aim at describing decentralized coordination approaches (Sudeikat et al., 2012). The inclusion of organizational models in CPS-modeling should allow for the following usages.

3.4.1 Descriptive Use

Documenting inter-agent patterns and best practices. E.g. in (Salazar et al., 2019) typical types of agents in industrial settings have been identified and documented and their interplay has been shown using an SGAM-based reference architecture. Also in (Musil et al., 2017) pattern for the construction of adaptive CPS have been indentified. The need for expressing the interplay of agents has led to a multi-layered descriptions, e.g. see (Musil et al., 2017). While the identification and documentation of Use Cases are specific to the individual system under development, archtetype organizational models can serve as domain independent patterns to be adjusted. In prior works, we have approached this for self-orgnaizing systems (Sudeikat and Renz, 2010) and also markets designs can be understood as patterns for inter-agent coordination (Xu et al., 2019).

3.4.2 Static Analysis

After an SGAM-based use case is augmented with an organizational model of the resulting system, the resulting architecture can be evaluated. While SGAM-based use cases describe the operation of system elements, a corresponding organizational model relates these elements to each other and their physical counterparts. A graph-based analysis of the interacting elements, e.g. analogous to (Razo-Zapata, 2017; Menci et al., 2020) allows to infer critical communication links and allows reasoning for resilience and robustness of the intended system. Based on specific performance indicators the recommendations of specific organizations can be derived.

3.4.3 Simulation-based Analysis

Simulation-based examinations of applications designs are particularly facilitated by OCMAS-models. Since these abstract from agent details, agent-based models of the organization can be derived. During iterative development, SGAM-based domain models allow to reason about the possible adjustments of physical and computational elements that form the context of the CPS. Use Cases and the suppelementing domain information prescribe the context of the CPS. The component layer describes the physical elements, i.e. the devices (sensors / actuators) as well as the computational resources which can be used to host applications. This includes the properties of physical elements and deployment constraints. This simulation-based analysis is exemplified in (zum Felde et al., 2021), where relevant domain artifacts are identified and an adaptive, distributed application design is examined and iterated using agent-based modeling. Based on a SGAM-based model of a drone-based logistics system, an iterative analysis allows to explore how architectural decisions affect the performance of the application-to-be.

3.4.4 Self-adaptive Systems

Explicit models for MAS organizations can be made subjects for adaptations. The organizations model can serve as a system element itself, which can be explicitly adjusted in order to adapt the system. Thus a future use is to enable self-adaptations by adjusting they organizational structure at run-time. This may range from creation of additional groups / teams at run-time to switching between organizational modes.

4 CHALLENGES

In order to support principled development procedures, e.g. extending current requirements analysis procedures, we see the following research challenges:

- Integration of the SGAM-based modeling and the corresponding use case methodology with follow-up development procedures. After a set of use cases have been derived, their implementations will split up the development / extension of the involved physical elements, service providers and agents. For each of these system elements modeling and development processes are available. Thus the integration and alignment of these developments has to be structured. We propose organizational models as an integrative, cross-cutting view for this purpose.
- Deriving objective criteria for deciding between application designs (hierarchical, decentralized or hybrid) and high-level design principles (e.g. bionic, self-organizing, holonic) (Leitao et al., 2016)). A mapping of architectural and organization patterns to qualitative criteria facilitates their selection in development projects. This requires a coherent view on the system context, requirements, and additional constraints. A starting point could be extended use case definitions for describing the intended macroscopic system dynamics and constraints.
- A conceptual model for describing and integrating decentralized application designs in CPS. Based on models for agent-based software development, organizational structures, actors, physical elements (see Section 3), decentralized coordination processes (Sudeikat et al., 2012) can be described and serve as patterns for application development.
- (Semi-) automated generation of simulations and testbeds for decentralized CPS, since simulations require integrating both physical elements (Carreira et al., 2020) and decentralized coordination processes (Sudeikat et al., 2012). The selection of different coordination processes requires simulation based analysises, possibly supported by model-driven techniques (e.g. see (Uslar et al., 2019)).

5 CONCLUSIONS

In this position paper, we outline work in progress on integrating and supplementing CPS-development with organizational models of MAS. We argued that organizational models, as used in MAS development, facilitate the design of *coherent* ensembles of systems. These systems originate from multi-paradigm modeling, thus a consistent view on their logical interactions and integration is beneficial. Besides the identification of the benefits of utilizing organizational modeling in CPS development, the integration in current development practices, the main usages and resulting challenges are outlined.

While the outlined lightweight, simulation-based analysis approach is used to teach the development of adaptive CPS, the indicated supplements and challenges are prospects for future work and collaboration. Future work comprises the development of guidelines and tooling for description of *collaboration patterns* in CPS, the *static analysis* of SGAM-based use cases and the utilization of OCMAS-models as first class elements for *adapting CPS at run-time*. Here we focus on SGAM-based models which address Smart Grids. Since comparable models have been derived for other domains as well, a transferability of our approach can be expected but remains to be examined in future works.

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