Self-Adaptive Regulation Mechanisms for a Trustworthy and Sustainable Industry of the Future

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Abstract. The increasing distribution of autonomous agents incorporating Artificial Intelligence technologies to operate (e.g., perceive, decide, interact, and act) in dynamic shared environments raises the challenge of ensuring their governance without limiting their autonomy. In multi-agent systems (MAS), regulation concepts and mechanisms, such as rules, norms, and sanctions, are usually integrated into what are called normative MAS to support balancing the agents' autonomy with the system's objectives. In our research, we explore the integration of regulation management mechanisms into MAS, emphasizing regulation adaptation mechanisms to enable the system to adapt to evolving contextual conditions at execution time. Regulation adaptation is an underexplored capability in MAS. We define a conceptual model and design the corresponding representations and management mechanisms that enable adaptation in regulated MAS. Regulation adaptation is useful in various domains, such as manufacturing systems, where adaptation can support their resilience, trustworthiness, and sustainability.

1 Introduction

Advances in Artificial Intelligence (AI) have enabled systems to become more decentralized, autonomous, and capable of interacting in dynamic environments. In socio-technical systems [1] like the Industry of the Future [25], cyber-physical systems (e.g., robots) and human stakeholders make autonomous decisions to achieve their individual goals, at best imperfectly aligned, which may lead to challenges in the achievement of the overall objectives of the system.

Multi-Agent Systems (MAS) offer the conceptual and practical foundations to govern these systems [24]. MAS are composed of autonomous agents that interact with each other in a shared environment. Inspired by human societies where *regulations* (e.g., laws, norms, sanctions) shape the expected behaviors of individuals, Normative MAS reifies these concepts, enabling governance of these systems. However, one of the main challenges in such artificial systems consists of integrating regulations in MAS to govern agents, while balancing their autonomy with the objectives of the system. Regulations can be regimented, limiting agents' autonomy, or enforced steering agents toward the expected behaviors.

In dynamic systems, particularly in the Industry of the Future, explicit representations of regulations are useful to support transparency and trustworthiness, both among agents and for human stakeholders who need to inspect or intervene in the decisions of the system. Moreover, the adaptability of regulations at execution time may support resilience in the face of changing execution environments or effective responses due to endogenous (e.g., product specification, failures) and exogenous (e.g., customer demands, sustainable requirements) changes. By enabling adaptation in regulation management, manufacturing MAS can fulfill the resilience, trustworthiness, and sustainability characteristics required for the Industry of the Future.

The objective of the thesis is to define a conceptual model and design the corresponding representations and management mechanisms that enable adaptation in regulated MAS. The research is structured in two primary research questions: **RQ1.** *What are the core elements for representing and managing regulations in MAS?* **RQ2.** *What are the core elements for enabling agents to adapt regulations in MAS?* Building on these questions, the thesis further explores the trustworthiness property and validates the proposed model in manufacturing systems, in the context of the Industry of the Future. This leads to the following secondary research questions: **RQ3.** *How to support trustworthiness in self-adaptive regulated MAS?* **RQ4.** *How to integrate self-adaptive regulated MAS to support sustainable manufacturing systems for the Industry of the Future?*

This paper is structured as follows. Section 2 presents the core elements of regulation management in MAS (Address **RQ1**). Section 3 details the core elements of regulation adaptation, and in Section 4 discusses the architectural design choices for enabling regulation adaptation (Address **RQ2**). Finally, Section 5 concludes and outlines the future works addressing **RQ2**, **RQ3**, and **RQ4**.

2 Regulation Management

To provide the basis for the next two sections, we present here the core elements for regulation management, i.e., regulation representations and capabilities.

Most works in the literature consider the representation of regulations in terms of constitutive and regulative norms [17, 13]. Constitutive norms specify how brute facts (e.g., a piece of paper) count as institutional facts (e.g., money) that are used as a shared "social reality" [22] to shape the behavior of individuals. Regulative norms prescribe obligations, permissions, or prohibitions on them based on institutional facts to regulate the behavior of agents [19]. There are, however, other regulations less explored in the literature, like sanction rules. Sanction rules are the means to enforce the behaviors

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prescribed by the regulative norms. They are vaguely defined and have diverse representations in the literature (e.g., [6, 7, 11]). In [31], we have defined sanction rules as specifying the consequence to the compliance or violation of regulative norms under certain conditions.

To complement these representations with the corresponding mechanisms for their management, we identify the following regulation capabilities as the abstract mechanisms to manage regulations. The capabilities are (i) *regiment*, which prevents agents from violating the regulations specified in the regulation specifications, (ii) *enforce*, which guides agents' behaviors towards the expected behaviors specified in the regulation specifications, and (iii) *adapt*, which enables the adaptation of the regulations that are regimented or enforced to cope with changing situations.

3 Regulation Adaptation

Once defined the abstract conceptual model for regulation management, we now detail the *adapt* capability, which is the capability of interest and sparsely explored in the literature (e.g., [5, 9, 12, 14, 18]). In [26], we have proposed a domain-independent and platform-independent regulation adaptation model that enables flexibility in the process of regulation adaptation. We propose to decompose the adapt capability into three sub-capabilities: (i) *detect* the potential regulations to be adapted, (ii) *design* the new, modified, suppressed regulations to adapt the detected ones, and (iii) *execute* the adaptation by applying the change in the regulation representation.

The proposed approach to regulation adaptation relies on reusing the same regulation concepts to govern the adaptation process itself. Constitutive norms define which state counts as an adaptation state, captured by a specific set of institutional facts called *adaptation facts*. An adaptation fact can be *detect-fact*, *design-fact*, or *execute-fact*, corresponding to situations that trigger the respective detect, design, or execute sub-capability. Regulative norms then specify obligations to achieve corresponding *adaptation goals*, i.e., *detect-goal*, *design-goal*, or *execute-goal*, aiming to guide the sub-capabilities in fulfilling the adaptation process.

4 Regulation Adaptation Architecture

Regulation architectures in MAS can be designed in different ways. We proposed a unified view combining the Multi-Agent Oriented Programming (MAOP) dimensions with the Architectural perspectives to identify the design options [30]. The MAOP dimensions perspective structures the regulation management through abstractions and mechanisms along the multi-agent oriented dimensions [4, 10]: (i) the Organization dimension, which concerns the social structure (e.g., roles, groups) in the Organization Oriented Programming [20], originating the *organization-centric* view; (ii) the Agent dimension, which concerns the mental state and deliberation of agents (e.g., beliefs, goals, plans) in the Agent Oriented Programming [23], originating the *agent-centric* view; (iii) the Environment dimension, which concerns the shared space (e.g., properties, operations) in the Environment Oriented Programming [21], originating the *environment-centric* view; and (iv) the Interaction dimension, which concerns the direct and indirect interactions (e.g., messages, speech acts) in the Interaction Oriented Programming [16], originating the *interaction-centric* view. When abstractions from multiple MAOP dimensions are used, it originates the *hybrid-centric* view. The other perspective is the Architectural, concerning how regulation management is distributed in MAS components, ranging from *fully-centralized* to *fully-decentralized*, with *semi-(de)centralized* designs.

Complementing what was done for regulation management, in [27], we have discussed how regulation adaptation can be arranged in MAS components. In an organization-centric view, regulations and adapt sub-capabilities can be centralized in a single component or distributed across multiple components. Similarly, in the agent-centric view, regulations and the adapt sub-capabilities can be centralized in a single agent or distributed among several agents. The environment- and interaction-centric views can complement regulation adaptation, e.g., using automated non-autonomous resources as environment abstractions or using dedicated interaction protocols as interaction abstractions. Finally, a hybrid-centric view allows regulation adaptation to combine abstractions from multiple MAOP dimensions, distributing representation and adapt sub-capabilities across them.

5 Conclusions and Future Work

The research conducted in the context of the Ph.D. investigates the integration of regulation management in MAS, with a focus on regulation adaptation. We addressed **RQ1** by identifying the core building blocks of regulation management, addressing representations and capabilities. We then explored the adapt capability, as per **RQ2**, defining the regulation adaptation sub-capabilities and the necessary representations to support the regulation adaptation process. We discussed architecture solutions for regulation adaptation, considering the structure in the MAOP dimensions and the distribution of regulation management components. The future work to completely answer the research questions is briefly discussed here.

Adaptation of the Regulation System Architecture Building on the identified regulation architectures, an interesting direction of **RQ2** is the adaptation of the regulation system architecture, e.g., shifting from organization-centric to agent-centric regulation or from fully-centralized to fully-decentralized regulation to manage the capabilities. This is motivated by the different benefits of each architecture. Agents enable localized regulation management, while organizations provide global regulation management, and centralized regulation ensures consistency, whereas decentralized regulation supports faster responses. The adaptation of regulation architecture, therefore, enables additional flexibility, allowing the system to apply the most suitable architecture to the current situation.

Prototype Implementation As part of **RQ2**, we plan to extend and integrate the Normative Programming Language (NPL) [15, 31] and Situated Artificial Institutions (SAI) [8] for enabling adaptation of constitutive norms, regulative norms, and sanction rules. NPL(s) and SAI can then be integrated into the JaCaMo [3] MAS framework to validate the conceptual regulation adaptation model and experiment in adapting regulation and architecture.

Explainability in Regulation Management The explicit representation of regulations and the agent-centric perspective on managing and adapting regulations open paths to explore the explainability, which is one dimension to support trustworthiness as per **RQ3**. Agents can justify and explain regulation management and adaptation decisions for other agents (e.g., inter-agent explainability [2]) and humans (possibly with different roles [28, 29]).

Regulating Manufacturing Systems To address **RQ4**, we aim (i) to explore the opportunities and challenges of integrating regulation management in manufacturing systems (conceptual perspective); and (ii) to validate the prototype from **RQ2** and the extension with **RQ3** with manufacturing case studies to support sustainability in the Industry of the Future.

Acknowledgements

This study is partially funded by the ANR-FAPESP NAIMAN project (ANR-22-CE23-0018-01, FAPESP 2022/03454-1). The author thanks her supervisors, Olivier Boissier, Luis G. Nardin, and Jaime S. Sichman, for their continuous guidance and support.

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