A Unified View on Regulation Management in Multi-Agent Systems

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Abstract. Regulating multi-agent system (MAS) to achieve a balance between the autonomy of agents and the control of the system is still a challenge. Regulation management in MAS has been conceptualized from various perspectives in the literature, whose intersections open up a wide range of design options. We propose a unified view on regulation management in MAS that identifies the range of design options with respect to three perspectives: the regulation capabilities, the multi-agent oriented programming dimensions, and the architectural style. We use our unified view to review and classify existing MAS frameworks in the literature, highlighting the dominant and underexplored views on regulation management in MAS.

Keywords: Regulation Management · Multi-Agent Systems · Multi-Agent Oriented Programming · Agent Architecture.

1 Introduction

For more than forty years, various approaches to the development of systems have been proposed in the field of multi-agent system (MAS). However, it is still a challenge to design systems that balance the autonomy of agents and the control of the system, which can be achieved by regulating MAS.

In this work, *regulation management* denotes the capabilities (e.g., regiment, enforce, adapt) and the representations (e.g., norms, policies, sanctions) used to regulate MAS. Regulation management has been conceptualized from various perspectives in the MAS literature. Regulations can be managed *top-down* (i.e., external to the agents) as part of an organization, e.g., functioning as *collective* mechanisms for guiding a group of agents toward expected behavior, and *bottom-up* (i.e., internal to the agents) as part of the agent's architecture, e.g., functioning as *individual* mechanisms for influencing the agent's behavior [3]. Regulation management can also be designed to adopt a *centralized* or *decentralized* architecture, and to impose rigid constraints that limit the autonomy of

agents (i.e., *regimented*) or soft constraints that nudge agents toward expected behavior (i.e., *enforced*) [19,22,25].

This diversity of perspectives on regulation management in MAS makes it challenging to grasp the range of design options available and identify the most suitable to effectively regulate MAS in line with the system's requirements. Even if researchers focusing on normative multi-agent system [4] have proposed a set of concepts, theories, models, architectures, and frameworks to regulate agents' behavior, to our knowledge, there is no unified view on the design options to manage regulations. Here, we fill this gap by proposing a unified view on regulation management in MAS based on three different perspectives and discussing the possible design options combining these perspectives to regulate MAS.

The remainder of the paper is structured as follows. Section 2 introduces the conceptual foundations of the three perspectives used to create our proposed unified view on regulation management in MAS: regulation capabilities, multi-agent oriented programming (MAOP) dimensions, and architectural styles. Section 3 presents the views on regulation management related to the MAOP dimensions perspective (Section 3.1) and the architectural perspective (Section 3.2), and details our unified view of regulation management in MAS (Section 3.3). Section 4 presents an analysis of various regulation management frameworks using our unified view, highlighting the dominant and underexplored views on regulation management in MAS. Finally, Section 5 concludes and presents future research directions.

2   Perspectives on Regulation Management

In this section, we introduce the three perspectives we chose to categorize the design options of regulation management in MAS (see Fig. 1): (i) the *Regulation Capabilities* (CAP) perspective refers to the functionalities, procedures, and mechanisms of the regulation management; (ii) the *MAOP Dimensions* (DIM) perspective conceptually structures regulation management using the abstractions in the Organization, Agent, Environment, and Interaction dimensions proposed in the MAOP paradigm; and (iii) the *Architectural* (ARC) perspective refers to the distribution of the components of the regulation management system.

Regulation Capabilities Perspective. This perspective identifies the functionalities, procedures, and mechanisms that an entity (e.g., organization or agent) or a component of an entity has to manage regulations in the MAS. The *create* capability enables entities to produce their representation and procedures to control their behaviors. Once regulations have been created, they can be regimented or enforced. The *regiment* capability prevents agents from violating their regulation, while the *enforce* capability involves monitoring agents' behavior, deliberating about the regulated agents' behavior, and applying sanctions. The *adapt* capability enables entities to adjust the regulations to cope with the dynamics of the system and contextual changes.
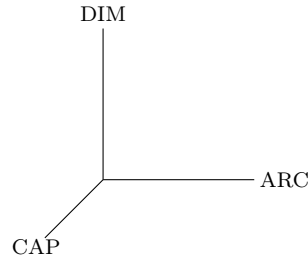
Fig. 1: An overview of the three perspectives on regulation management: (i) the *Regulation Capabilities* (CAP) perspective, (ii) the *MAOP Dimensions* (DIM) perspective, and (iii) the *Architectural* (ARC) perspective.

The agents' deliberation to comply with or violate regulations is not a capability in the context of regulation management since, by definition, agents are autonomous entities whose deliberations may be influenced but not controlled by regulation management systems. Mechanisms that constrain agents' decisions and make them obedient to regulations are also not a capability in the context of regulation management, as they are the agents' strategy and reflect their autonomy.

In this work, we are interested in the regiment, enforce, and adapt capabilities, because they are used at runtime and their execution depends on the conceptual and operational structure of regulation management. The create capability is not in the scope of this paper; we assume that the regulation representations are defined by the system designer.

MAOP Dimensions Perspective. The MAOP paradigm [5] integrates four main MAS dimensions for the purpose of separation of concerns [16]:

– The *Organization* dimension [38] refers to a social structure composed of groups of agents that are coordinated to achieve organizational goals. This dimension includes abstractions and mechanisms to structure and manage roles and responsibilities to coordinate agents' activities.
– The *Agent* dimension [42] refers to autonomous agents that perceive and act in the environment. This dimension includes abstractions and mechanisms to describe the mental state and the deliberation of agents.
– The *Environment* dimension [39] refers to the shared space and surrounding conditions to enable agents to interact among themselves and act on and access environment resources. This dimension includes abstractions and mechanisms for defining and managing shared space and environment resources made available to agents.
– The *Interaction* dimension [23] refers to the interconnection of the Agent, Environment, and Organization dimensions. It includes abstractions and mechanisms to describe and manage the direct and indirect interactions between components in each dimension.

The MAOP Dimensions perspective is a way of structuring regulation management based on the MAS abstractions proposed by the MAOP paradigm, originating the *organization-centric*, *agent-centric*, *environment-centric*, and *interaction-centric* regulation management views.

Architectural Perspective. The architectural style perspective refers to the distribution of components of the regulation management system, ranging from *centralized* to *decentralized*. In a centralized regulation management system, the capabilities and representations are performed each by a single component. In a decentralized regulation management system, the capabilities and representations are distributed among multiple components. Semi-(de)centralized regulation management systems are also possible, in which some capabilities or representations are centralized while others are decentralized.

3   Views on Regulation Management

In this section, we describe how regulations can be managed with respect to the perspectives presented in Section 2. First, we describe the multi-agent oriented views on regulation management based on the MAOP Dimensions perspective (Section 3.1). Second, we describe the architectural views on regulation management based on the Architectural perspective (Section 3.2). Finally, we present and discuss the possible design options combining the three perspectives as a unified view of regulation management (Section 3.3).

3.1   Multi-Agent Oriented Views on Regulation Management

Regulation management has been studied in various scientific communities with different emphases. The COIN[3] community has traditionally adopted a top-down approach, emphasizing regulation management at the macro level through abstractions and dedicated mechanisms to steer agents toward global objectives. In contrast, the SASO[4] and the Social Simulation[5] communities have explored regulation management from a bottom-up approach, using abstractions and dedicated mechanisms to regulate agents from the micro level.

Despite the different emphases, these approaches can be mapped to the MAOP dimensions, which separate the concerns in MAS, to originate the *organization-centric*, the *agent-centric*, the *environment-centric*, and the *interaction-centric* views. The separation of concerns enables a clear identification of how the components of the regulation management are mapped to (i) organization abstractions related to representations and management of social structures of agents (i.e., Organization dimension), (ii) agent abstractions related to internal representations and management within individual autonomous agents (i.e.,

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[3] COIN(E) Workshop (`https://www2.pcs.usp.br/~coin`).

[4] SASO Conference (`http://www.saso-conference.org`) recently renamed ACSOS Conference (`https://acsos.github.io`).

[5] ESSA (`http://www.essa.eu.org`) and JASSS (`https://www.jasss.org`).

Legend

Organization | Deliberation Engine | Regulation Representation | → Regulation Data

Agent | Mental State Representation | Regulation Management Capabilities | – –> Regulation Control

Environment | → Mental State Data

(a) An organization-centric regulation management where the regulation representations and regulation management capabilities are handled with abstractions and mechanisms of the Organization dimension.

(b) An agent-centric regulation management where the regulation representations and regulation management capabilities are handled with abstractions and mechanisms of the Agent dimension.
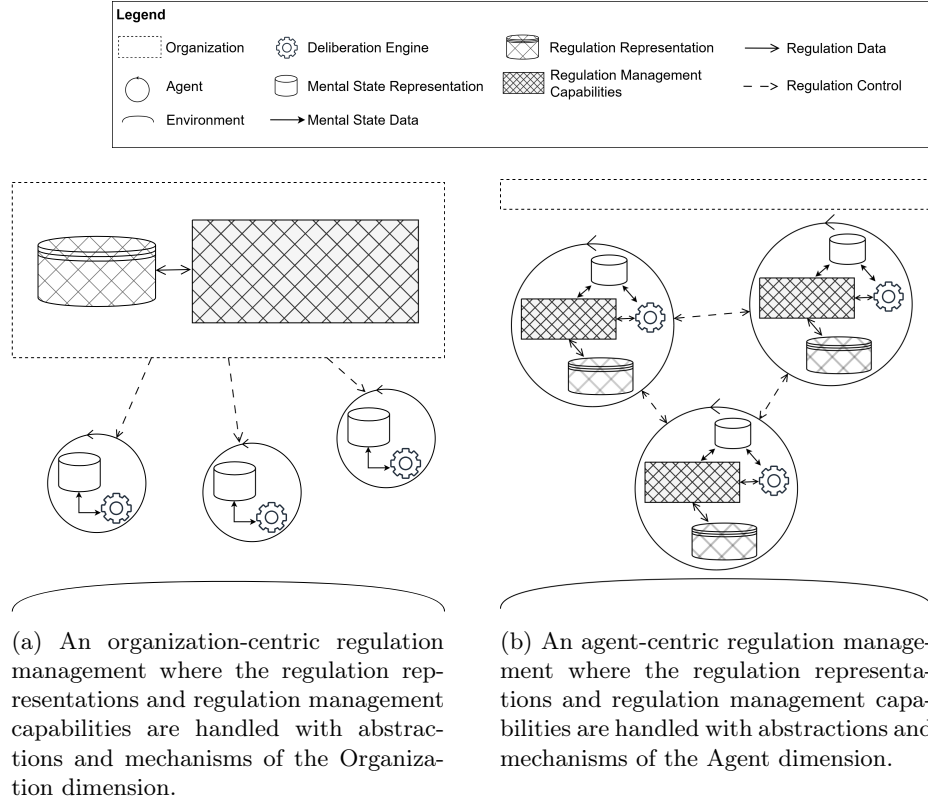
Fig. 2: Organization-centric and agent-centric regulation management views in the MAOP Dimensions perspective on regulation management in MAS.

Agent dimension), (iii) environment abstractions related to internal representations and management within non-autonomous entities (i.e., Environment dimension), and (iv) interaction abstractions related to interconnections and communication among the components of the organization, agents, and environment (i.e., Interaction dimension). These components and representations are implemented using dedicated programming primitives provided by the supporting platform used to develop the multi-agent system.

In this paper, we will focus mainly on the organization-centric and the agent-centric views (see Fig. 2) with a short discussion at the end of this section on the environment-centric and the interaction-centric views to complete the multi-agent oriented views on regulation management in MAS.

Definition 1. *Organization-Centric Regulation Management (OCR)*
The organization-centric regulation management denotes a view in the MAOP Dimensions perspective in which the representations and capabilities of regulation

management are realized with abstractions (e.g., roles, groups) and mechanisms of the Organization dimension of the MAOP paradigm.

The organization-centric regulation management view refers to regulation management that is carried out by components of the organization (see Fig. 2a). The *organization components*[6] hold the regulation representations and carry out the capabilities to regulate the behavior of agents. Regulations are represented and managed externally to the *domain agents* from the Agent dimension and to the *domain artifacts* from the Environment dimension[7].

Definition 2. *Agent-Centric Regulation Management (ACR) The agent-centric regulation management denotes a view in the MAOP Dimensions perspective in which the representations and capabilities of regulation management are realized with abstractions (e.g., beliefs, goals, plans) and mechanisms of the Agent dimension of the MAOP paradigm.*

The agent-centric regulation management view refers to regulation management that is carried out by the components of domain agents (see Fig. 2b). The domain agents' components are their mental state (i.e., representation of the agent's beliefs, goals, and plans) and their deliberation mechanisms. The combination of representations and capabilities of regulation management with the mental state and deliberations of the agents enables the agents to make decisions on the management of regulations on their own. The agent-centric regulation management view, on the one hand, allows agents to manage regulations based on their perception and participation in the domain problem; on the other hand, it may restrict the agents' deliberations by not taking into account the MAS collective state.

Under certain circumstances, neither the organization-centric nor the agent-centric view of regulation management alone is practical or effective to regulate agents in MAS. In complex and dynamic systems like smart cities, for instance, it is often infeasible for an organization-centric view to prescribe and control every possible situation without reducing the agents' autonomy. On the other hand, a fully agent-centric view may maintain the agents' autonomy but cause the system's inconsistency or unpredictability due to the agents' limited perception and decentralized decisions. Thus, by integrating these two views into a hybrid regulation management view we can balance the agents' autonomy with the system control.

Definition 3. *Hybrid Organization-centric and Agent-centric Regulation Management (HCR) The hybrid organization-centric and agent-centric*

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[6] The organization components are strongly dependent on the specific MAS platform. They can be dedicated regulation management mechanisms in the organization, or use primitives of other dimensions (e.g., in JaCaMo [6] there are dedicated organization agents, artifacts, and interactions, while in EI/EIDE [35] there are governor agents). These will be discussed in more detail in Section 4.

[7] Domain agents and domain artifacts are dedicated to the management of domain knowledge and problems.

regulation management denotes a view in the MAOP Dimensions perspective in which the representations and capabilities of regulation management are realized with abstractions and mechanisms of both the Organization and Agent dimensions of the MAOP paradigm.

The hybrid organization-centric and agent-centric regulation management view, henceforth *hybrid-centric regulation management view*, enables both the components of the organization and domain agents to participate in the management of regulations.

Next, we provide a brief overview of the other two views in the MAOP Dimensions perspective, i.e., the environment-centric and interaction-centric views on regulation management.

In the environment-centric regulation management view, regulations are managed using abstractions and mechanisms of the Environment dimension, e.g., by defining domain artifacts entitled to carry out regulation management capabilities (e.g., [37,40]). Regimentations can be regimented through the use of environmental infrastructures that strictly constrain agents not to violate regulations. Constraining infrastructures or barriers function as both a domain and a regulation restriction to agents' behavior (e.g., [10]). The organization may also employ domain artifacts to deploy the enforce capability, entirely or partially. For example, the organization can use radar cameras (i.e., domain artifacts in the environment) to monitor vehicles' speed and automatically sanction those detected exceeding the speed limit.

In the interaction-centric regulation management view, regulations are managed using abstractions and mechanisms of the Interaction dimension. For example, communication protocols can be seen as a way to implement the regiment capability, while social commitments or interaction policies (e.g., [2,15,17]) can be seen as a way to implement the enforce capability.

3.2 Architectural Views on Regulation Management

In this section, we analyze the architectural views on regulation management. Considering that both regulation representations and regulation management capabilities can be centralized or distributed, we can identify three architectural views on regulation management (see Table 1): fully-centralized, fully-decentralized, and semi-(de)centralized.

Definition 4. *Fully-Centralized Regulation Management (FCR) The fully-centralized regulation management denotes a view in the Architectural perspective in which the representations and each of the capabilities of regulation management are handled each by a single component.*

In the fully-centralized view, the regulation management has a single component holding the regulation representations and single components for each regulation management capability. The main advantage of systems adopting the fully-centralized regulation management view is their consistency and homogeneity in regulating agents since they avoid the need for consensus or negotiation

Regulation Representation	Regulation Management Capabilities	
	Centralized	Distributed
Centralized	FCR	SDR
Distributed	SDR	FDR

Table 1: Architectural views on regulation management with respect to the regulation management capabilities and regulation representation. FCR means fully-centralized regulation management, SDR means semi-(de)centralized regulation management, and FDR means fully-decentralized regulation management.

mechanisms for managing regulations. However, these systems have disadvantages inherent in centralized systems, e.g., lack of scalability.

Definition 5. *Fully-Decentralized Regulation Management (FDR) The fully-decentralized regulation management denotes a view in the Architectural perspective in which the representations and capabilities of regulation management are handled by multiple distributed components.*

In the fully-decentralized view, the regulation management is implemented by multiple components that could be within a single or multiple entities. Thus, several independent components handle their own representations of regulations and implement their own regulation management capabilities. This decentralization may create inconsistencies or conflicts that may require additional mechanisms to be avoided or resolved. Fig. 2b illustrates an example of the fully-decentralized view, where the regulation management is carried out by several independent components in various agents.

Definition 6. *Semi-(De)centralized Regulation Management (SDR) The semi-(de)centralized regulation management denotes a view in the Architectural perspective in which the representations or capabilities of regulation management are handled partially by single components and partially by multiple distributed components.*

The semi-(de)centralized view is an intermediary architectural style between the fully-centralized and fully-decentralized views on regulation management. In the semi-(de)centralized view, regulation management is implemented by multiple centralized and decentralized components within a single or multiple entities.

Several degrees of decentralization designs are possible. Closer to the fully-centralized view, we have a design in which the regulation representations are distributed in multiple components and used by a single component centralizing the regulation management capabilities for making regulation decisions. We refer to this design option as the *semi-centralized regulation management view*. Closer to the fully-decentralized view, we have a design in which the regulation representations are centralized in a single component and used by regulation management capabilities distributed in multiple and independent components.

We refer to this design option as the *semi-decentralized regulation management view*. While the regulation representations may present inconsistencies in the semi-centralized view, the regulation management capabilities may present inconsistencies in the semi-decentralized view. In both views, additional mechanisms are needed to overcome these inconsistencies.

3.3   A Unified View on Regulation Management

In this section, we propose our unified view on regulation management in MAS. Figure 3 illustrates this unified view resulting from the combination of the MAOP Dimensions perspective (organization-centric, hybrid-centric, and agent-centric) and the Architectural perspective (i.e., fully-centralized, semi-(de)centralized, and fully-decentralized) plus the Regulation Capabilities perspective. For the sake of simplicity, we chose to represent in Fig. 3 only the partial and full regulation management capabilities without exhaustively mapping all possible combinations of regiment, enforce, and adapt capabilities.

In the organization-centric regulation management view, the regiment capability prevents agents from performing actions in the environment or interacting with other agents according to prohibition regulations. Regimentation results in rigid systems [25]. The enforce capability relaxes this regiment capability rigidity by allowing agents to violate regulations. However, this relaxation sets the need for monitoring the domain agents' behavior, deliberating about regulations, and applying sanctions, if applicable. The adapt capability enables the regulation management to cope with changes to internal (i.e., organization) or external (i.e., environment or agent) factors.

The organization-centric regulation management view can be designed from a fully-centralized to fully-decentralized architecture. View 1 (Fig. 3) illustrates the fully-centralized organization-centric view, in which a single component of the organization manages all the regulations in MAS. The representations and capabilities of regulation management are concentrated in this organization component. In this view, it is feasible to carry out the regiment capability since there is a single component that defines and a single component that deliberates about regulations. However, the enforce and adapt capabilities may require additional components to avoid bottlenecks. View 2 (Fig. 3) illustrates the fully-decentralized organization-centric view, in which in a single organization, several organization components are responsible for managing regulations. This distribution of responsibility mitigates the bottlenecks identified in View 1. View 2 can be realized as a single organization split into several subdivisions (e.g., units, departments) in which each subdivision has its own independent regulation management or several independent organizations in which each organization has its own regulation management (e.g., [12]). Between View 1 and View 2, there are several semi-(de)centralized regulation management possibilities, considering the centralization or distribution of the regulation representations and regulation management capabilities. For example, the organization may have multiple regulation representations that are used by a single component responsible for
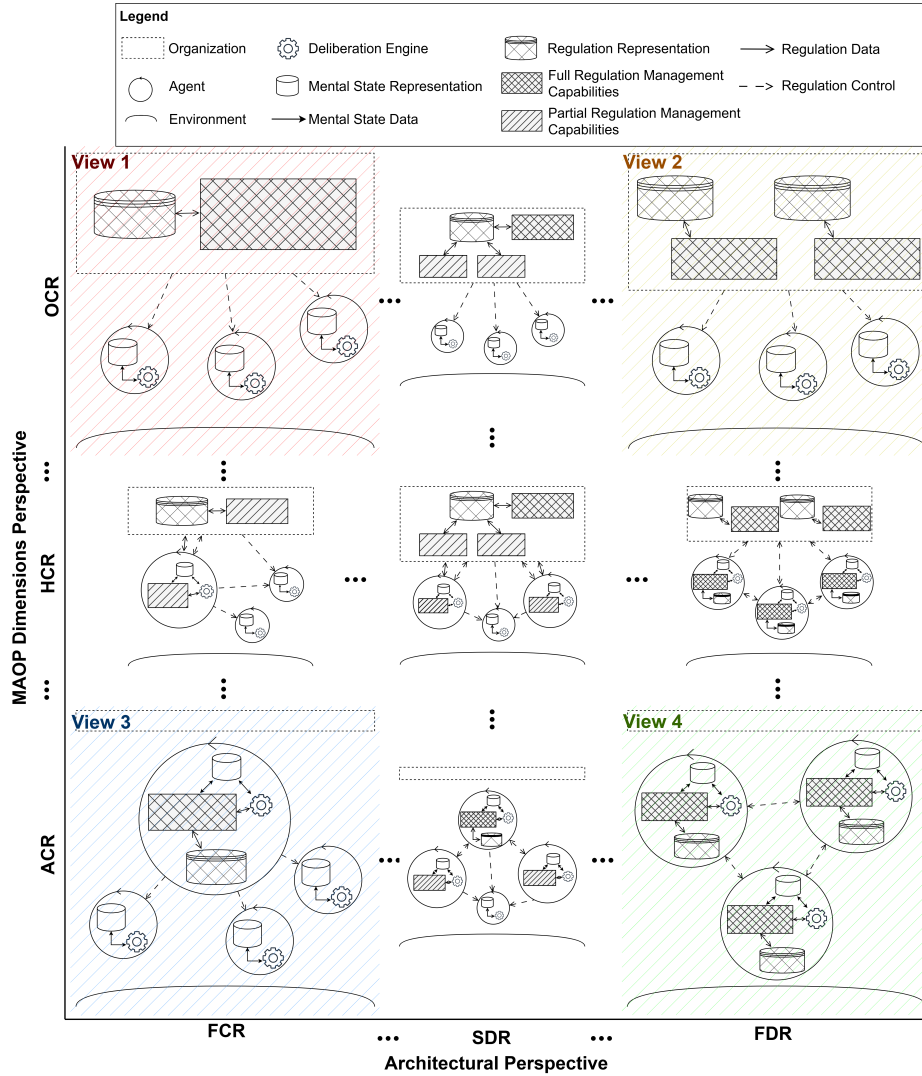
Fig. 3: A unified view on regulation management in MAS combining the MAOP Dimensions and the Architectural perspectives.

all regulation management capabilities (i.e., semi-centralized view). The organization may also implement a single regulation representations component that is used by multiple components carrying out the regulation management capabilities (i.e., semi-decentralized view).

In the agent-centric regulation management view, the regiment capability cannot be carried out as, by principle, agents are autonomous. Thus, only the enforce and adapt capabilities can be carried out in this view. The enforce ca-

pability enables agents to monitor other agents' behavior, deliberate about regulations, and apply sanctions, e.g., aiming to encourage others to comply with regulations. The adapt capability enables agents to interpret and adjust regulations dynamically based on internal (i.e., agent's mental state) and external (i.e., environmental) factors.

The agent-centric regulation management view can be designed from a fully-centralized to a fully-decentralized architectural view. View 3 (Fig. 3) illustrates the fully-centralized agent-centric view, in which a single domain agent handles the regulations (i.e., regulation representations) and regulates the other domain agents (i.e., carries out the regulation management capabilities).View 4 (Fig. 3) illustrates the fully-decentralized agent-centric view, in which multiple domain agents handle regulation representations and carry out regulation management capabilities to regulate the other agents' behavior. Between View 3 and View 4, there are several semi-(de)centralized regulation management possibilities. In a semi-centralized view, a possible scenario is when we have two agents managing regulations, both have the regulation representations (i.e., distributed), yet each carries out a single regulation management capability, e.g., one agent carries out the enforce capability and the other the adapt capability (i.e., from a global view, the regulation management capabilities are centralized). In a semi-decentralized view, a possible scenario is when several agents manage regulations, while one have the regulation representations and carries out all regulation management capabilities, the others only carry out partial regulation management capabilities. Thus, the regulation representations are centralized, and the regulation management capabilities are decentralized.

In the hybrid-centric regulation management view, the number of design options increases considering the combinations of the Architectural perspective and the Regulation Capabilities perspective tailored for the organization-centric and agent-centric views. Recall that the regiment capability is only carried out by components in the organization. On the other hand, the enforce and adapt capabilities may be realized by components in the organization or domain agent. These components may have different regulation representations and carry out different regulation management capabilities that complement each other in the regulation of MAS. The organization components may manage regulations according to the global objectives and expectations, while the domain agent components may enforce and adapt regulations at the individual level based on the agent's mental state and local context.

The hybrid-centric regulation management view can be designed spanning from a fully-centralized to a fully-decentralized architectural view. Due to the large number of possibilities of hybrid views, we do not explore in detail all of them here, but we focus on a few possibilities. A hybrid-centric fully-centralized view is captured in a scenario in which the organization carries out the regulation regulations and a partial set of regulation management capabilities (e.g., regiment and adapt capabilities), whereas a single domain agent carries out the complementary partial capability (e.g., enforce capability). Note that because the regulation representations are not part of the agent carrying out the enforce

capability, the organization must share with the agent those it does possess. In the hibrid-centric fully-decentralized view, multiple components in the organization and domain agents have the regulation representations and carry out all regulation management capabilities. This is the most complex view captured in the current unified view, as only the Organization and Agent dimensions are considered. However, if the other MAOP dimensions are considered, we may find more complex views.

4   Analysis of Regulation Management MAS Frameworks

In this section, we use the unified view presented in Section 3.3 to classify the existing MAS frameworks in the literature. We structure the analysis in this unified view on regulation management of MAS along the MAOP Dimensions perspective.

4.1   Organization-Centric Regulation Management View

Table 2 presents the analysis of MAS frameworks adopting the organization-centric regulation management view with respect to the Regulation Capabilities and Architectural perspectives.

Organization-Centric Framework	OCR	
	CAP	**ARC**
EI/EIDE [35]	Regiment, Enforce	FCR
OperA [1]	Regiment, Enforce, Adapt	FCR
JaCaMo [6]	Regiment, Enforce, Adapt	FCR
InstAL [36]	Enforce, Adapt	SDR
López y López et al. [29]	Enforce, Adapt	SDR
n-BDI [14]	Enforce, Adapt	SDR
NorJADE [30]	Regiment, Enforce, Adapt	SDR
ROMAS-Magentix2 [20]	Regiment, Enforce, Adapt	SDR

Table 2: Analysis of organization-centric regulation management frameworks w.r.t. the Regulation Capabilities and the Architectural perspectives.

Referring to the fully-centralized regulation architectures and their capabilities, both EI/EIDE [35] and OperA [1] rely on the organization structure that regiments agents' interactions. JaCaMo [6] implements the regiment capability by preventing the realization of prohibited actions defined in the regulations. The enforce capability is realized by coupling the organization model with organization agents in EI/EIDE and OperA or with organization artifacts in JaCaMo. Despite the use of multiple organization agents or organization artifacts, the decisions about the enforcement of regulations are made by the organization

model. This leads us to classify them as fully-centralized regulation architecture. Regarding the adapt capability, in InstAL, JaCaMo, and OperA regulations can be added and removed ad-hoc through the specification of conditions that simply activate and deactivate regulations at runtime based on environmental factors. Another possibility in JaCaMo and OperA is the possibility to change the organization specification, which includes the regulation representations. In EI/EIDE there are no primitive operations for the adaptation, but other proposals (e.g., [7,9]) have circumvented these limitations.

Regarding the semi-(de)centralized regulation architectures, InstAL [36] models multiple interacting institutions, connected through a single bridge institution and a social oracle that provides an agnostic interface for agents to observe the social state. The handling of violations is under the responsibility of the agents participating in the institution. Therefore, we classify InstAL as semi-centralized regulation architecture. Recent research in the revision of regulations has been proposed (e.g., [33]) as a way to adapt regulations. ROMAS-Magentix2 [20] supports two forms of regulation management. First, the traditional centralized organization-centric regulation architecture integrates the enforce and adapt capabilities (i.e., with ad-hoc conditions or through reorganization). Second, regulations can be formalized through social contracts between agents associated with a dedicated authority that manages the enforce and adapt capabilities. Other semi-(de)centralized regulation architectures on regulation management are presented in NorJADE [30], López y López et al. [29], and n-BDI [14]. Although their proposal for normative agent architecture, the normative system is realized with a centralized component for regulation representations and distributed components carrying out regulation management capabilities using organization abstractions (i.e., roles). Hence, these characteristics lead us to classify them as semi-decentralized organization-centric frameworks. In n-BDI [14], the enforce capability is realized by a centralized automatic mechanism that always applies sanctions due to compliance with or violation of regulations, while the adapt capability is managed by some expert agents by evaluating the salience of regulations (i.e., when a regulation is no longer salient, it is discarded). Changes in the regulations are informed to the domain agents. López y López et al. and NorJADE define roles of agents carrying out the enforce and adapt capabilities. López y López et al. define defenders and promoters in charge of the enforce capability and legislators for the adapt capability. In NorJADE, the enforce capability is carried out by the regulation management system and agents with the role of enforcer. The adapt capability is carried out by some specific agents empowered to adapt the regulations. NorJADE also includes the regiment capability, which is carried out by a regimented mechanism in the regulation management system that prevents the execution of interdicted actions.

4.2   Agent-Centric Regulation Management View

Table 3 presents the analysis of MAS frameworks adopting the agent-centric regulation management view with respect to the Regulation Capabilities and Architectural perspectives.

Agent-Centric Framework	ACR	
	CAP	**ARC**
Jason Normative Agent [43]	Enforce	FDR
EMIL-A [13]	Adapt	FDR

Table 3: Analysis of the agent-centric regulation management frameworks w.r.t. the Regulation Capabilities and the Architectural perspectives.

Few MAS frameworks for the agent-centric regulation management have been proposed. Jason Normative Agent [43] incorporates the regulation representations and the enforce capability in the agent architecture, allowing agents to independently manage the regulations (i.e., fully-dencentralized architectural view). Jason Normative Agent proposes a sanctioning norm enforcement process model that enables agents to (i) detect any regulated actions, (ii) evaluate norms and sanctions, and (iii) apply sanctions. EMIL-A [13] proposes a fully-decentralized regulation management architecture, with all agents capable of managing regulations. The adapt capability is driven by the salience of regulations within the agent's recognition module. An extension [34] incorporates the enforce capability.

4.3   Hybrid-Centric Regulation Management View

Table 4 presents the analysis of MAS frameworks adopting the hybrid-centric regulation management view with respect to the Regulation Capabilities and Architectural perspectives.

Hybrid-Centric Framework	OCR		ACR	
	CAP	**ARC**	**CAP**	**ARC**
ANTE [28]	Enforce	FCR	Adapt	FDR

Table 4: Analysis of the hybrid organization-centric and agent-centric regulation management frameworks w.r.t. the Regulation Capabilities and the Architectural perspectives.

ANTE [28] is the only MAS framework that we have identified as hybrid-centric regulation management. Agents in ANTE can participate in a negotiation protocol that leads to the creation of a norm-governed relationship formalized in a contract. The normative context, which can be seen as a centralized organization-centric regulation management, endows the enforce capability responsible for monitoring and sanctioning (i) according to the norms established in the contract, and (ii) by assessing the trust of agents. The adapt capability, instead, is realized by agents through the negotiation of new or established contracts.

4.4   Remarks

The Organization, Agent, Environment, and Interaction dimensions in the MAOP Dimensions perspective introduce a separation of concerns for regulation management in MAS. These dimensions are implemented by using dedicated programming abstractions provided by the MAS platforms. Depending on the MAS platform, the organization dimension, besides dedicated shared representations, can implement its mechanisms using abstractions belonging to the other dimensions. For instance, on the JaCaMo platform, the organization components are implemented using dedicated agents, artifacts, and interaction primitives, while in López y López et al. the organization components are only implemented by dedicated organization agents.

Analyzing the literature from the lens of the unified view, we identified a predominance of organization-centric frameworks and a limited exploration of agent-centric frameworks. For the organization-centric view, all regulation management capabilities are well supported, although the adapt capability is weakly explored. In traditional organization-centric frameworks with an explicit representation of the organization, the adaptation is addressed with a basic specification of ad-hoc conditions or relying on a significant reorganization process that, besides adapting the regulations, also adapts the entire organization structure. The few works that explore the adaptation of regulation representations are directed by organization agent primitives.

For the agent-centric view, we have identified several proposals on normative agents [11] in the literature; however, the majority of them propose obedient agents, where regulation representations and compliance decisions are hard-coded into the agent's architecture (e.g. [8,26,27,32,41]). By hard-coding obedience in agents, no external mechanisms are required for regimentation or enforcement. Other proposals recognize the importance of allowing agents to decide and instead focus on deliberation mechanisms to comply with regulations (e.g. [18,21,24,31]). Despite these contributions, our focus is on the regiment, enforce, and adapt capabilities. Having analyzed the existing agent-centric frameworks and their regulation management capabilities, we note that the agent-centric view is little explored in the literature. This is surprising, as the agent-centric regulation management view serves as a foundational basis for developing self-organizing and self-regulated systems. This gap also explains the scarcity of hybrid-centric proposals, which, despite encompassing numerous design possibilities, are rarely realized in practice.

Regarding the Architecture perspective, we can observe that organization-centric regulation management frameworks tend to have a fully-centralized regulation or a semi-(de)centralized regulation architecture. Conversely, in the agent-centric regulation management frameworks there is a tendency to adopt a fully-decentralized regulation architecture.

5   Conclusions and Future Work

The diverse approaches on regulation management in MAS pose challenges in understanding the range of available design options and identifying the most suitable ones based on the system requirements. We proposed a unified view based on three perspectives on regulation management: Regulation Capabilities, MAOP Dimensions, and Architectural.

We discussed how regulation management can be designed using the abstractions from the MAOP Dimensions perspective, with an emphasis on organization-centric and agent-centric regulation management views and their combination, the hybrid-centric regulation management view. We then discussed the Architectural perspective, encompassing the fully-centralized, fully-decentralized, and semi-(de)centralized regulation management views. We proposed a unified view that combines these two perspectives and discussed the Regulation Capabilities perspective on regulation management. We then analyzed regulation management frameworks in MAS using the unified view and identified interesting tendencies and underexplored views.

The unified view serves as a versatile reference grid for identifying emerging challenges and opportunities in regulation management in MAS. For instance, by focusing on a single capability, e.g., it is possible to examine in-depth only the adapt capability considering its mechanisms, features, and implications across the MAOP Dimensions combined with the Architectural perspectives.

Although providing a broader perspective on the design options for regulation management, we acknowledge that our unified view has some limitations. For example, we identify the possibility of environment-centric and interaction-centric views, but a detailed analysis of these two MAOP dimensions remains open. We have used the unified view to evaluate MAS frameworks, we have not yet conceptually evaluated the benefits and limitations of each design option. Future work should systematically compare these design options to guide system designers in selecting and deploying effective regulation management in MAS.

Furthermore, it is interesting to note that if a framework provides good support to implement regulation management within all MAOP dimensions, it could easily adapt to diverse views from the MAOP Dimensions perspective, including hybrid combinations. Similarly, if a framework provides good support to implement centralized and decentralized regulation management architectures, it could easily adopt all the views from the Architectural perspective. Finally, when a framework integrates comprehensive support for both perspectives, therefore, it could easily implement all the views presented in the unified view, achieving a flexible and versatile regulation management framework in MAS. Interestingly yet, by achieving a versatile regulation management framework, adaptation may be targeted not only on the regulation representation but also on the architectural style and distribution of capabilities among the different dimensions.

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