Managing Conflict Resolution in Norm-Regulated Environments[⋆]

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Abstract. Norms are the obligations, permissions and prohibitions associated with members of a society. Norms provide a useful abstraction with which to specify and regulate the behaviour of self-interested software agents in open, heterogeneous systems. Any realistic account of norms must address their dynamic nature: the norms associated with agents will change as agents act (and interact) – prohibitions can be lifted, obligations can be fulfilled, and permissions can be revoked as a result of agents' actions. These norms may at times *conflict* with one another, that is, an action may be simultaneously prohibited and obliged (or prohibited and permitted). Such conflicts cause norm-compliant agents to experience a paralysis: whatever they do (or not do) will go against a norm. In this paper we present mechanisms to detect and resolve normative conflicts. We achieve more expressiveness, precision and realism in our norms by using *constraints* over first-order variables. The mechanisms to detect and resolve norm conflicts take into account such constraints and are based on first-order unification and constraint satisfaction. We also explain how the mechanisms can be deployed in the management of norms regulating environments for software agents.

1 Introduction

Norms are the obligations, permissions and prohibitions associated with members of a society [3, 18]. Norms provide a useful abstraction to specify and regulate the observable behaviour in electronic environments of self-interested, heterogeneous software agents [2, 6]. Norms also support the establishment of organisational structures for coordinated resource sharing and problem solving [8, 19]. Norm-regulated environments may experience problems when norms associated with their agents are in *conflict* – actions that are forbidden, may, at the same time, also be obliged and/or permitted.

We illustrate such situations with a scenario in which software agents share information. A norm stipulates that "everyone is forbidden to share any information with agent ag_1" (that is, everyone is forbidden to $\mathit{share}(\mathit{Info}, ag_1)$). However,

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as agents interact, a new norm stipulates that "everyone is obliged to share a particular piece of information info_1 with all other agents" (that is, everyone is obliged to $\mathit{share}(\mathit{info}_1, X)$)[1]. These two norms are in conflict regarding action *share*/2 and some of its possible values. Normative conflicts "paralyse" norm-compliant software agents because whatever they do (or refrain from doing) goes against a norm.

In this paper, we propose a means to automatically detect and resolve norm conflicts. We make use of first-order unification [7] to find out if and how norms overlap in their *scope of influence* [15]. If such a conflict is detected, a resolution can be found by proposing a *curtailment* of the conflicting norms. We curtail norms by adding constraints, thus limiting their scope of influence. For example, if we add the constraint $\mathit{Info} \neq \mathit{info}_1$ to the prohibition above, we curtail this norm excluding info_1 from its scope of influence – the norm becomes "everyone is forbidden to share any information, excluding info_1, with ag_1". The scope of influence of the prohibition becomes restricted and does not overlap with the influence of the obligation. Alternatively, if we add the constraint $X \neq ag_1$ to the obligation above, we curtail its scope of influence to exclude a value, thus avoiding the conflict with the prohibition.

In next Section we present our approach to norm-governed agency. In Section 3 we define norm conflicts and how to resolve them. Section 4 presents algorithms for the management of norm-regulated environments, that is, the adoption and removal of norms. In Section 5 we explain a simple mechanism endowing agents with norm-awareness. Section 6 explores indirect conflicts arising from relationships among actions. In Section 7 we survey related work. In Section 8 we draw conclusions and give directions for future work.

2 Norm-Governed Agency

Our model of norm-governed agency assumes that agents take on roles within a society or organisation and that these roles have norms associated with them. Roles, as used in, *e.g.*, [20], help us abstract from individual agents, defining a pattern of behaviour to which any agent that adopts a role ought to conform. We shall make use of two finite, non-empty sets, $\mathit{Agents} = \{a_1, \ldots, a_n\}$ and $\mathit{Roles} = \{r_1, \ldots, r_m\}$, representing, respectively, the sets of agent identifiers and role labels. Central to our model is the concept of actions performed by agents:

Definition 1. *$\langle a : r, \bar{\varphi}, t\rangle$ represents a specific action $\bar{\varphi}$ (a ground first-order atomic formula), performed by $a \in \mathit{Agents}$ adopting $r \in \mathit{Roles}$ at time $t \in \mathbb{N}$.*

Although agents are regarded as performing their actions in a distributed fashion (thus contributing to the overall enactment of the system), we propose a global account for all actions performed. It is important to record the authorship of actions and the time when they occur. The set Ξ stores such tuples recording

[1] Info, X are variables and ag_1, info_1 are constants identifying a particular agent and a particular piece of information, respectively.

actions of agents and represents a *trace* or a history of the enactment of a society of agents from a global point of view:

Definition 2. *A global enactment state Ξ is a finite, possibly empty, set of tuples $\langle a\!:\!r, \bar{\varphi}, t\rangle$.*

A global enactment state Ξ can be "sliced" into many partial states $\Xi_a = \{\langle a\!:\!r, \bar{\varphi}, t\rangle \in \Xi \,|\, a \in \mathit{Agents}\}$ containing all actions of a specific agent a. Similarly, we could have partial states $\Xi_r = \{\langle a : r, \bar{\varphi}, t\rangle \in \Xi \,|\, r \in \mathit{Roles}\}$, representing the global state Ξ "sliced" across the various roles. We make use of a global enactment state to simplify our exposition; however, a fully distributed (and thus more scalable) account of enactment states can be achieved by slicing them as above and managing them in a distributed fashion.

2.1 Norm Specification

We extend the notion of a norm as presented in [26]. We adopt the notation of [20] for specifying norms, complementing it with *constraints* [14]. Constraints are used to *refine* the influence of norms on specific actions. A syntax for constraints is introduced as follows:

Definition 3. *Constraints, represented as γ, are any construct of the form $\tau \lhd \tau'$, where τ, τ' are first-order terms (that is, a variable, a constant or a function applied to terms) and $\lhd \in \{=, \neq, >, \geq, <, \leq\}$.*

We shall make use of numbers and arithmetic functions to build terms τ. Arithmetic functions may appear infix, following their usual conventions[2]. Some sample constraints are $X < 120$ and $X < (Y + Z)$. Norms are thus defined:

Definition 4. *A norm ω is a tuple $\langle \nu, t_d, t_a, t_e\rangle$, where ν is any construct of the form $\mathsf{O}_{\tau_1:\tau_2}\varphi \wedge \bigwedge_{i=0}^{n}\gamma_i$ (an obligation), $\mathsf{P}_{\tau_1:\tau_2}\varphi \wedge \bigwedge_{i=0}^{n}\gamma_i$ (a permission) or $\mathsf{F}_{\tau_1:\tau_2}\varphi \wedge \bigwedge_{i=0}^{n}\gamma_i$ (a prohibition), where τ_1, τ_2 are terms, φ is a first-order atomic formula and γ_i, $0 \leq i \leq n$, are constraints. The components $t_d, t_a, t_e \in I\!N$ are, respectively, the time when ν was declared (introduced), when ν becomes active and when ν expires, $t_d \leq t_a \leq t_e$.*

Term τ_1 identifies the agent(s) to which the norm is applicable and τ_2 is the role of such agent(s). $\mathsf{O}_{\tau_1:\tau_2}\varphi \wedge \bigwedge_{i=0}^{n}\gamma_i$ thus represents an obligation on agent τ_1 taking up role τ_2 to bring about φ, subject to constraints γ_i, $0 \leq i \leq n$. The γ_i's express constraints on those variables occurring in φ.

In the definition above we only cater for conjunctions of constraints. If disjunctions are required then a norm must be established for each disjunct. For instance, if we required the norm $\mathsf{P}_{A:R}\mathit{move}(A) \wedge A < 10 \vee A = 15$ then we must break it into two norms $\mathsf{P}_{A:R}\mathit{move}(A) \wedge A < 10$ and $\mathsf{P}_{A:R}\mathit{move}(A) \wedge A = 15$. We assume an implicit universal quantification over variables in ν. For instance, $\mathsf{P}_{A:R}p(X, b, c)$ stands for $\forall A \in \mathit{Agents}.\forall R \in \mathit{Roles}.\forall X.\mathsf{P}_{A:R}p(X, b, c)$.

[2] We adopt Prolog's convention [1] using strings starting with a capital letter to represent variables and strings starting with a small letter to represent constants.

We propose to formally represent the normative positions of all agents taking part in a virtual society, from a global perspective. By "normative position" we mean the "social burden" associated with individuals [12], that is, their obligations, permissions and prohibitions:

Definition 5. *A global normative state Ω is a finite and possibly empty set of tuples $\omega = \langle \nu, t_d, t_a, t_e \rangle$.*

A global normative state, expressed by Ω, complements the enactment state of a virtual society, expressed by Ξ, with information on the normative positions of individual agents. The management (*i.e.*, creation and updating) of global normative states is an interesting area of research. A practical approach is that of [11]: rules depict how norms should be inserted and removed as a result of agents' actions. A sample rule is

$$\langle Ag_1 : seller, sold(Ag_2, Good, Price), T\rangle \rightsquigarrow \oplus\langle \mathsf{O}_{Ag_2:buyer} pay(Ag_1, Price), (T+1), (T+1), (T+5)\rangle$$

representing that if an agent Ag_1 acting as a seller agrees to selling to Ag_2 some *Good* at cost *Price* then we introduce (denoted by the "$\oplus$" operator) an obligation on Ag_2 acting as a buyer, to pay Ag_1 the agreed *Price* within 5 "ticks" of a global clock. Similarly to Ξ, we use a single normative state Ω to simplify our exposition; however, we can also slice Ω into various sub-sets and manage them in a distributed fashion as explored in [9].

3 Norm Conflicts

We provide definitions for norm conflicts, enabling their detection and resolution. Constraints confer more expressiveness and precision on norms, but the mechanisms for detection and resolution must factor them in. We use first-order unification [7] and constraint satisfaction [14] as the building blocks of our mechanisms. Unification allows us *i)* to detect whether norms are in conflict and *ii)* to detect the set of actions that are under the influence of a norm. Initially, we define substitutions:

Definition 6. *A substitution σ is a finite and possibly empty set of pairs x/τ, where x is a variable and τ is a term.*

We define the application of a substitution in accordance with [7] . In addition, we describe, how substitutions are applied to norms (X stands for O, P or F):

1. $c \cdot \sigma = c$ for a constant c.
2. $x \cdot \sigma = \tau \cdot \sigma$ if $x/\tau \in \sigma$; otherwise $x \cdot \sigma = x$.
3. $p^n(\tau_0, \ldots, \tau_n) \cdot \sigma = p^n(\tau_0 \cdot \sigma, \ldots, \tau_n \cdot \sigma)$.
4. $(\mathsf{X}_{\tau_1:\tau_2}\varphi \wedge \bigwedge_{i=0}^{n} \gamma_i) \cdot \sigma = (\mathsf{X}_{(\tau_1\cdot\sigma):(\tau_2\cdot\sigma)}\varphi \cdot \sigma) \wedge \bigwedge_{i=0}^{n}(\gamma_i \cdot \sigma)$.
5. $\langle \nu, t_d, t_a, t_e\rangle \cdot \sigma = \langle (\nu \cdot \sigma), t_d, t_a, t_e\rangle$

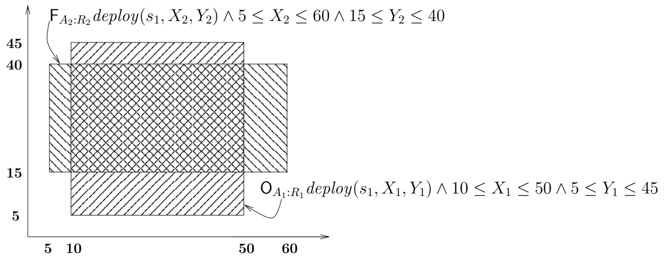
A substitution σ is a *unifier* of two terms τ_1, τ_2, if $\tau_1 \cdot \sigma = \tau.\sigma$. Unification is a fundamental problem in automated theorem proving and many algorithms have been proposed [7]; recent work offers means to obtain unifiers efficiently. We shall use unification in the following way:

Definition 7. *unify*(τ_1, τ_2, σ) *holds iff* $\tau_1 \cdot \sigma = \tau_2 \cdot \sigma$*, for some* σ*. unify*$(p^n(\tau_0, \ldots, \tau_n), p^n(\tau'_0, \ldots, \tau'_n), \sigma)$ *holds iff unify*$(\tau_i, \tau'_i, \sigma), 0 \leq i \leq n$.

The *unify* relationship checks if a substitution σ is indeed a unifier for τ_1, τ_2, but it can also be used to find σ. We assume that *unify* is a suitable implementation of a unification algorithm which *i)* always terminates (possibly failing, if a unifier cannot be found); *ii)* is correct; and *iii)* has a linear computational complexity.

3.1 Conflict Detection

Conflict detection consists of checking if the variables of a prohibition and those of a permission/obligation have overlapping values. The values of the arguments of a norm specify its scope of influence, that is, which agent/role the norm concerns, and which values of the action it addresses. In Fig. 1 we show two



$\mathsf{F}_{A_2:R_2} deploy(s_1, X_2, Y_2) \wedge 5 \leq X_2 \leq 60 \wedge 15 \leq Y_2 \leq 40$
$\mathsf{O}_{A_1:R_1} deploy(s_1, X_1, Y_1) \wedge 10 \leq X_1 \leq 50 \wedge 5 \leq Y_1 \leq 45$
45
40
15
5
5
10
50
60

Fig. 1. Conflict Detection: Overlap in Scopes of Influence

norms over action *deploy*(S, X, Y), establishing that sensor S is to be deployed on grid position (X, Y). The norms are $\mathsf{O}_{A_1:R_1} deploy(s_1, X_1, Y_1) \wedge 10 \leq X_1 \leq 50 \wedge 5 \leq Y_1 \leq 45$ and $\mathsf{F}_{A_2:R_2} deploy(s_1, X_2, Y_2) \wedge 5 \leq X_2 \leq 60 \wedge 15 \leq Y_2 \leq 40$, their scopes shown as rectangles filled with different patterns. The overlap of their scopes is the rectangle in which both patterns appear together. Norm conflict is formally defined as follows:

Definition 8. *Norms* $\omega, \omega' \in \Omega$ *are in conflict under substitution* σ*, denoted as* **conflict**$(\omega, \omega', \sigma)$*, iff the following conditions hold:*

1. $\omega = \langle (\mathsf{F}_{\tau_1:\tau_2} \varphi \wedge \bigwedge_{i=0}^{n} \gamma_i), t_d, t_a, t_e \rangle$, $\omega' = \langle (\mathsf{O}'_{\tau'_1:\tau'_2} \varphi' \wedge \bigwedge_{i=0}^{n} \gamma'_i), t'_d, t'_a, t'_e \rangle$,
2. *unify*$(\langle \tau_1, \tau_2, \varphi \rangle, \langle \tau'_1, \tau'_2, \varphi' \rangle, \sigma)$, *satisfy*$(\bigwedge_{i=0}^{n} \gamma_i \wedge (\bigwedge_{i=0}^{m} \gamma'_i \cdot \sigma))$
3. *overlap*(t_a, t_e, t'_a, t'_e).

That is, a conflict occurs if *i)* a substitution σ can be found that unifies the variables of two norms[3], and *ii)* the conjunction $\bigwedge_{i=0}^{n} \gamma_i \wedge (\bigwedge_{i=0}^{m} \gamma'_i) \cdot \sigma)$ of constraints from both norms can be satisfied[4] (taking σ under consideration), and

[3] A similar definition is required to address the case of conflict between a prohibition and a permission – the first condition should be changed to $\omega' = \langle (\mathsf{P}'_{\tau'_1:\tau'_2} \varphi' \wedge \bigwedge_{i=0}^{n} \gamma'_i), t'_d, t'_a, t'_e \rangle$. The rest of the definition remains the same.

[4] We assume an implementation of the *satisfy* relationship based on "off-the-shelf" constraint satisfaction libraries such as those provided by SICStus Prolog [25] and it holds if the conjunction of constraints is satisfiable.

iii) the activation period of the norms overlap. The *overlap* relationship holds if *i)* $t_a \leq t'_a \leq t_e$; or *ii)* $t'_a \leq t_a \leq t'_e$.

For instance, $\mathsf{P}_{A:R}p(c, X) \wedge X > 50$ and $\mathsf{F}_{a:b}p(Y, Z) \wedge Z < 100$ are in conflict. We can obtain a substitution $\sigma = \{A/a, R/b, Y/c, X/Z\}$ which shows how they overlap. Being able to construct such a unifier is a first indication that there may be a conflict or *overlap* of influence between both norms regarding the defined action. The constraints on the norms may restrict the overlap and, therefore, leave actions under certain variable bindings free of conflict. We, therefore, have to investigate the constraints of both norms in order to see if an overlap of the values indeed occurs. In our example, the permission has a constraint $X > 50$ and the prohibition has $Z < 100$. By using the substitution X/Z, we see that $50 < X < 100$ and $50 < Z < 100$ represent ranges of values for variables X and Z where a conflict will occur.

For convenience (and without any loss of generality) we assume that our norms are in a special format: any non-variable term τ occurring in ω is replaced by a fresh variable X (not occurring anywhere in ω) and a constraint $X = \tau$ is added to ω. This transformation can be easily automated by scanning ω from left to right, collecting all non-variable terms $\{\tau_1, \ldots, \tau_n\}$; then we add $\wedge_{i=1}^{n} X_i = \tau_i$ to ν. For example, norm $\mathsf{P}_{A:R}p(c, X) \wedge X > 50$ is transformed into $\mathsf{P}_{A:R}p(C, X) \wedge X > 50 \wedge C = c$.

3.2 Conflict Resolution

We propose to resolve norm conflicts by manipulating the constraints on their variables, thus removing any overlap in their values. In Fig. 2 we show the norms of Fig. 1 without the intersection between their scopes of influence –

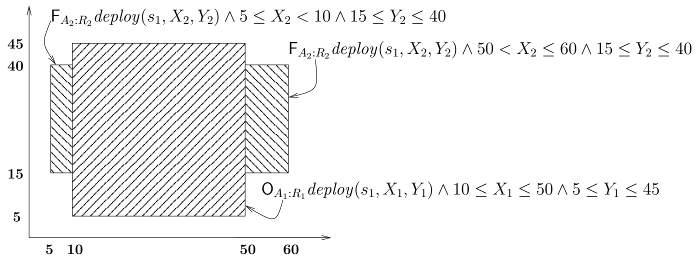

$\mathsf{F}_{A_2:R_2}deploy(s_1, X_2, Y_2) \wedge 5 \leq X_2 < 10 \wedge 15 \leq Y_2 \leq 40$
$\mathsf{F}_{A_2:R_2}deploy(s_1, X_2, Y_2) \wedge 50 < X_2 \leq 60 \wedge 15 \leq Y_2 \leq 40$
$\mathsf{O}_{A_1:R_1}deploy(s_1, X_1, Y_1) \wedge 10 \leq X_1 \leq 50 \wedge 5 \leq Y_1 \leq 45$
45
40
15
5
5
10
50
60

Fig. 2. Conflict Resolution: Curtailment of Scopes of Influence

the prohibition has been *curtailed*, its scope being reduced to avoid the values that the obligation addresses. Specific constraints are added to the prohibition in order to perform this curtailment; these additional constraints are derived from the obligation, as we explain below. In our example above, we obtain two prohibitions, $\mathsf{F}_{A_2:R_2}deploy(s_1, X_2, Y_2) \wedge 5 \leq X_2 < 10 \wedge 15 \leq Y_2 \leq 40$ and $\mathsf{F}_{A_2:R_2}deploy(s_1, X_2, Y_2) \wedge 50 < X_2 \leq 60 \wedge 15 \leq Y_2 \leq 40$.

We formally define below how the curtailment of norms takes place. It is important to notice that the curtailment of a norm creates a new (possibly empty) set of curtailed norms:

Definition 9. *Relationship* **curtail**$(\omega, \omega', \Omega)$*, where* $\omega = \langle \mathsf{X}_{\tau_1:\tau_2}\varphi \wedge \bigwedge_{i=0}^{n} \gamma_i, t_d, t_a, t_e\rangle$ *and* $\omega' = \langle \mathsf{X}'_{\tau'_1:\tau'_2}\varphi' \wedge \bigwedge_{j=0}^{m} \gamma'_j, t'_d, t'_a, t'_e\rangle$ *(*X *and* X' *being either* O, F *or* P*) holds iff* Ω *is a possibly empty and finite set of norms obtained by curtailing* ω *with respect to* ω'*. The following cases arise:*

1. *If* **conflict**$(\omega, \omega', \sigma)$ *does not hold then* $\Omega = \{\omega\}$*, that is, the curtailment of a non-conflicting norm* ω *is* ω *itself.*
2. *If* **conflict**$(\omega, \omega', \sigma)$ *holds, then* $\Omega = \{\omega_0^c, \ldots, \omega_m^c\}$*, where* $\omega_j^c = \langle \mathsf{X}_{\tau_1:\tau_2}\varphi \wedge \bigwedge_{i=0}^{n} \gamma_i \wedge (\neg\gamma'_j \cdot \sigma), t_d, t_a, t_e\rangle$*,* $0 \leq j \leq m$*.*

In order to curtail ω, thus avoiding any overlapping of values its variables may have with those variables of ω', we must "merge" the negated constraints of ω' with those of ω. Additionally, in order to ensure the appropriate correspondence of variables between ω and ω' is captured, we must apply the substitution σ obtained via **conflict**$(\omega, \omega', \sigma)$ on the merged negated constraints.

By combining the constraints of $\nu = \mathsf{X}_{\tau_1:\tau_2}\varphi \wedge \bigwedge_{i=0}^{n} \gamma_i$ and $\nu' = \mathsf{X}'_{\tau'_1:\tau'_2}\varphi' \wedge \bigwedge_{j=0}^{m} \gamma'_j$, we obtain the curtailed norm $\nu^c = \mathsf{X}_{\tau_1:\tau_2}\varphi \wedge \bigwedge_{i=0}^{n} \gamma_i \wedge \neg(\bigwedge_{j=0}^{m} \gamma'_j \cdot \sigma)$. The following equivalences hold:

$$\mathsf{X}_{\tau_1:\tau_2}\varphi \wedge \bigwedge_{i=0}^{n} \gamma_i \wedge \neg(\bigwedge_{j=0}^{m} \gamma'_j \cdot \sigma) \equiv \mathsf{X}_{\tau_1:\tau_2}\varphi \wedge \bigwedge_{i=0}^{n} \gamma_i \wedge (\bigvee_{j=0}^{m} \neg\gamma'_j \cdot \sigma)$$

That is, $\bigvee_{j=0}^{m}(\mathsf{X}_{\tau_1:\tau_2}\varphi \wedge \bigwedge_{i=0}^{n} \gamma_i \wedge \neg(\gamma'_j \cdot \sigma))$. This shows that each constraint on ν' leads to a possible solution for the resolution of a conflict and a possible curtailment of ν. The curtailment thus produces a set of curtailed norms $\nu_j^c = \mathsf{X}_{\tau_1:\tau_2}p(t_1, \ldots, t_n) \wedge \bigwedge_{i=0}^{n} \gamma_i \wedge \neg\gamma'_j \cdot \sigma, 0 \leq j \leq m$.

Although each of the $\nu_j^c, 0 \leq j \leq m$ represents a solution to the norm conflict, we advocate that *all* of them have to be added to Ω in order to replace the curtailed norm. This would allow a preservation of as much of the original scope of the curtailed norm as possible.

As an illustrative example, let us suppose $\Omega = \{\langle \mathsf{F}_{A:R}p(C, X) \wedge C = c \wedge X > 50, t_d, t_a, t_e\rangle\}$. If we try to introduce a new norm $\omega' = \langle \mathsf{P}_{B:S}p(Y, Z) \wedge B = a \wedge S = r \wedge Z > 100, t'_d, t'_a, t'_e\rangle$ to Ω, then we detect a conflict. This conflict can be resolved by curtailing one of the two conflicting norms. The constraints in ω' are used to create such a curtailment. The new permission ω' contains the following constraints: $B = a$, $S = r$ and $Z > 100$. Using σ, we construct copies of ω, but adding $\neg\gamma'_i \cdot \sigma$ to them. In our example the constraint $Z > 100$ becomes $\neg(Z > 100) \cdot \sigma$, that is, $X \leq 100$. With the three constraints contained in ω', three options for curtailing ω can be constructed. A new Ω' is constructed, containing *all* the options for curtailment:

$$\Omega' = \left\{ \begin{array}{l} \langle \mathsf{P}_{B:S}p(Y, Z) \wedge B = a \wedge S = r \wedge Z > 100, t'_d, t'_a, t'_e\rangle \\ \langle \mathsf{F}_{A:R}p(C, X) \wedge C = c \wedge X > 50 \ \wedge A \neq a, t_d, t_a, t_e\rangle \\ \langle \mathsf{F}_{A:R}p(C, X) \wedge C = c \wedge X > 50 \ \wedge R \neq r, t_d, t_a, t_e\rangle \\ \langle \mathsf{F}_{A:R}p(C, X) \wedge C = c \wedge X > 50 \ \wedge X \leq 100, t_d, t_a, t_e\rangle \end{array} \right\}$$

For each $\neg\gamma'_i \cdot \sigma$ ($A \neq a$, $R \neq r$ and $X \leq 100$ in our example), the original prohibition is extended with one of these constraints and added as a new, more restricted prohibition to Ω'. Each of these options represents a part of the scope of influence regarding actions of the original prohibition ω, restricted in such a way that a conflict with the permission is avoided. In order to allow a check whether any other action that was prohibited by ω is prohibited or not, it is necessary to make all three prohibitions available in Ω'. If there are other conflicts, additional curtailments may be necessary.

3.3 An Implementation of Norm Curtailment

We show in Figure 3 a prototypical implementation of the curtailment process as a logic program. We show our logic program with numbered lines to enable the easy referencing of its constructs. Lines 1–7 define **curtail**, and lines 8–14 define

```
 1 $\mathbf{curtail}(\omega, \omega', \Omega) \leftarrow$
 2     $\omega = \langle \mathsf{X}_{\tau_1:\tau_2} \varphi \wedge \bigwedge_{i=0}^{n} \gamma_i, t_d, t_a, t_e \rangle \wedge$
 3     $\omega' = \langle \mathsf{X}'_{\tau'_1:\tau'_2} \varphi' \wedge \bigwedge_{j=0}^{m} \gamma'_j, t'_d, t'_a, t'_e \rangle \wedge$
 4     $\mathbf{conflict}(\omega, \omega', \sigma) \wedge$
 5     $merge([(\neg\gamma'_0 \cdot \sigma), \ldots, (\neg\gamma'_m \cdot \sigma)], (\bigwedge_{i=0}^{n} \gamma_i), \widehat{\Gamma}) \wedge$
 6     $setof(\langle \mathsf{X}_{\tau_1:\tau_2} \varphi \wedge \Gamma, t_d, t_a, t_e \rangle, member(\Gamma, \widehat{\Gamma}), \Omega)$
 7 $\mathbf{curtail}(\omega, \omega', \{\omega\})$

 8 $merge([], \_, [])$
 9 $merge([(\neg\gamma' \cdot \sigma)|Gs], (\bigwedge_{i=0}^{n} \gamma_i), [\Gamma|\widehat{\Gamma}]) \leftarrow$
10     $satisfy((\bigwedge_{i=0}^{n} \gamma_i) \wedge (\neg\gamma' \cdot \sigma)) \wedge$
11     $\Gamma = (\bigwedge_{i=0}^{n} \gamma_i) \wedge (\neg\gamma' \cdot \sigma) \wedge$
12     $merge(Gs, (\bigwedge_{i=0}^{n} \gamma_i), \widehat{\Gamma})$
13 $merge([\_|Gs], (\bigwedge_{i=0}^{n} \gamma_i), \widehat{\Gamma}) \leftarrow$
14     $merge(Gs, (\bigwedge_{i=0}^{n} \gamma_i), \widehat{\Gamma})$
```

Fig. 3. Implementation of **curtail** as a Logic Program

an auxiliary predicate *merge*/3. Lines 1–6 depict the case when the norms are in conflict: the test in line 4 ensures this. Line 5 invokes the auxiliary predicate *merge*/3 which, as the name suggests, merges the conjunction of γ_i's with the negated constraints γ'_j's. Line 6 assembles Ω by collecting the members Γ of the list $\widehat{\Gamma}$ and using them to create curtailed versions of ω. The elements of the list $\widehat{\Gamma}$ assembled via *merge*/3 are of the form $(\bigwedge_{i=0}^{n} \gamma_i) \wedge (\neg\gamma'_j \cdot \sigma)$ – additionally, in our implementation we check if each element is satisfiable[5] (line 10). The rationale for this is that there is no point in creating a norm which will never be applicable as its constraints cannot be satisfied, so these are discarded during their preparation.

3.4 Curtailment Policies

Rather than assuming that a specific deontic modality is always curtailed[6], we propose to explicitly use *policies* determining, given a pair of norms, which one is to be curtailed. Such policies confer more flexibility on our curtailment mechanism, allowing for a fine-grained control over how norms should be handled:

[5] We have made use of SICStus Prolog [25] constraint satisfaction libraries [13].

[6] In [26], for instance, prohibitions are always curtailed. This ensures the choices on the agents' behaviour are kept as open as possible.

Definition 10. *A policy π is a tuple $\langle \omega, \omega', (\bigwedge_{i=0}^{n} \gamma_i)\rangle$ establishing that ω should be curtailed (and ω' should be preserved), if $(\bigwedge_{i=0}^{n} \gamma_i)$ hold.*

A sample policy is $\langle\langle \mathsf{F}_{A:R} p(X, Y), T_d, T_a, T_e\rangle, \langle \mathsf{P}_{A:R} p(X, Y), T'_d, T'_a, T'_e\rangle, (T_d < T'_d)\rangle$. It expresses that any prohibition held by any agent that corresponds to the pattern $\mathsf{F}_{A:R} p(X, Y)$ has to be curtailed, if the additional constraint, which expresses that the prohibition's time of declaration T_d precedes that of the permission's T'_d, holds. Adding constraints to policies allows us a fine-grained control of conflict resolution, capturing classic forms of deontic conflict resolution – the constraint in the example establishes a precedence relationship between the two norms known as *lex posterior* (see Section 7 for more details). We shall represent a set of such policies as Π.

4 Management of Normative States

In this section we explain how our approach to conflict detection and resolution can be used to manage normative states Ω. We explain how we preserve conflict-freedom when adopting a new norm as well as how norms are removed – when a norm is removed we must guarantee that any curtailment it caused is undone.

4.1 Norm Adoption

The algorithm in Fig. 4 describes how an originally conflict-free (possibly empty) set Ω can be extended in a fashion that resolves any emerging conflicts during

```
algorithm adoptNorm($\omega, \Omega, \Pi, \Omega'$)
input $\omega, \Omega, \Pi$
output $\Omega'$
begin
  $\Omega' := \emptyset$
  if $\Omega = \emptyset$ then
    $\Omega' := \Omega \cup \{\omega\}$
  else
    for each $\omega' \in \Omega$ do
      if conflict($\omega, \omega', \sigma$) then // test for conflict
        if $\langle \omega_\pi, \omega'_\pi, (\bigwedge_{i=0}^{n} \gamma_i)\rangle \in \Pi$ and // test policy
          $unify(\omega, \omega_\pi, \sigma)$ and $unify(\omega', \omega'_\pi, \sigma)$ and $satisfy(\bigwedge_{i=0}^{n}(\gamma_i \cdot \sigma))$ then
        begin
          curtail($\omega, \omega', \Omega''$)
          $\Omega' := \Omega \cup \Omega''$
        end
        else
          if $\langle \omega'_\pi, \omega_\pi, (\bigwedge_{i=0}^{n} \gamma_i)\rangle \in \Pi$ and // test policy
            $unify(\omega, \omega_\pi, \sigma)$ and $unify(\omega', \omega'_\pi, \sigma)$ and $satisfy(\bigwedge_{i=0}^{n}(\gamma_i \cdot \sigma))$ then
          begin
            curtail($\omega', \omega, \Omega''$)
            $\Omega' := (\Omega - \{\omega'\}) \cup (\{\omega\} \cup \Omega'')$
          end
end
```

Fig. 4. Norm Adoption Algorithm

norm adoption. With that, a conflict-free Ω is always transformed into a conflict-free Ω' that may contain curtailments. The algorithm makes use of a set Π of policies determining how the curtailment of conflicting norms should be done.

When a norm is curtailed, a set of new norms replace the original norm. This set of norms is collected into Ω'' by $\mathbf{curtail}(\omega, \omega', \Omega'')$. A curtailment takes place if there is a conflict between ω and ω'. The conflict test creates a unifier σ re-used in the policy test. When checking for a policy that is applicable, the algorithm uses unification to check *(a)* whether ω matches/unifies with ω_π and ω' with ω'_π; and *(b)* whether the policy constraints hold under the given σ. If a previously agreed policy in Π determines that the newly adopted norm ω is to be curtailed in case of a conflict with an existing $\omega' \in \Omega$, then the new set Ω' is created by adding Ω'' (the curtailed norms) to Ω. If the policy determines a curtailment of an existing $\omega' \in \Omega$ when a conflict arises with the new norm ω, then a new set Ω' is formed by *a)* removing ω' from Ω and *b)* adding ω and the set Ω'' to Ω.

4.2 Norm Removal

As well as adding norms to normative states we also need to support their removal. Since the introduction of a norm may have interfered with other norms, resulting in their curtailment, when that norm is removed we must *undo* the curtailments it caused, that is, we must return (or "roll back") to a previous form of the normative state. In order to allow curtailments of norms to be undone, we record the complete *history* of normative states representing the evolution of normative positions of agents:

Definition 11. *$\mathcal{H}$ is a non-empty and finite sequence of tuples $\langle i, \Omega, \omega, \pi \rangle$, where $i \in I\!N$ represents the order of the tuples, Ω is a normative state, ω is a norm and π is a policy.*

We shall denote the empty history as $\langle\ \rangle$. We define the concatenation of sequences as follows: if $\mathcal{H}$ is a sequence and h is a tuple, then $\mathcal{H} \bullet h$ is a new sequence consisting of $\mathcal{H}$ followed by h. Any non-empty sequence $\mathcal{H}$ can be decomposed as $\mathcal{H} = \mathcal{H}' \bullet h \bullet \mathcal{H}''$, $\mathcal{H}'$ and/or $\mathcal{H}''$ possibly empty. The following properties hold for our histories $\mathcal{H}$:

1. $\mathcal{H} = \langle 0, \emptyset, \omega, \pi \rangle \bullet \mathcal{H}'$
2. $\mathcal{H} = \mathcal{H}' \bullet \langle i, \Omega', \omega', \pi' \rangle \bullet \langle i+1, \Omega'', \omega'', \pi'' \rangle \bullet \mathcal{H}''$
3. $\mathit{adoptNorm}(\omega_i, \Omega_i, \{\pi_i\}, \Omega_{i+1})$

The first condition establishes the first element of a history to be an empty Ω. The second condition establishes that the tuples are completely ordered on their first component. The third condition establishes the relationship between any two consecutive tuples in histories: normative state Ω_{i+1} is obtained by adding ω_i to Ω_i adopting policy π_i.

$\mathcal{H}$ is required to allow the retraction of a norm in an ordered fashion, as not only the norm itself has to be removed but also all the curtailments it caused when it was introduced in Ω. $\mathcal{H}$ contains a tuple $\langle i, \Omega, \omega, \pi \rangle$ that indicates the introduction of norm ω and, therefore, provides us with a normative state Ω *before* the introduction of ω. The effect of the introduction of ω can be reversed by using Ω and redoing (performing a kind of "roll forward") all the inclusions of norms according to the sequence represented in $\mathcal{H}$ via *adoptNorm*.

This mechanism is detailed in Figure 5: algorithm *removeNorm* describes how to remove a norm ω given a history $\mathcal{H}$; it outputs a normative state Ω and an updated history $\mathcal{H}'$ and works as follows. Initially, the algorithm checks if ω indeed appears in $\mathcal{H}$ – it does so by matching $\mathcal{H}$ against a pattern of a sequence in which ω appears as part of a tuple (notice that the pattern initialises the new history $\mathcal{H}'$). If there is such a tuple in $\mathcal{H}$, then we initialise Ω as Ω_k,

```
algorithm $removeNorm(\omega, \mathcal{H}, \Omega, \mathcal{H}')$
input $\omega, \mathcal{H}$
output $\Omega, \mathcal{H}'$
begin
  if $\mathcal{H} = \mathcal{H}' \bullet \langle k, \Omega_k, \omega, \pi_k \rangle \bullet \cdots \bullet \langle n, \Omega_n, \omega_n, \pi_n \rangle$ then
  begin
    $\Omega := \Omega_k$
    for $i = k + 1$ to $n$ do
    begin
      adoptNorm$(\omega_i, \Omega, \{\pi_i\}, \Omega')$
      $\mathcal{H}' := \mathcal{H}' \bullet \langle i, \Omega, \omega_i, \pi_i \rangle$
      $\Omega := \Omega'$
    end
  end
  else
  begin
    $\mathcal{H} = \mathcal{H}'' \bullet \langle n, \Omega_n, \omega_n, \pi_n \rangle$
    $\Omega := \Omega_n$, $\mathcal{H}' := \mathcal{H}$
  end
end
```

Fig. 5. Algorithm to Remove Norms

that is, the normative state *before* ω was introduced. Following that, the **for** loop implements a *roll forward*, whereby new normative states (and associated history $\mathcal{H}'$) are computed by introducing the $\omega_i, k+1 \leq i \leq n$, which come after ω in the original history $\mathcal{H}$. If ω does not occur in any of the tuples of $\mathcal{H}$ (this case is catered by the **else** of the **if** construct) then the algorithm uses pattern-matching to decompose the input history $\mathcal{H}$ and obtain its last tuple – this is necessary as this tuple contains the most recent normative state Ω_n which is assigned to Ω; the new history $\mathcal{H}'$ is the same as $\mathcal{H}$.

5 Norm-Aware Agent Societies

With a set Ω that reflects a conflict-free global normative situation, agents can test whether their actions are norm-compliant. In order to check actions for norm-compliance, we again use unification. If an action unifies with a norm, then it is within its scope of influence:

Definition 12. *$\langle a : r, \bar{\varphi}, t \rangle$, is within the scope of influence of $\langle \mathsf{X}_{\tau_1:\tau_2} \varphi \wedge \bigwedge_{i=0}^{n} \gamma_i$, $t_d, t_a, t_e \rangle$ (where X is either O, P or F) iff the following conditions hold:*

1. *unify$(\langle a, r, \bar{\varphi} \rangle, \langle \tau_1, \tau_2, \varphi \rangle, \sigma)$ and satisfy$(\bigwedge_{i=0}^{n} \gamma_i \cdot \sigma)$*
2. *$t_a \leq t \leq t_e$*

This definition can be used to establish a predicate check/2, which holds if its first argument, a candidate action (in the format of the elements of Ξ of Def. 2), is within the influence of a prohibition ω, its second parameter. Figure 6 shows

```
check(Action, ω) ←
    $Action = \langle a : r, \bar{\varphi}, t\rangle \wedge$
    $\omega = \langle(\mathsf{F}_{\tau_1:\tau_2}\varphi \wedge \bigwedge_{i=0}^{n}\gamma_i), t_d, t_a, t_e\rangle \wedge$
    $unify(\langle a, r, \bar{\varphi}\rangle, \langle \tau_1, \tau_2, \varphi\rangle, \sigma) \wedge satisfy(\bigwedge_{i=0}^{n}\gamma_i \cdot \sigma) \wedge t_a \leq t \leq t_e$
```

Fig. 6. Check if Action is within Influence of a Prohibition

the definition of this relationship as a logic program. Similarly to the check of conflicts between norms, it tests *i)* if the agent performing the action and its role unify with the appropriate terms τ_1, τ_2 of ω; *ii)* if the actions $\bar{\varphi}, \varphi$ themselves unify; and *iii)* the conjunction of the constraints of both norms can be satisfied, all under the same unifier σ. Lastly, it checks if the time of the action is within the norm temporal influence.

6 Indirect Conflicts

In our previous discussion, norm conflicts were detected via a direct comparison of atomic formulae representing actions. However, conflicts and inconsistencies may also arise *indirectly* via relationships among actions. For instance, if an agent has associated norms $\mathsf{P}_{A:R}p(X)$ and $\mathsf{F}_{A:R}q(X, X)$ and that the action $p(X)$ amounts to the action $q(X, X)$, then we can rewrite the permission as $\mathsf{P}_{A:R}q(X, X)$ and identify an *indirect* conflict between the two norms. We use a set of *domain axioms* in order to declare such domain-specific relationships between actions:

Definition 13. *The set of domain axioms, denoted as Δ, are a finite and possibly empty set of formulae $\varphi \to (\varphi'_1 \wedge \cdots \wedge \varphi'_n)$ where $\varphi, \varphi'_i, 1 \leq i \leq n$, are atomic first-order formulae.*

In order to address indirect conflicts between norms based on domain-specific relationships of actions, we have to adapt our curtailment mechanism. With the introduction of domain axioms $\varphi \to (\varphi'_1 \wedge \cdots \wedge \varphi'_n)$, the conflict check has to be performed for each of the conjuncts in this relationship. For example, if we have $\Delta = \{(p(X) \to q(X, X) \wedge r(X, Y))\}$ and $\langle \mathsf{P}_{A:R}p(X), t_d, t_a, t_e\rangle$, then actions $q(X, X)$ and $r(X, Y)$ are also permitted. If we also have $\langle \mathsf{F}_{A:R}q(X, X), t_d, t_a, t_e\rangle$ then an indirect conflict occurs. We now revisit Def. 8, extending it to address indirect conflicts:

Definition 14. *An indirect conflict arises between two norms ω, ω' under a set of domain axioms Δ and a substitution σ, denoted as* **conflict**$^*(\Delta, \omega, \omega')$*, iff:*

1. **conflict**$(\omega, \omega', \sigma)$*, or*
2. $\omega = \langle(\mathsf{X}_{\tau_1:\tau_2}\varphi \wedge \bigwedge_{i=0}^{n}\gamma_i), t_d, t_a, t_e\rangle$*, there is an axiom* $(\varphi' \to (\varphi'_1 \wedge \cdots \wedge \varphi'_m)) \in \Delta$ *such that* $unify(\varphi, \varphi', \sigma')$*, and* $\bigvee_{i=1}^{m}$ **conflict**$^*(\Delta, \langle(\mathsf{X}_{\tau_1:\tau_2}\varphi'_i \wedge \bigwedge_{i=0}^{n}\gamma_i), t_d, t_a, t_e\rangle \cdot \sigma', \omega')$,

The above definition recursively follows a chain of indirect conflicts, looking for any two conflicting norms. Case 1 provides the base case of the recursion, checking if norms ω, ω' are in direct conflict. Case 2 addresses the general recursive case: if a norm X (that is, O, P or F) on an action φ unifies with φ' on the left-hand side of a domain axiom $(\varphi \rightarrow (\varphi'_1 \wedge \cdots \wedge \varphi'_m)) \in \mathit{\Delta}$, then we "transfer" the norm from φ to $\varphi'_1, \ldots, \varphi'_m$, thus obtaining $\langle(\mathsf{X}_{\tau_1:\tau_2}\varphi'_i \wedge \bigwedge_{i=0}^{n} \gamma_i), t_d, t_a, t_e\rangle, 1 \leq i \leq m$. If we (recursively) find an indirect conflict between ω' and at least one of these norms, then an indirect conflict arises between the original norms ω, ω'. It is important to notice that the substitution σ' that unifies φ and φ' is factored in the mechanism: we apply it to the new φ'_is in the recursive call(s).

Domain axioms may also accommodate the delegation of actions between agents. Such a delegation transfers norms across the agent community and, with that, conflicts also. We introduce a special logical operator $\varphi \xrightarrow{\tau_1:\tau_2\ \tau'_1:\tau'_2} (\varphi'_1 \wedge \cdots \wedge \varphi'_n)$ to represent that agent τ_1 adopting role τ_2 can transfer any norms on action φ to agent τ'_1 adopting role τ'_2, which should carry out actions $\varphi'_1 \wedge \cdots \wedge \varphi'_n$ instead. We formally capture the meaning of this operator as follows:

3. $\omega = \langle(\mathsf{X}_{\tau_1:\tau_2}\varphi \wedge \bigwedge_{i=0}^{n} \gamma_i), t_d, t_a, t_e\rangle$, *there is a delegation axiom* $(\varphi \xrightarrow{\tau_1:\tau_2\ \tau'_1:\tau'_2} (\varphi'_1 \wedge \cdots \wedge \varphi'_m)) \in \mathit{\Delta}$, *s.t. unify*$(\langle\varphi, \tau_1, \tau_2\rangle, \langle\varphi', \tau'_1, \tau'_2\rangle, \sigma')$, *and* $\bigvee_{i=1}^{m}$ **conflict**$^*(\mathit{\Delta}, \langle(\mathsf{X}_{\tau'_1:\tau'_2}\varphi'_i \wedge \bigwedge_{i=0}^{n} \gamma_i), t_d, t_a, t_e\rangle \cdot \sigma', \omega')$

That is, we obtain a domain axiom and check if its action, role and agent unify with those of ω. The norm will be transferred to the new actions $(\varphi'_1 \wedge \cdots \wedge \varphi'_m)$ but these will be associated with a possibly different agent/role pair $\tau'_1{:}\tau'_2$. The new norms are recursively checked and if at least one of them conflicts with ω', then an indirect conflict arises. Means to detect loops in delegation must be added to the definition above.

7 Related Work

Efforts to keep law systems conflict-free can be traced back to the jurisprudential practice in human society. Inconsistency in law is an important issue and legal theorists use a diverse set of terms such as, for example, *normative inconsistencies/conflicts*, *antinomies*, *discordance*, etc., in order to describe this phenomenon. There are three classic strategies for resolving deontic conflicts by establishing a precedence relationship between norms: *legis posterioris* – the most recent norm takes precedence, *legis superioris* – the norm imposed by the strongest power takes precedence, and *legis specialis* – the most specific norm takes precedence [17].

Early investigations into norm conflicts were outlined in [21], describing three forms of conflict/inconsistency as *total-total*, *total-partial* and *intersection.* These are special cases of the intersection of norms as described in [16] – a permission entailing the prohibition, a prohibition entailing the permission or an overlap of both norms.

In [22, 23], aspects of legal reasoning such as non-monotonic reasoning in law, negation and conflict are discussed. It is pointed out that legal reasoning is often based on *prima facie* incompatible premises, which is due to the defeasibility of legal norms and the dynamics of normative systems, where new norms may contradict older ones (principle of *legis posterioris*), the concurrence of multiple legal sources with normative power distributed among different bodies issuing contradicting norms (principle of *legis superioris*), and semantic indeterminacy. To resolve such conflicts, it is proposed to establish an ordering among norms according to criteria such as hierarchy (*legis superioris*), chronology (*legis posterioris*), speciality (exception to the norm are preferred) or hermeneutics (more plausible interpretations are preferred). The work presented in [16] discusses in part these kinds of strategies, proposing conflict resolution according to the criteria mentioned above.

The work described in [5] analyses different normative conflicts – in spite of its title, the analysis is an informal one. That work differentiates between actions that are simultaneously prohibited and permitted – these are called *deontic inconsistencies* – and actions that are simultaneously prohibited and obliged – these are called *deontic conflicts*. The former is merely an "inconsistency" because a permission may not be acted upon, so no real conflict actually occurs. On the other hand, those situations when an action is simultaneously obliged and prohibited represent conflicts, as both obligations and prohibitions influence behaviours in an incompatible fashion. Our approach to detecting deontic conflict can capture the three forms of conflict/inconsistency of [21], *viz.* total-total, total-partial and intersection, respectively, when the permission entails the prohibition, when the prohibition entails the permission and when they simply overlap. Finally, we notice that the *world knowledge* explained in [5], required to relate actions, can be formally captured by our indirect norm conflicts depicted in Section 6.

The work presented in this paper is an adaptation and extension of [16, 26] and [10], also providing an investigation into deontic modalities for representing normative concepts [4, 24]. In [26], a conflict detection and resolution based on unification is introduced: we build on that research, introducing constraints to the mechanisms proposed in that work.

8 Conclusions, Discussion and Future Work

We have presented mechanisms to detect and resolve conflicts in norm-regulated environment. Such conflicts arise when an action is simultaneously obliged and prohibited/permitted. We represent norms as first-order atomic formulae whose variables can have arbitrary constraints associated – this allows for more expressive norms, with a finer granularity and greater precision. The mechanisms are based on first-order unification and constraint satisfaction, extending the work of [26], and addressing a more expressive class of norms. Our conflict resolution mechanism amounts to manipulating the constraints of norms to avoid overlapping values of variables – this is called the "curtailment" of variables/norms.

A prototypical implementation of the curtailment process is given as a logic program and is used in the management of the normative state of an agent society. We have also introduced an algorithm to manage the adoption of possibly conflicting norms, whereby explicit policies depict how the curtailment between specific norms should take place, as well as an algorithm depicting how norms should be removed, thus undoing the effects of past curtailments.

In this work we only considered norms with universal quantifiers over discrete domains. These assumptions limit the applicability of our solution. Universally quantified permissions capture a common sense of norm: an agent is permitted to perform an action with any value its quantified variables may get (and which satisfy the constraints); the same holds for prohibitions. However, obligations are conventionally existential: an agent is obliged to perform an action once with one of its possible values.

We are currently exploiting our approach in mission-critical scenarios [27], including, for instance, combat and disaster recovery (*e.g.* extreme weather conditions and urban terrorism). Our goal is to describe mission scripts as sets of norms: these will work as contracts that teams of human and software agents can peruse and make sense of. Mission-critical contracts should allow for the delegation of actions and norms, via pre-established relationships between roles: we have been experimenting with special "count as" operators which neatly capture this. Additionally, our mission-critical contracts should allow the representation of plan scripts with the breakdown of composite actions into the simplest atomic actions. Norms associated with composite actions will be distributed across the composite actions, possibly being delegated to different agents and/or roles.

References

1. K. R. Apt. *From Logic Programming to Prolog.* Prentice-Hall, U.K., 1997.
2. A. Artikis, L. Kamara, J. Pitt, and M. Sergot. A Protocol for Resource Sharing in Norm-Governed Ad Hoc Networks. volume 3476 of *LNCS*. Springer-Verlag, 2005.
3. R. Conte and C. Castelfranchi. Understanding the Functions of Norms in Social Groups through Simulation. In N. Gilbert and R. Conte, editors, *Artificial Societies: The Computer Simulation of Social Life*, pages 252–267, London, 1995. UCL Press.
4. F. Dignum. Autonomous Agents with Norms. *A.I. & Law*, 7:69–79, 1999.
5. A. Elhag, J. Breuker, and P. Brouwer. On the Formal Analysis of Normative Conflicts. *Information & Comms. Techn. Law*, 9(3):207–217, Oct. 2000.
6. M. Esteva, J. Padget, and C. Sierra. Formalizing a Language for Institutions and Norms. volume 2333 of *LNAI*. Springer-Verlag, 2001.
7. M. Fitting. *First-Order Logic and Automated Theorem Proving.* Springer-Verlag, New York, U.S.A., 1990.
8. I. Foster, C. Kesselman, and S. Tuecke. The Anatomy of the Grid: Enabling Scalable Virtual Organizations. *Int' J. Supercomputer Applications*, 15(3):209–235, 2001.
9. D. Gaertner, A. García-Camino, P. Noriega, J.-A. Rodríguez-Aguilar, and W. Vasconcelos. Distributed Norm Management in Regulated Multi-agent Systems. In *Procs. 6th Int'l Joint Conf. on Autonomous Agents & Multiagent Systems (AAMAS'07)*, Honolulu, Hawai'i, May 2007.

10. A. García-Camino, P. Noriega, and J.-A. Rodríguez-Aguilar. An Algorithm for Conflict Resolution in Regulated Compound Activities. In *7th Annual Int'l Workshop "Engineering Societies in the Agents World" (ESAW'06)*, Dublin, Ireland, Sept. 2006.
11. A. García-Camino, J.-A. Rodríguez-Aguilar, C. Sierra, and W. Vasconcelos. A Rule-based Approach to Norm-Oriented Programming of Electronic Institutions. *ACM SIGecom Exchanges*, 5(5):33–40, Jan. 2006.
12. A. García-Camino, J.-A. Rodriguez-Aguilar, C. Sierra, and W. W. Vasconcelos. A Distributed Architecture for Norm-Aware Agent Societies. In *DALT 2005*, volume 3904 of *LNAI*. Springer-Verlag, 2005.
13. J. Jaffar and M. J. Maher. Constraint Logic Programming: A Survey. *Journal of Logic Progr.*, 19/20:503–581, 1994.
14. J. Jaffar, M. J. Maher, K. Marriott, and P. J. Stuckey. The Semantics of Constraint Logic Programs. *Journal of Logic Progr.*, 37(1-3):1–46, 1998.
15. M. Kollingbaum. *Norm-governed Practical Reasoning Agents.* PhD thesis, University of Aberdeen, 2005.
16. M. Kollingbaum, T. Norman, A. Preece, and D. Sleeman. Norm Refinement: Informing the Re-negotiation of Contracts. In *Procs. Workshop on Coordination, Organization, Institutions and Norms in Agent Systems (COIN@ECAI'06)*, Riva del Garda, Italy, Aug. 2006.
17. J. A. Leite, J. J. Alferes, and L. M. Pereira. Multi-Dimensional Dynamic Knowledge Representation. volume 2173 of *LNAI*. Springer-Verlag, 2001.
18. F. López y López. *Social Power and Norms: Impact on Agent Behaviour.* PhD thesis, Univ. of Southampton, June 2003.
19. T. Norman, A. Preece, S. Chalmers, N. Jennings, M. Luck, V. Dang, T. Nguyen, V. Deora, J. Shao, W. Gray, and N. Fiddian. Agent-based Formation of Virtual Organisations. *Knowledge Based Systems*, 17:103–111, 2004.
20. O. Pacheco and J. Carmo. A Role Based Model for the Normative Specification of Organized Collective Agency and Agents Interaction. *Autonomous Agents and Multi-Agent Systems*, 6(2):145–184, 2003.
21. A. Ross. *On Law and Justice.* Stevens & Sons, 1958.
22. G. Sartor. The Structure of Norm Conditions and Nonmonotonic Reasoning in Law. In *Procs. 3rd Int'l Conf. on A.I. & Law (ICAIL'91)*, Oxford, England, July 1991.
23. G. Sartor. A Simple Computational Model for Nonmonotonic and Adversarial Legal Reasoning. In *Procs. 4th Int'l Conf. on A.I. & Law (ICAIL'93)*, Amsterdam, The Netherlands, June 1993.
24. M. Sergot. A Computational Theory of Normative Positions. *ACM Trans. Comput. Logic*, 2(4):581–622, 2001.
25. Swedish Institute of Computer Science. *SICStus Prolog*, 2005. `http://www.sics.se/isl/sicstuswww/site/index.html`, viewed on 10 Feb 2005 at 18.16 GMT.
26. W. Vasconcelos, M. Kollingbaum, T. Norman, and A. García-Camino. Resolving Conflict and Inconsistency in Norm-Regulated Virtual Organizations. In *Procs. 6th Int'l Joint Conf. on Autonomous Agents & Multiagent Systems (AAMAS'07)*, Honolulu, Hawai'i, May 2007.
27. S. M. White. Requirements for Distributed Mission-Critical Decision Support Systems. In *Procs 13th Annual IEEE Int'l Symp. & Workshop on Eng. of Computer-Based Systs. (ECBS'06)*, 2006.