An Adaptive Regulation Management System for Multi-Agent Systems: A Normative Approach

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Next in Line...

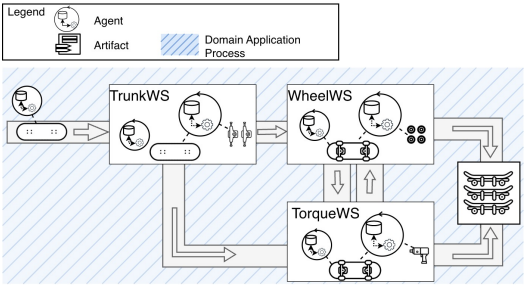
Context

- Dynamic environments (e.g., industry)
- *Multi-Agent Systems* (MAS)
  - autonomous agents
  - decentralized decisions

Example

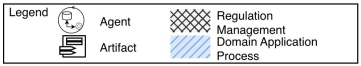
Skateboard assembly line controlled by MAS

- product-centric agents that handle customized skateboard orders
- assembly-process agents that operate on the workstations



Fábrica do Futuro, University of São Paulo https://sites.usp.br/fabricadofuturo/

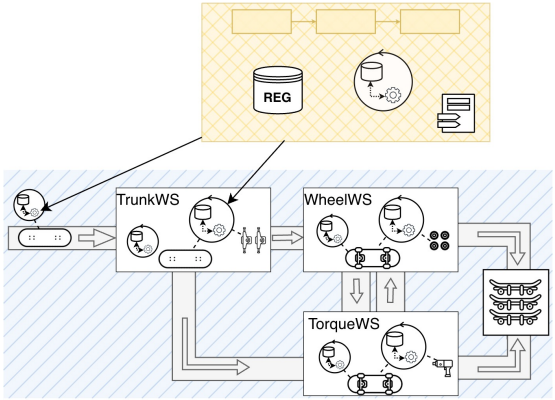
Aim: Resilience and Flexibility



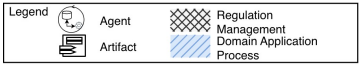
Regulations management systems can be integrated into MAS to guide agents' behaviors

Example

- guide product-centric agents in specifying the admissible next steps to be performed
- guide assembly-process agents in performing the required operations at each workstation



Challenge

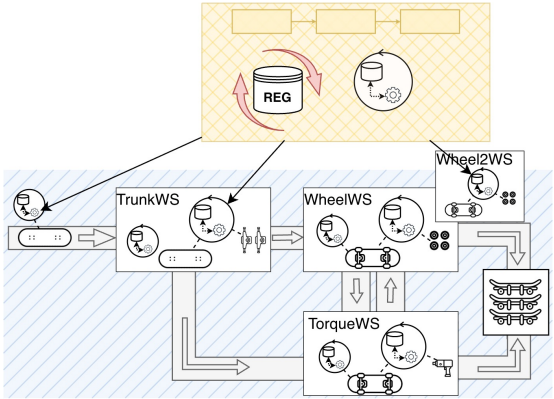


Adapt the regulations to cope with changing

- Contextual Requirements

Example

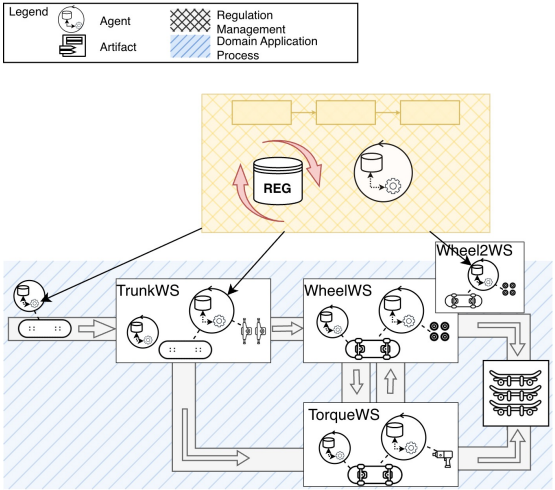
→ Adapt the **Regulations Representation** to incorporate new operations and workstations



Challenge

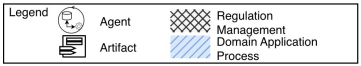
Adapt the regulations to cope with changing

- Contextual Requirements → *main focus of the existing adaptation models*



Yan, E., Nardin, L., Boissier, O., & Sichman, J. A regulation adaptation model for multi-agent systems. ECAI 2025

Challenge

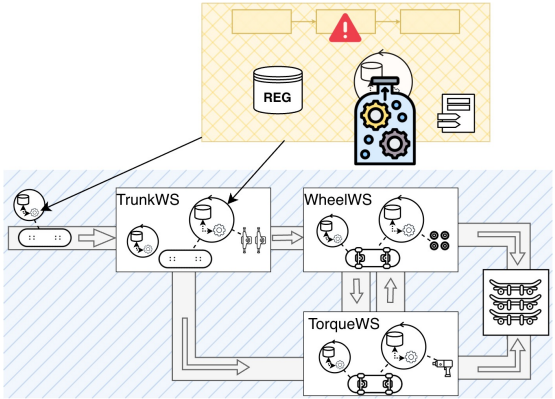


Adapt the regulations to cope with changing

- Contextual Requirements
- Functional Requirements
- Non-Functional Requirements

Example

In case of *bottleneck* in the regulation management



Challenge

Adapt the regulations to cope with changing

- Contextual Requirements
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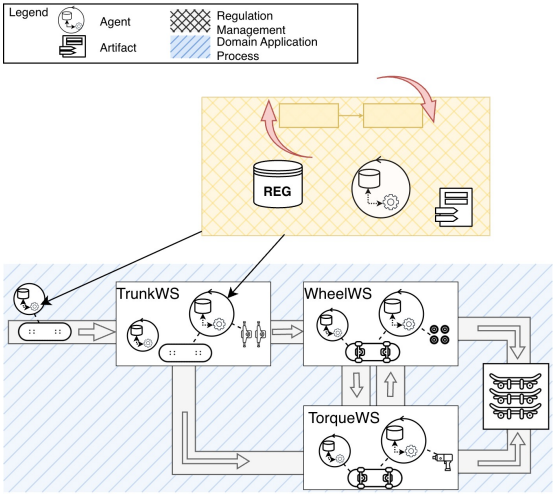
- Non-Functional Requirements

Example

In case of *bottleneck* in the regulation management
→ Adapt the:

1. **Regulation Process**, e.g., simplifying the process of the regulation management



Challenge

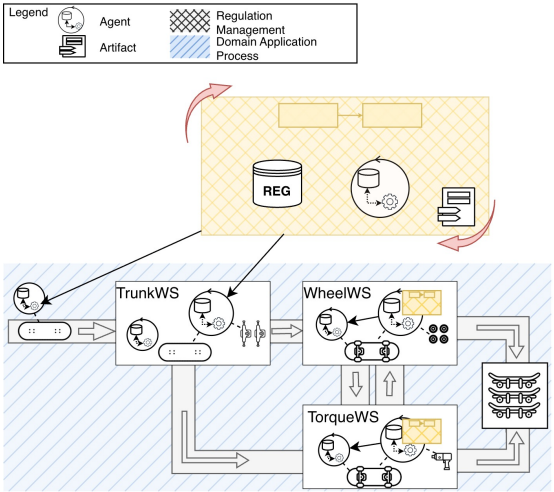
Adapt the regulations to cope with changing

- Contextual Requirements
- Functional Requirements
- Non-Functional Requirements

Example

In case of *bottleneck* in the regulation management
→ Adapt the:

1. **Regulation Process**, e.g., simplifying the process of the regulation management
2. **Regulation Architecture**, e.g., distributing the regulation management to assembly-process agents



Challenge

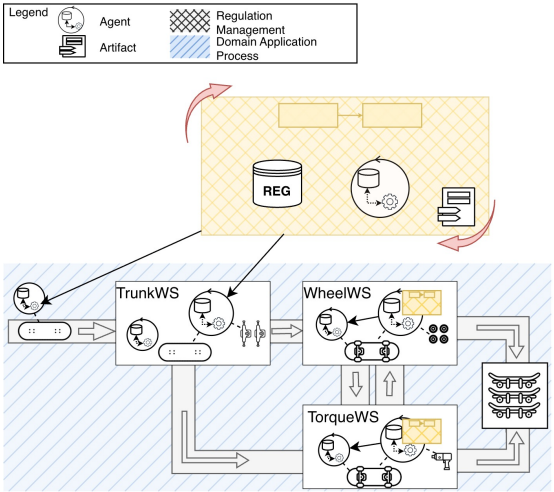
Adapt the regulations to cope with changing

- Contextual Requirements
- Functional Requirements → *no existing work*
- Non-Functional Requirements → *no existing work*

Example

In case of *bottleneck* in the regulation management
→ Adapt the:

1. **Regulation Process**, e.g., simplifying the process of the regulation management
2. **Regulation Architecture**, e.g., distributing the regulation management to assembly-process agents



Objective

Objective

Design an adaptive regulation management system for MAS

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Design an adaptive regulation management system for MAS

Enabling the adaptation of:

→ *Regulation Process*

→ *Regulation Architecture*

Research Questions

RQ1 What are the core elements for the *regulation management* of MAS?

RQ2 What are the core elements for *adapting* the regulation management of MAS?

Next in Line...

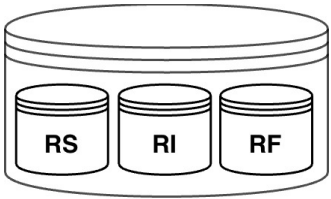
Regulations Representation

Explicit representations of

- Constitutive Norms
  $cns ::= \langle \texttt{constitutive}, condition, brute, institutional \rangle$
- Regulative Norms
  $rns ::= \langle \texttt{regulative}, condition, subject, modality, object \rangle$
- Sanction Rules
  $srs ::= \langle \texttt{sanction}, condition, sanctioned, \{\langle s\text{-}reg, status \rangle\}, content \rangle$

Regulations Representation is composed of
$REG = \langle RS, RI, RF \rangle$

- Regulation Specification RS
- Regulation Instance RI
- Regulation Fact RF

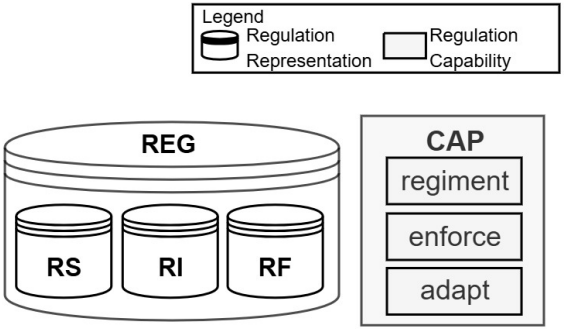


Regulation Capabilities

A regulation capability *cap* denotes the procedural or declarative definitions of the functions to manage *REG*

$CAP \subseteq \{regiment, enforce, adapt\}$

- *regiment*
- *enforce*
- *adapt*



Regulation Capabilities

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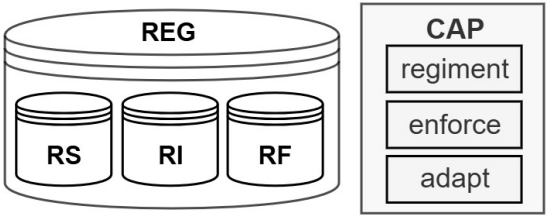
$CAP \subseteq \{regiment, enforce, adapt\}$

- *regiment*
- *enforce*
  - *detect*
  - *evaluate*
  - *execute*
- *adapt*
  - *detect*
  - *design*
  - *execute*

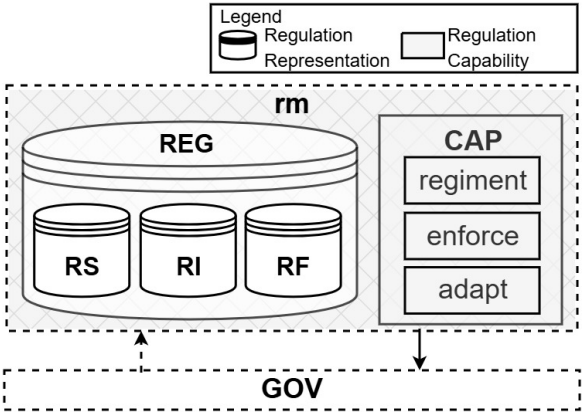


Regulation Management Element

Regulation Management Element
$rm = \langle REG, CAP, GOV \rangle$

- *REG* Regulations Representation
- *CAP* Regulation Capabilities

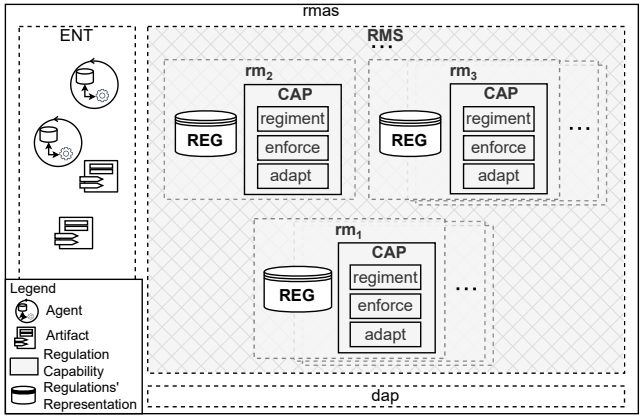
to govern entities participating in *GOV*



Regulation Management System

Regulated MAS $rmas ::= \langle ENT, RMS, dap \rangle$

- $ENT = \langle AG, ART \rangle$ MAS Entities
- $RMS = \{rm_1, ..., rm_n\}$ Regulation Management System
- *dap* domain application process



Next in Line...

Adapting the Regulation Management: A Normative Approach

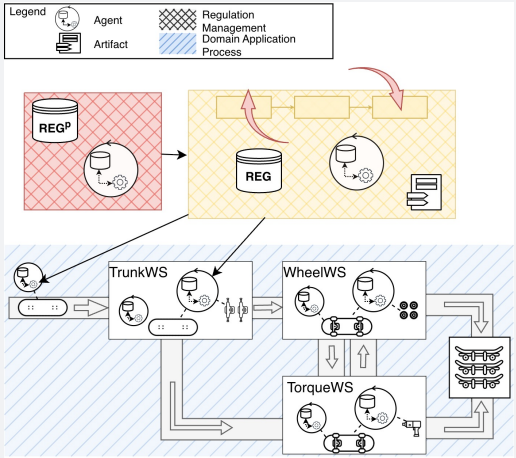
We define dedicated *Regulation Management Elements* to govern and adapt the deployment of the regulation process and regulation architecture together with

- **Representations** of the regulation process and regulation architecture
- **Language Constructs** to express their deployment
- **Regulations Representation** to govern their deployment
- **Adapt Capabilities** to adapt their deployment at runtime

Process Regulation Management Element

A *process regulation management element* that governs the deployment of the regulation process

Example

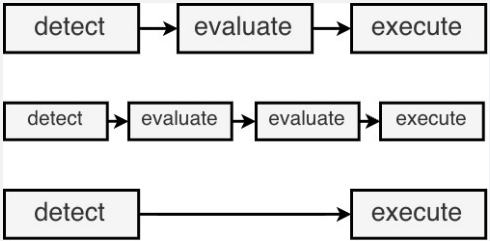


Representing the Regulation Process

The regulation process $proc ::= \langle sub_1^{cap}, ..., sub_n^{cap} \rangle$ denotes the order of execution of the sub-capabilities of a regulation capability *cap*

Example

Possible regulation processes of the `enforce` capability



Language Constructs for Deploying the Regulation Process

Language construct to denote a *requirement* of a new regulation process *proc* in a regulation capability *cap*:

- $\texttt{required}(\langle proc, cap \rangle)$

Language constructs to denote the *deployment* of a regulation process *proc*:

- $\texttt{realized}(\langle proc, cap \rangle)$
- $\texttt{managed}(\langle proc, cap \rangle)$

Regulations Representation for the Regulation Process

- *Constitutive norms* for stating a required regulation process based on *brute* facts under some *conditions*

Example

$$\begin{aligned}\mathrm{cns}_1 = \langle &\texttt{constitutive}, \texttt{timeCritical} \wedge \langle\langle \texttt{detect}, \texttt{evaluate}, \texttt{execute}\rangle, \texttt{enforce}\rangle,\\ &\texttt{bottleneck},\\ &\texttt{required}(\langle\langle \texttt{detect}, \texttt{execute}\rangle, \texttt{enforce}\rangle)\rangle\end{aligned}$$

- *Regulative norms* for guiding agents in the deployment of the required regulation process

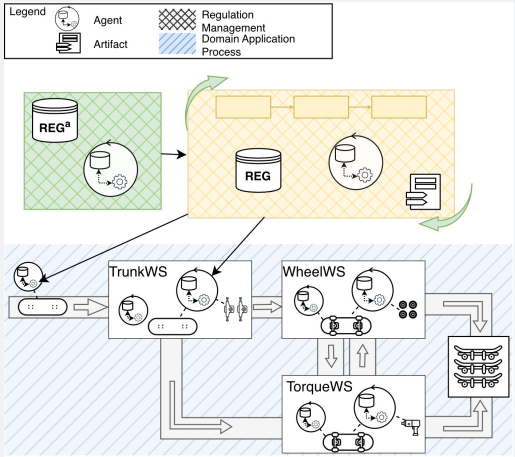
Example

$$\begin{aligned}\mathrm{rns}_2 = \langle &\texttt{regulative}, \texttt{required}(\langle\langle \texttt{detect}, \texttt{execute}\rangle, \texttt{enforce}\rangle\rangle,\\ &\texttt{skGovernor},\\ &\texttt{obligation}, \texttt{managed}(\langle\langle \texttt{detect}, \texttt{execute}\rangle, \texttt{enforce}\rangle)\end{aligned}$$

Architecture Regulation Management Element

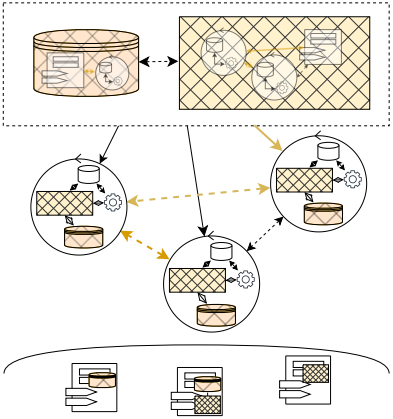
An *architecture regulation management element* that governs the deployment of the regulation architecture

Example



Representing the Regulation Architecture

- Functional Structure $FUN \subseteq \{\texttt{acr}, \texttt{ecr}, \texttt{icr}, \texttt{ocr}\}$
  - `acr` agent-centric regulation
  - `ecr` environment-centric regulation
  - `icr` interaction-centric regulation
  - `ocr` organization-centric regulation



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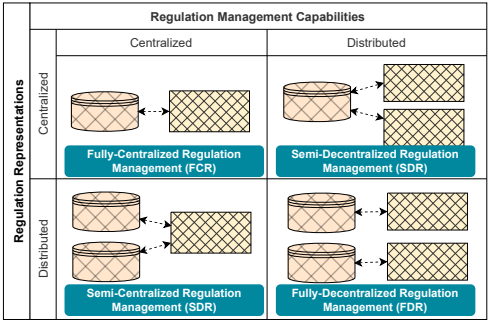
Representing the Regulation Architecture

- Functional Structure $FUN \subseteq \{\texttt{acr}, \texttt{ecr}, \texttt{icr}, \texttt{ocr}\}$
  - `acr` agent-centric regulation
  - `ecr` environment-centric regulation
  - `icr` interaction-centric regulation
  - `ocr` organization-centric regulation
- Control Structure $con \in \{\texttt{fcr}, \texttt{scr}, \texttt{sdr}, \texttt{fdr}\}$
  - `fcr` fully-centralized regulation
  - `scr` semi-centralized regulation
  - `sdr` semi-decentralized regulation
  - `fdr` fully-decentralized regulation



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Representing the Regulation Architecture

- Functional Structure $FUN \subseteq \{\texttt{acr}, \texttt{ecr}, \texttt{icr}, \texttt{ocr}\}$
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  - `icr` interaction-centric regulation
  - `ocr` organization-centric regulation
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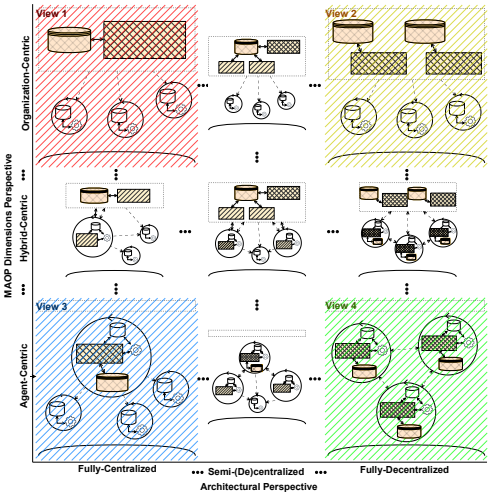
  - `fcr` fully-centralized regulation
  - `scr` semi-centralized regulation
  - `sdr` semi-decentralized regulation
  - `fdr` fully-decentralized regulation

Regulation Architecture $arc ::= \langle FUN, con \rangle$



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Language Constructs for Deploying the Regulation Architecture

Language construct to denote a *requirement* of a new regulation architecture:

- `required`(*arc*)

Language constructs to denote the *deployment* of a regulation architecture:

- `realized`(*arc*)
- `represented`(*REG*)
- `managed`(*CAP*)
- `deployed`(*x*, *entity*)
  - `deployed`(`realized`(*arc*), *entity*)
  - `deployed`(`represented`(*REG*), *entity*)
  - `deployed`(`managed`(*CAP*), *entity*)

Regulations Representation for the Regulation Architecture

- *Constitutive norms* for stating a required regulation architecture based on *brute* facts under some *conditions*

Example

$$\begin{aligned}\mathrm{cns}_1 = \langle & \texttt{constitutive}, \texttt{highLoad} \wedge \langle \{\texttt{ocr}\}, \texttt{fcr} \rangle, \\ & \texttt{bottleneck}, \\ & \texttt{required}(\langle \{\texttt{ocr}, \texttt{acr}\}, \texttt{sdr} \rangle) \rangle\end{aligned}$$

- *Regulative norms* for guiding agents in the deployment of the required regulation architecture

Example

$$\begin{aligned}\mathrm{rns}_1 = \langle & \texttt{regulative}, \texttt{required}(\langle \{\texttt{ocr}, \texttt{acr}, \texttt{sdr}\} \rangle), \\ & \texttt{skGovernor}, \\ & \texttt{obligation}, \texttt{realized}(\langle \{\texttt{ocr}, \texttt{acr}\}, \texttt{sdr} \rangle) \rangle\end{aligned}$$

Regulations Representation for the Regulation Architecture

- *Regulative norms* for guiding agents in the deployment of the required regulation architecture

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Example

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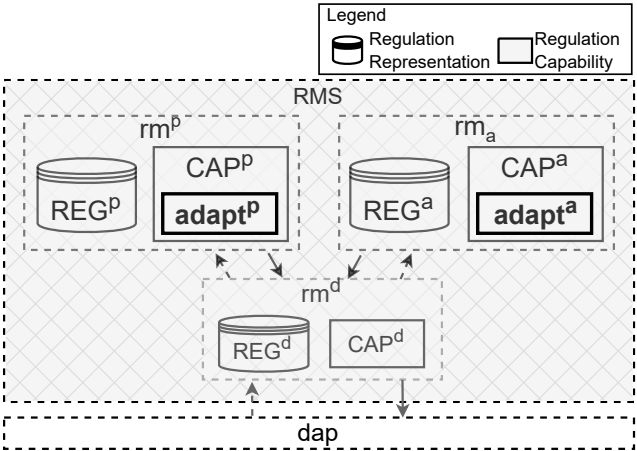
Adapting the Regulation Process and Regulation Architecture

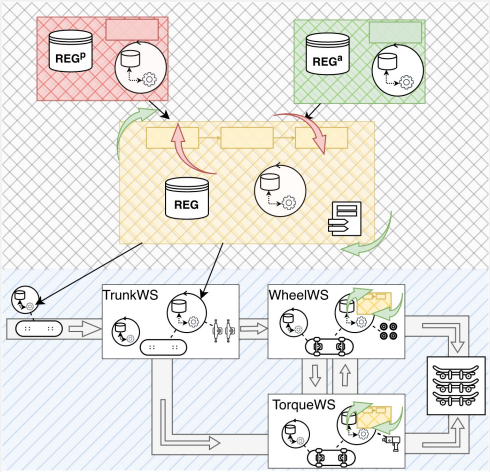


Adapting the Regulation Process and Regulation Architecture

Example

Prototype implementation of the Skateboard case study with the adaptive regulation management system in

- *JaCaMo* MAS framework
- *NPL(s)* and *SAI* normative engines



Next in Line...

Conclusions

RQ1 What are the core elements for the *regulation management* of MAS?
Regulation Management System

- *Regulation Management Element*
  - Regulations Representation
  - Regulation Capabilities

RQ2 What are the core elements for *adapting* the regulation management?
Process and Architecture Regulation Management Elements

- *Process and Architecture Regulations Representation* expressed with
  - Regulation Process and Architecture Representations
  - Regulation Process and Architecture Language Constructs
- *Regulation Process and Architecture Adapt Capabilities*

Thank you for your attention!

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