*TLP* **13** (4–5): Online Supplement, July 2013. © 2013 [LAURA GIORDANO, ALBERTO MARTELLI, MATTEO SPIOTTA and DANIELE THESEIDER DUPRÉ]

URL: http://dx.doi.org/10.1017/S1471068413000409

# *Business process verification with constraint temporal answer set programming**

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*submitted 10 April 2013; revised 23 June 2013; accepted 5 July 2013*

**Abstract**

The paper provides a framework for the verification of business processes, based on an extension of answer set programming (ASP) with temporal logic and constraints. The framework allows to capture expressive fluent annotations as well as data awareness in a uniform way. It allows for a declarative specification of a business process but also for encoding processes specified in conventional workflow languages. Verification of temporal properties of a business process, including verification of compliance to business rules, is performed by bounded model checking techniques in Answer Set Programming, extended with constraint solving for dealing with conditions on numeric data.

## 1 Introduction

The verification of business process compliance to business rules and regulations has gained a lot of interest in recent years, leading to the development of a process annotation approach (Governatori and Sadiq 2009; Hoffmann *et al.* 2009; Weber *et al.* 2010): information relevant for compliance verification is added, capturing the semantics of atomic tasks execution through preconditions and effects. The treatment of data in process verification has also attracted growing interest, with the definition of *artifact-centric* and *data-centric* process models (Nigam and Caswell 2003; Deutsch *et al.* 2009).

In this paper we combine the two perspectives and propose a framework, based on Answer Set Programming (ASP) (Gelfond 2007), for the specification and verification of business processes, which integrates the treatment of data in business processes with an expressive treatment of annotations, that allows for the specification of conditional effects of atomic tasks as well as for the definition of causal dependencies

* This research has been partially supported by Regione Piemonte, Project ICT4LAW, and by the Compagnia di San Paolo.

https://doi.org/10.1017/S1471068413000409 Published online by Cambridge University Press

among annotations. This semantic specification provides background knowledge common to the process and to the compliance rules to be verified. Following (D'Aprile *et al.* 2010), annotations are specified by an action theory which defines the direct and indirect effects and the preconditions of atomic tasks; effects are fluents representing properties of the world that are affected by the execution of the tasks and are subject to the compliance rules. We adopt a similar approach to capture data properties. Formulas involving conditions on such data may be verified, and to deal with numeric data we rely on constraint solving.

In particular, we combine two extensions of ASP: Temporal ASP in (Giordano *et al.* 2013a), which allows for the specification of temporal action domains, and the Constraint ASP approach in (Gebser *et al.* 2009) where ASP is enriched with constraint solving in a modular way: constraints are labeled as true or false by the ASP solver, and a constraint solver performs propagation on the constraint store possibly detecting inconsistency.

This approach is well suited for a declarative specification of the business process, which has been advocated by many authors in the literature (Singh 2000; van der Aalst and Pesic 2006; Montali *et al.* 2010), but it also allows for encoding processes specified in current business process management systems. In the paper we concentrate on the latter option, showing how a model in a subset of the YAWL language (van der Aalst and ter Hofstede 2005), and its annotations, can be mapped into the framework.

Verification of business process properties, including compliance to business rules, is done through Bounded Model Checking (Biere *et al.* 2003) and exploits the approach in (Giordano *et al.* 2013a) for DLTL bounded model checking in ASP, which extends Bounded LTL Model Checking with Stable Models in (Heljanko and Niemelä 2003).

## 2 Example

As a motivating example, let us consider a variation of the order-production-delivery business process model in (Knuplesch *et al.* 2010) whose model in YAWL is in Figure 1. It involves *net variables* (i.e., global variables) like the piece number of an order, an integer *pn*; the model provides information on which atomic task has the variable as output ("Process Order", in the example) and XOR splits include conditions on such a variable (Appendix A illustrates the basic control flow elements used). The process in Figure 1 should be checked to be compliant with respect to business rules such as:

(a) After confirming an order, goods have to be shipped eventually.
(b) An order shall either be confirmed or declined.
(c) Orders with a piece number beyond 50000 shall be approved before they are confirmed.
(d) For orders of a non-premium customer with a piece number beyond 80000 a solvency check is necessary before assessing the order.

https://doi.org/10.1017/S1471068413000409 Published online by Cambridge University Press

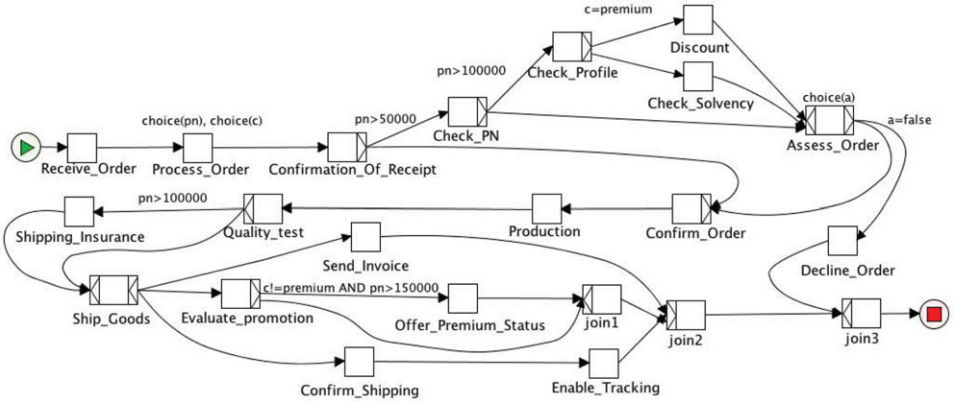



Fig. 1. (Colour online) Example business process in YAWL.

Such rules hold, except for the last one: for orders of a non-premium customer with a piece number between 80000 and 100000, flow goes from "Check PN" to "Assess Order" without executing "Check Solvency".

Rule verification requires establishing a link between atomic tasks in the business process and domain properties in rules, especially in case different tasks have effect on the same property, or tasks have effects on properties that are related to the ones occurring in the rules. This issue motivates the idea of a semantic *annotation* of the atomic tasks, in terms of their effects and preconditions (Governatori and Sadiq 2009). As background knowledge, in (Hoffmann *et al.* 2009; Weber *et al.* 2010) process annotation includes a domain ontology, namely a theory in clausal form. Our approach to process annotation builds on work in reasoning about actions and change (Reiter 2001) and, specifically, is based on the temporal action language in (Giordano *et al.* 2013a) enriched with constraint atoms (Gebser *et al.* 2009) to express conditions on process variables both in the process model and in rules to be verified, as detailed in the next section.

## 3 A constraint temporal action language

In this section we recall the temporal logic DLTL (Henriksen and Thiagarajan 1999) and the temporal ASP language in (Giordano *et al.* 2013a), extending them with constraints in the line of (Gebser *et al.* 2009).

DLTL extends LTL with temporal operators enriched with program expressions; the next state modality can be indexed by actions, and the until operator $\mathcal{U}^{\pi}$ can be indexed by a program $\pi$ which, as in PDL (Harel 1984), can be a regular expression built from atomic actions using sequence (;), nondeterministic choice (+) and finite iteration (*).

We further extend DLTL allowing, as a base case of formulae, constraints in a language $\mathscr{C}$. Such constraints involve a set $\mathscr{V}$ of variables, and suitable function and relation symbols, but we will refer to them as *constraint atoms* since, as in (Gebser *et al.* 2009), they will be treated as atoms at the answer set level, and at the temporal logic level. Similarly to (Gebser *et al.* 2009), a function $\gamma : \mathscr{C} \rightarrow C$ maps

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constraint atoms to constraints in the sense of (Dechter 2003): each $x \in \mathscr{V}$ has a domain $dom(x)$ (which in this paper we assume to be finite), and a constraint $c \in C$ is a pair $(S, R)$ where $R$ is a k-ary relation on a vector $S$ of variables in $\mathscr{V}$: for $S = (x_1, \ldots, x_k)$, $R \subseteq dom(x_1) \times \ldots \times dom(x_k)$. For a constraint $c = (S, R)$, let $S(c) = S$ and $R(c) = R$. Given an assignment $A : \mathscr{V} \rightarrow \bigcup_{x \in \mathscr{V}} dom(x)$, where $A(x) \in dom(x)$, for a constraint $(S, R)$, with $S = (x_1, \ldots, x_k)$, let $A(S) = (A(x_1), \ldots, A(x_k))$. The mapping $\gamma$ provides a predefined interpretation of the constraint language, i.e., it defines whether an assignment $A$ satisfies a $g \in \mathscr{C}$, which we write $A \models_\gamma g$ and holds iff $A(S(\gamma(g))) \in R(\gamma(g))$. E.g., for the constraint language with variables $\{x, y, z, \ldots\}$, all with the integer domain, and the usual arithmetic operators and relations, for which $\gamma$ provides the usual interpretation, for the assignment $A((x, y, z)) = (10, 20, 15)$ we have that $A \models_\gamma x + y > z$.

Let $\Sigma = \{a_1, \ldots, a_n\}$ be a finite non-empty alphabet of actions. Let $\Sigma^*$ and $\Sigma^\omega$ be the set of finite and infinite words on $\Sigma$. Let $\Sigma^\infty = \Sigma^* \cup \Sigma^\omega$. We denote by $\sigma, \sigma'$ the words over $\Sigma^\omega$ and by $\tau, \tau'$ the words over $\Sigma^*$. Moreover, we denote by $\leqslant$ the usual prefix ordering over $\Sigma^*$, namely, $\tau \leqslant \tau'$ iff $\exists \tau''$ such that $\tau\tau'' = \tau'$, and $\tau < \tau'$ iff $\tau \leqslant \tau'$ and $\tau \neq \tau'$. For $u \in \Sigma^\infty$, we denote by $prf(u)$ the set of finite prefixes of $u$.

Let the set of programs (regular expressions) generated by $\Sigma$ be $Prg(\Sigma) ::= a \mid \pi_1 + \pi_2 \mid \pi_1; \pi_2 \mid \pi^*$, where $a \in \Sigma$ and $\pi_1, \pi_2, \pi$ range over $Prg(\Sigma)$. A set of finite words can be associated with each program by the mapping $[[]] : Prg(\Sigma) \rightarrow 2^{\Sigma^*}$ in the usual way.

Let $\mathscr{P} = \{p_1, p_2, \ldots\}$ be a countable set of atomic propositions, let $\mathscr{C}$ be a constraint language, such that, for $g \in \mathscr{C}$, $\gamma(g) \in C$ is a constraint on a subset of variables $\mathscr{V}$, with domains $dom(x)$ for $x \in \mathscr{V}$, where $D = \bigcup_{x \in \mathscr{V}} dom(x)$. The set of formulas of DLTL$(\Sigma, \mathscr{C})$ is:

$$\text{DLTL}(\Sigma, \mathscr{C}) ::= \top \mid \bot \mid p \mid g \mid \neg\alpha \mid \alpha \vee \beta \mid \alpha \mathscr{U}^\pi \beta$$

where $\top$ and $\bot$ stand for *true* and *false*, $p \in \mathscr{P}$, $g \in \mathscr{C}$, $\pi \in Prg(\Sigma)$ and $\alpha, \beta$ range over DLTL$(\Sigma, \mathscr{C})$. From the until operator, the derived modalities $\langle\pi\rangle$, $[\pi]$, $\bigcirc$ (next), $\mathscr{U}$, $\Diamond$ and $\Box$ can be defined as follows: $\langle\pi\rangle\alpha \equiv \top \mathscr{U}^\pi \alpha$, $[\pi]\alpha \equiv \neg\langle\pi\rangle\neg\alpha$, $\bigcirc\alpha \equiv \bigvee_{a \in \Sigma} \langle a \rangle \alpha$, $\alpha \mathscr{U} \beta \equiv \alpha \mathscr{U}^{\Sigma^*} \beta$, $\Diamond\alpha \equiv \top \mathscr{U} \alpha$, $\Box\alpha \equiv \neg\Diamond\neg\alpha$, where, in $\mathscr{U}^{\Sigma^*}$, $\Sigma$ is taken to be a shorthand for the program $a_1 + \ldots + a_n$.

A model of DLTL$(\Sigma, \mathscr{C})$ is a triple $M = (\sigma, V, v)$ where $\sigma \in \Sigma^\omega$, $V : prf(\sigma) \rightarrow 2^{\mathscr{P}}$ is a valuation function for propositions, and $v : prf(\sigma) \rightarrow (\mathscr{V} \rightarrow D)$ provides, for each $\tau \in prf(\sigma)$, an assignment $v(\tau)$ for constraint variables. A prefix $\tau$ of $\sigma$ identifies the state reached after executing $\tau$. Given a model $M = (\sigma, V, v)$, a prefix $\tau \in prf(\sigma)$ and a formula $\alpha$, the satisfiability of a formula $\alpha$ at $\tau$ in $M$, written $M, \tau \models \alpha$, is defined as usual for boolean formulas, and as follows for $p \in \mathscr{P}$, $g \in \mathscr{C}$ and until formulas:

- $M, \tau \models p$ iff $p \in V(\tau)$;
- $M, \tau \models g$ iff $v(\tau) \models_\gamma g$;
- $M, \tau \models \alpha \mathscr{U}^\pi \beta$ iff there exists $\tau' \in [[\pi]]$ such that $\tau\tau' \in prf(\sigma)$ and $M, \tau\tau' \models \beta$. Moreover, for every $\tau''$ such that $\varepsilon \leqslant \tau'' < \tau'$, $M, \tau\tau'' \models \alpha$.

A formula $\alpha$ is satisfiable iff there is a model $M = (\sigma, V, v)$ and a finite word $\tau \in prf(\sigma)$ such that $M, \tau \models \alpha$.

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Observe that, although the extended DLTL language includes (constraint) variables, we assume that such variables have finite domains; hence, the language is, essentially, a propositional language, and its decidability follows from the decidability of DLTL (Henriksen and Thiagarajan 1999).

A *domain description* is a pair $(P, \mathcal{Q})$, where $P$ is a set of laws describing the effects and executability preconditions of actions, and $\mathcal{Q}$ is a set of DLTL formulas.

Laws in $P$ are defined as follows[1]. A *fluent literal* $l$ is a $p \in \mathscr{P}$ or its negation $\neg p$. A *constraint literal* is a $g \in \mathscr{C}$. If $l$ is a fluent literal, or $\bot$, representing the inconsistency, then $[a]l, \bigcirc l$ (for $a \in \Sigma$) are *temporal fluent literals*. If $l$ is a constraint literal, then $[a]l, \bigcirc l$ (for $a \in \Sigma$) are *temporal constraint literals*. We use *temporal literal* as a shorthand for temporal (fluent or constraint) literal. *Dynamic constraint literals* are constraint literals in the language $\mathscr{C}$ extended with variables $\mathscr{V}^\circ = \{x^\circ,$ for $x \in \mathscr{V}\}$; variable $x^\circ$ represents "$x$ in the next state". Given a literal $l$ of any of the types above, *not* $l$ represents the default negation of $l$. A literal, possibly preceded by a default negation, will be called an *extended literal*. Laws in $P$ have the form

$$l_0 \leftarrow l_1, \ldots, l_m, not\ l_{m+1}, \ldots, not\ l_n \tag{1}$$

where $l_0$ is a fluent literal or temporal fluent literal, and $l_1, \ldots, l_n$ are fluent literals, constraint literals, temporal literals or dynamic constraint literals, with the following restrictions: (i) If $l_0$ is a fluent literal, then the body cannot contain temporal literals or dynamic constraint literals; (ii) If $l_0 = [a]l$, then the temporal literals in the body must have the form $[a]l'$; (iii) If $l_0 = \bigcirc l$, then the temporal literals in the body must have the form $\bigcirc l'$.

A *state* is a set of fluent literals and an assignment to constraint variables. A state is said to be *consistent* if it is not the case that both $f$ and $\neg f$ belong to the state, or that $\bot$ belongs to the state. The execution of an action in a state may possibly change the values of fluents in the state through its direct and indirect effects, as well as the values of constraint variables, thus giving rise to a new state. We assume that a law as (1) can be applied in all states while, when prefixed with **Init**, it only applies to the initial state. With the restrictions (i) - (iii) on (1), possible successors of a state $S$ only depend on $S$.

In (Giordano *et al.* 2013a) the semantics of a domain description is defined by extending the notion of *answer set* (Gelfond 2007) to *temporal answer sets*, so to capture the linear structure of temporal models. In particular, the notion of temporal literals is extended to those of the form $[a_1; \ldots; a_k]l$ for an action sequence $a_1; \ldots; a_k$ and a fluent literal $l$; a *partial temporal interpretation over* $\sigma$, where $\sigma \in \Sigma^\omega$, is defined as a pair $(\sigma, S)$ where $S$ is a set of temporal literals $[a_1; \ldots; a_k]l$, such that $a_1 \ldots a_k$ is a prefix of $\sigma$, and $S$ is required not to contain $[a_1; \ldots; a_k]\bar{l}$ where $\bar{l}$ is the complementary literal of $l$. Membership of $[a_1; \ldots; a_k]l$ in $S$ means that $l$ is true in the state after executing $a_1 \ldots a_k$.

[1] To avoid confusion with constraint variables, we do not define laws with variables, which, as usual in ASP, would be a shorthand for the set of their ground instances.

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*Temporal answer sets* of the first component $P$ of a domain description are defined in (Giordano *et al.* 2013a) as partial temporal interpretations, extending the notion of answer set to compute a different reduct for each prefix $a_1 \dots a_k$ of a $\sigma$. Such a reduct is a set of rules of the form $[a_1; \dots; a_k](H \leftarrow Body)$.

In order to extend temporal answer sets to take constraint literals into account, we follow (Gebser *et al.* 2009), where a constraint answer set is defined with respect to an assignment to constraint variables. We then define a constraint temporal answer set with respect to a $v : prf(\sigma) \rightarrow (V[P] \rightarrow D)$ which provides, for each prefix of $\sigma$, an assignment for variables $V[P] \subseteq \mathscr{V}$ occurring in constraint atoms in $P$.

Satisfiability of literals is defined extending (Giordano *et al.* 2013a). Note that while for temporal (fluent and constraint) literals we take into account the next state, for dynamic constraint literals the assignments at both the current state and the next one have to be considered. To simplify the definition, we extend $v$ to $\hat{v}$ which, for each prefix $a_1 \dots a_k$ of $\sigma$, provides an assignment also to variables $x^\circ \in \mathscr{V}^\circ$ as follows: $\hat{v}(a_1 \dots a_k)(x^\circ) = v(a_1 \dots a_k a_{k+1})(x)$ , where $a_1 \dots a_k a_{k+1}$ is a prefix of $\sigma$. Then, satisfiability of literals in $(\sigma, S)$ at $k$ (where $\sigma = a_1 \dots a_k, \dots$), wrt to a $v$, is defined as follows, where $l$ is a fluent literal, $g$ is a constraint or dynamic constraint literal, $h$ is a fluent or constraint literal, *not* $m$ is an extended literal:

$(\sigma, S), v, k \not\models \bot$
$(\sigma, S), v, k \models l$ *iff* $[a_1; \dots; a_k] l \in S$,
$(\sigma, S), v, k \models g$ *iff* $\hat{v}(a_1 \dots a_k) \models_\gamma g$
$(\sigma, S), v, k \models [a]h$ *iff* $(\sigma, S), v, k+1 \models h$, or $a \neq a_{k+1}$
$(\sigma, S), v, k \models \bigcirc h$ *iff* $(\sigma, S), v, k+1 \models h$
$(\sigma, S), v, k \models not\ m$ *iff* $(\sigma, S), v, k \not\models m$

The following definitions are similar to the definition of constraint reduct in (Gebser *et al.* 2009), simplifying or eliminating rules based on the interpretation of constraint literals; we start by defining the reduct of a single rule for a sequence $a_1, \dots, a_k$.

*Definition 1*
The *constraint reduct* of a rule $\Box(H \leftarrow Body)$ in $P$, wrt to $(\sigma, S)$, to $v : prf(\sigma) \rightarrow (V[P] \rightarrow D)$ and to the prefix $a_1, \dots, a_k$ of $\sigma$, is:

- none, if for some (temporal, extended, dynamic) constraint literal $l$ in $Body$, $(\sigma, S), v, a_1 \dots a_k \not\models l$
- $[a_1, \dots, a_k](H \leftarrow Body')$ otherwise, where $Body'$ is $Body$ with (temporal, extended, dynamic) constraint literals removed.

*Definition 2*
The *constraint reduct,* $P^{(\sigma,S),v}_{a_1,\dots,a_k}$*, of* $P$ *relative to* $(\sigma, S)$*, to the prefix* $a_1, \dots, a_k$ *of* $\sigma$ *and to* $v : prf(\sigma) \rightarrow (V[P] \rightarrow D)$, is the set of all the rules

$$[a_1; \dots; a_k](H \leftarrow t_1, \dots, t_m)$$

such that $[a_1; \dots; a_k](H \leftarrow t_1, \dots, t_m, not\ t_{m+1}, \dots, not\ t_n)$ is the constraint reduct of a rule in $P$ wrt $(\sigma, S)$, $v$ and $a_1, \dots, a_k$; moreover, $(\sigma, S), a_1, \dots, a_k \not\models t_i$, for all $i = m+1, \dots, n$. The *constraint reduct* $P^{(\sigma,S),v}$ *of* $P$ *relative to* $(\sigma, S)$ *and* $v$ is the union of all reducts $P^{(\sigma,S),v}_{a_1,\dots,a_k}$ for all prefixes $a_1, \dots, a_k$ of $\sigma$.

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*Definition 3*
A partial temporal interpretation $(\sigma, S)$ is a *constraint temporal answer set of* $P$ wrt $v$ if $(\sigma, S)$ is a temporal answer set (Giordano *et al.* 2013a) of the constraint reduct $P^{(\sigma,S),v}$, i.e., $S$ is minimal among the $R$ such that $(\sigma, R)$ satisfies the rules in $P^{(\sigma,S),v}$.

*Well-defined domain descriptions* are defined in (Giordano *et al.* 2013a) as the ones for which $P$ has total temporal answer sets, and it is observed that total temporal answer sets correspond to temporal models (as in the semantics of DLTL). The same holds for the case with constraints, given a $v$ which provides, for the temporal answer set and the temporal model, the same interpretation for constraint atoms. I.e., given a constraint temporal answer set $(\sigma, S)$ of $P$ wrt $v$, the corresponding temporal model is $(\sigma, V_S, v)$ where $p \in V_S(a_1, \ldots, a_h)$ if and only if $[a_1; \ldots; a_h]p \in S$, for all propositions $p \in \mathscr{P}$. This leads to the following definition of extension of a domain description.

*Definition 4*
An *extension of a well-defined domain domain description* $(P, \mathscr{Q})$ *wrt* $v$ is a (total) constraint temporal answer set $(\sigma, S)$ of $P$ wrt $v$ such that the corresponding temporal model $(\sigma, V_S, v)$ satisfies the formulae in $\mathscr{Q}$.

Verifying that a DLTL$(\Sigma, \mathscr{C})$ formula $\alpha$ is valid in a well-defined domain description $(P, \mathscr{Q})$ means checking that there is no extension of $(P, \mathscr{Q})$ satisfying $\neg\alpha$, i.e., there are no $\sigma, S, v$ such that $(\sigma, S)$ is an extension of $(P, \mathscr{Q} \cup \{\neg\alpha\})$ wrt $v$.

## 4 Process modeling and annotation

In (D'Aprile *et al.* 2010) we proposed to specify annotations in the action theory in (Giordano *et al.* 2013a) to define direct and indirect effects of atomic tasks, as well as their preconditions. In the following we describe how the extended action language with constraints introduced in section 3 can be used as an annotation language.

An *action law* has a temporal literal $[a]l$ as head:

$$[a]l \leftarrow l_1, \ldots, l_m not\ l_{m+1}, \ldots, not\ l_n$$

In case $l$ is a fluent literal, it specifies that, under the conditions in the body, an action $a$ (a task in the process) has $l$ as a direct effect. In case $l$ is a constraint literal (e.g., $0 \leqslant x \leqslant 1000$ to represent that $a$ provides a value to $x$ in its domain, or in a subset of a common domain for all variables) it specifies an effect on process data[2].

Nonmonotonic persistence of fluents can also be specified with action laws such as:

$$[a]f \leftarrow f, not\ [a]\neg f$$

[2] As in (Gebser *et al.* 2009), a rule $c \leftarrow Body$ with a constraint in the head is intended as the (less readable) $\bot \leftarrow not\ c, Body$.

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A *precondition law* is an action law with $[a]\bot$ as head and it specifies that action $a$ cannot be executed under the conditions in the body, which can be conditions on fluents, or constraints on process variables, e.g.:

$$[a]\bot \leftarrow x \geqslant 10000$$

means that $a$ cannot be executed if $x \geqslant 10000$, i.e., it has $x < 10000$ as precondition.

*Causal laws* are used, in reasoning about actions and change, to specify relations between fluents, and therefore side effects of actions (*ramifications*). In the action language in (Giordano *et al.* 2013a), *static* causal laws involve fluent literals, while *dynamic* causal laws involve temporal fluent literals. For example, the static law $f \leftarrow g$ makes $f$ true whenever $g$ is true, while the dynamic law $\bigcirc f \leftarrow \neg g, \bigcirc g$ makes $f$ true when $g$ becomes true; but $f$ may later be made false while $g$ is still true.

Dynamic causal laws are useful, among other things, for a flexible modeling of processes with respect to rules they should be compliant with: in particular, to allow for activities that trigger obligations (e.g., confirming an order triggers the obligation to ship goods) and activities that cancel them (e.g., if the customer is allowed to cancel the order after confirmation, this cancels the obligation). Then, rather than verifying that obligations, once triggered, are eventually fulfilled (in the example, goods are shipped), one should verify that they are eventually either fulfilled or canceled. In (Giordano *et al.* 2013b) we present a general treatment, in our framework, of the types of obligations that in (Governatori 2010) are pointed out to be relevant for business process verification.

### *4.1 Declarative vs workflow specification of business processes*

In this section we shortly describe how our language can be used for a declarative specification of business processes as well as for encoding a workflow representation of such processes.

The declarative specification of business processes has been advocated by many authors (Singh 2000; van der Aalst and Pesic 2006; Montali *et al.* 2010) as opposed to the more rigid transition based approach, which can be more constraining than necessary as regards the order of actions. A declarative specification of a business process can be given by exploiting the action theory above to define the effects of atomic tasks as well as their executability preconditions and, possibly, temporal logic constraints.

For instance, the fact than an order can be processed only after it has been received can be modeled by a precondition law: $[process_order]\bot \leftarrow not\ order_received$ To guarantee that it will be eventually executed, we can add in $\mathscr{C}$ the DLTL formula: $\Box[receive_order]\Diamond\langle process_order\rangle\top$.

Observe that, as DLTL is an extension of LTL, it is possible to provide an encoding in our language of all constraints in the ConDec language (Pesic and van der Aalst 2006). The additional expressivity, which comes from the presence of program expressions in DLTL, allows for a very compact encoding of certain declarative properties of the domain dealing with finite iterations. For instance,

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the property "action b must be executed immediately after any even occurrence of action a in a run" can be expressed by the temporal constraint: $\Box[(a;\Sigma^*;a)^*]\langle b\rangle\top)$, where $\Sigma^*$ represents any finite action sequence[3].

On the other hand, workflow representation is widely used in process management systems and it represents a natural choice for modeling processes.

A translation from a workflow language to the action theory (or directly to ASP) can be defined. In particular, the basic constructs of the YAWL language[4] can be represented in the action language as follows, based on the enabling of arcs and tasks (details are provided in Appendix A). A precondition for the execution of a task *a* is its being enabled (represented by a fluent *enabled_a*). Causal laws define that it is enabled when its only incoming arc is enabled (another fluent), or it is an AND-join and all incoming arcs are enabled, or it is a XOR-join and one incoming arc is enabled. The execution of a task disables (in action laws) the incoming arcs and enables the outgoing arcs; in case there is a nondeterministic XOR-split (named deferred choice in YAWL), the execution of one of the next tasks also disables arcs corresponding to other choices. For XOR-splits, which in YAWL have conditions on net variables associated with alternative arcs, such conditions are included in the action laws for arc enabling. In the example in section 2, the enabling for outgoing arcs from Confirm_Receipt is as follows (an implicit default is intended in YAWL on the arc to Confirm_Order):

$$[Confirm_Receipt]en_Confirm_Receipt_Check_PN \leftarrow pn > 50000$$
$$[Confirm_Receipt]en_Confirm_Receipt_Confirm_Order \leftarrow not\ pn > 50000$$

Values of a process variable *x* persist, except in case of tasks *a* which have *x* as output (a piece of information which is in the YAWL model); we represent this as the task having as effect the fluent *change_x* which is non persistent, and false by default:

$$x^\circ = x \leftarrow \bigcirc\neg change_x$$
$$[a]change_x$$
$$\neg change_x \leftarrow not\ change_x$$

## 5 Translation to ASP

In (Giordano *et al.* 2013a), a translation of domain descriptions to ASP is defined, as well as an encoding in ASP of Bounded Model Checking (BMC) (Biere *et al.* 2003). BMC looks for paths representing possible executions of a system, and satisfying the required temporal formulae (including the negation of the formula to be proved valid). It can be shown that the search can be restricted to infinite paths which can be finitely represented as paths of length *k* with a back loop from state *k* to a

[3] In (D'Aprile *et al.* 2010) it has been shown that program expressions can be used to model the control flow of a business process in a rigid way. However, the solution in (D'Aprile *et al.* 2010) does not allow to deal with parallelism and non-structured workflows.

[4] We refer to YAWL as it is an open system, but our goal is not to reproduce its full semantics, since it includes constructs like the OR-join whose semantics is computationally complex.

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previous state in the path. BMC then searches paths whose finite representation has a length bounded by an integer $k$, iteratively increasing $k$ until a run satisfying the required temporal formulae is found (if one exists). The translation in (Giordano *et al.* 2013a) is defined so that extensions of the domain description correspond to answer sets of its ASP translation; in this way, an ASP solver can be used for finding extensions of $(P, \mathcal{Q} \cup \{\neg\alpha\})$, i.e., counterexamples to the validity of $\alpha$ in $(P, \mathcal{Q})$.

The translation is based on a representation of states as integers, starting from 0, so that state $i$ is the state after a prefix $a_1, \ldots, a_i$ of a $\sigma$; it uses the predicates: $occurs(Action, State)$, which means that $Action$ occurs in $State$, $holds(Literal, State)$, meaning that $Literal$ is satisfied at $State$, and $sat(Formula, State)$ meaning that a DLTL $Formula$ is satisfied at $State$.

For example, an action law $\Box([a](\neg)f_0 \leftarrow t_1, \ldots, t_m, not\ t_{m+1}, \ldots, not\ t_n)$ is translated to

$$(\neg)holds(f_0, S') \leftarrow state(S), S' = S + 1, occurs(a, S), h_1 \ldots h_m, not\ h_{m+1} \ldots not\ h_n$$

where $h_i = (\neg)holds(f_i, S')$ if $t_i = [a](\neg)f_i$ and $h_i = (\neg)holds(f_i, S)$ if $t_i = (\neg)f_i$.

The translation can be extended to a domain description $(P, \mathcal{Q})$ with constraints in section 3 as follows, using $value(x, S)$ to represent the value of process variable $x$ in state $S$. Following (Gebser *et al.* 2009), instances of $value(x, S)$ for different instances of $S$ will be CSP variables in the Constraint ASP program. Each constraint literal $g$ in $(P, \mathcal{Q})$ is given a unique name $name_g$, and the following rule is added to the definition of $sat$:

$$sat(name_g, S) \leftarrow state(S), g_S$$

where $g_S$ is $g$ with each variable $x$ replaced with $value(x, S)$. Similarly, for a dynamic constraint literal $d$ named $name_d$, the rule:

$$sat(name_d, S) \leftarrow state(S), S' = S + 1, d_{S,S'}$$

is added, where $d_{S,S'}$ is $d$ with variables $x \in \mathcal{V}$ replaced with $value(x, S)$ and variables $x^\circ \in \mathcal{V}^\circ$ replaced with $value(x, S')$.

For constraint literals $g$, $[a]g$, $\bigcirc g$ occurring in laws in $P$, the translation (exemplified above for action laws) is similar to the one for non-constraint literals, except that $g_S$ and $g_{S'}$ are used in place of $holds(f, S)$ and $holds(f, S')$. For dynamic constraint literals, $d_{S,S'}$ is used[5].

For example, the translations of the enabling condition for the XOR-split example in section 4.1, and of the persistence of the value for variable $pn$ are:

$$\begin{aligned} holds(en_Confirm_Receipt_Check_PN, S') \leftarrow\ & state(S), S' = S + 1, \\ & occurs(Confirm_Receipt, S), value(pn, S)\ \$ > 50000 \\ value(pn, S')\ \$ = value(pn, S) \leftarrow\ & state(S), S' = S + 1, not\ holds(change_pn, S') \end{aligned}$$

where, as in (Gebser *et al.* 2009), we emphasize with "$" relations in constraint atoms[6].

[5] Again, as in (Gebser *et al.* 2009), a rule $c \leftarrow Body$ with a constraint atom in the head is intended as $\leftarrow not\ c, Body$.

[6] Since our implementation is based on *clingcon*, the system in (Gebser *et al.* 2009; Ostrowski and Schaub 2012), which deals only with the integer domain, the translation of variables with enumerated type (like $c$

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The BMC encoding considers two states different if they differ on fluents (as in Giordano *et al.* 2013a), or on constraint literals in the domain description. In this sense, a state corresponds to a set of states in the sense of section 3, which assign single values to variables.

The correspondence results in (Giordano *et al.* 2013a) still hold. In particular:

*Proposition 1*
There is a one to one correspondence between the extensions $(\sigma, S)$ of a domain description, such that $\sigma$ can be finitely represented as a finite path with a back loop, and constraint answer sets (Gebser *et al.* 2009) of its translation.

The extension and the corresponding constraint answer set R are associated with the same temporal model $(\sigma, V, v)$, in particular, an extension wrt $v$ corresponds to an answer set R wrt a $v_R$, where $v_R(value(x, s)) = v(a_1, \ldots, a_s)(x)$, with $a_1, \ldots, a_s \in prf(\sigma)$.

## 6 Business process verification

The approach in (Giordano *et al.* 2013a) is well suited for reasoning about systems with infinite computations. However, in a YAWL model only executions that reach the end are considered sound (van der Aalst *et al.* 2008) (soundness includes other issues and its verification is a problem by itself, but we do not address it in this paper). To model this we include the formula $\Diamond end$ in the domain description, where *end* is a fluent which becomes true when the end condition is reached; we also introduce a *dummy* action, which does not change the state, and it is only executable (and is the only executable action) when the end condition is reached: its infinite repetition at the end of a finite execution transforms it in an infinite one with a loop (given by the *dummy* action). In practice, as an optimization of the ASP representation of BMC, we can avoid looking for arbitrary models with loops and restrict to computations corresponding to finite traces.

The basic iterative procedure of BMC is a partial decision procedure for checking validity: if no model exists, it would never stop. Completeness can be obtained for general formulae or for special classes of formulae with the techniques described in (Biere *et al.* 2003; Clarke *et al.* 2004; Biere *et al.* 2006; Giordano *et al.* 2012), and involves identifying a *completeness threshold*, i.e. a value $t$ such that validity of a formula $\alpha$ can be checked without using a value $> t$ for the bound $k$ (i.e., if a model satisfying $\neg\alpha$ exists, one can be found using bounds up to $t$). For example, the approach to completeness in (Giordano *et al.* 2012) could be extended to the language with constraints in this paper. Computing thresholds, however, is in general challenging from a computational point of view even for special types of formulae; therefore, existing approaches would not necessarily provide a feasible solution in a wide range of practical cases. For loop-free workflows, like the one in the example in section 2, there is a longest run, whose length can be used as threshold.

in the example, for the customer type) departs from the one described above, being based on parametric fluents $var(name, value)$, so that, e.g., a condition $c = premium$ becomes $holds(var(c, V), S), V = premium$.

https://doi.org/10.1017/S1471068413000409 Published online by Cambridge University Press

We experimented the approach on a machine with Intel Xeon E5520 processors (2.26 Ghz) using *clingcon* (Gebser *et al.* 2009; Ostrowski and Schaub 2012), and an encoding with an optimization for the persistence of variable values.

For the example in section 2, rules (c) and (d) can be encoded, respectively, as:

$$\Box(pn > 50000 \wedge \langle Confirm_Order \rangle \top \rightarrow a = true) \tag{2}$$

$$\Box(pn > 80000 \wedge c \neq premium \wedge \langle Assess_Order \rangle \top \rightarrow solvency_check_done) \tag{3}$$

where $solvency_check_done$ is an effect of $Check_Solvency$.

The length of the longest run is 21 and can be computed in 1.35 s using the translated domain description (searching for a run of length $k$, not necessarily reaching the end, for increasing values of $k$, and stopping when no such run is found). Using such a threshold, validity of (2) can be proved in 0.12 s, and a counterexample for (3) can be found in 0.10 s. If *clingcon* is not asked to return an assignment of single values to constraint variables, it computes a *weak* constraint answer set (Ostrowski 2012), where an approximation of the restricted domain for variables is given; in this case, in the computed answer set, the value of $pn$ after $Process_Order$, i.e., $value(pn, s)$ for $s \geqslant 3$, is given the domain [80001..100000], because the ASP solver assigns true to $value(pn, s) > 80000$ and false to $value(pn, s) > 100000$, and this is consistent for the constraint solver.

Similar running times were obtained for a variation of the example with run length up to 30 and more complex constraints, where branching is conditioned on the total cost $tc$ of the order, given by $pn * uc$ (a unit cost, known to be in a given range), possibly modified by a discount.

In appendix B we report more experiments on the feasibility and scalability of the approach with current Constraint ASP technology. For the case where the process structure is a sequence of blocks similar to the one in the running example, we show problems where verification runs in seconds for processes with up to 200 activities (a size which is in line with the one of real-world processes in (Fahland *et al.* 2011)) and run length of more than 100 activities. The additional cost of constraint solving is acceptable, even though this does not hold when constraints involve expressions with several variables.

When there is significant parallelism in the process, all the interleavings are considered, however, verification is shown to run in a minute or less for problems where the number of different executions is up to $10^{28}$.

## 7 Conclusions and related work

The paper presents an approach to the verification of the compliance of business processes, which allows to capture expressive fluent annotations as well as data awareness in a uniform way. The business process, its semantic annotation and the norms are encoded using temporal ASP rules, and temporal logic formulae. Compliance verification can be performed using BMC techniques in Constraint ASP, based on the approach developed in (Giordano *et al.* 2013a) for DLTL bounded model checking in ASP, which extends the approach for bounded LTL

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model checking with Stable Models in (Heljanko and Niemelä 2003). This paper enhances the approach to process compliance verification in (D'Aprile *et al.* 2010) by taking into consideration the data perspective, and especially arithmetic constraints, and alternative ways of modeling business processes. The paper concentrates on business process verification, but the proposed approach can also be used for the verification of clinical guidelines in the line of (Bottrighi *et al.* 2010), where, however, conditions on (numerical) data are not explicit modeled.

In (Knuplesch *et al.* 2010) a constraint solver is used to compute in advance consistent sets of conditions on numeric data (occurring in the model and in the formula to be verified), then performing model checking using such sets as abstractions of actual values. In our approach, the Constraint ASP solver performs both tasks at once.

The idea of introducing annotations on business processes for compliance verification has been proposed in (Ghose and Koliadis 2007; Governatori and Sadiq 2009; Weber *et al.* 2010). In particular, in (Governatori and Sadiq 2009) annotations and normative specifications are provided in the same logical language, the Formal Contract Language, combining Defeasible Logic (Antoniou *et al.* 2001) and Deontic Logic of Violations (Governatori and Rotolo 2006). Compliance is verified by traversing the graph describing the process and identifying the effects of tasks and the obligations triggered by task execution. Algorithms for propagating obligations through the process graph are defined.

In (Hoffmann *et al.* 2009) effects and preconditions of atomic tasks are sets of atomic formulas, and background knowledge is a theory in clausal form; I-Propagation (Weber *et al.* 2010) is exploited for computing annotations. In our approach the domain theory contains, rather than general clauses, directional causal rules (which avoid unintended conclusions when reasoning about side effects), and domain annotations are combined with data properties in a uniform approach.

An annotation approach is also used in (Lu *et al.* 2006) for the automatic verification of correctness of workflow models based on Hoare semantics.

In (Deutsch *et al.* 2009) a service over an artifact schema is defined as a triple: a precondition, a post-condition and a set of rules in a first-order temporal logic, which define changes on state relations. The authors identify a class of *guarded* artifacts for which verification of properties in a (guarded) first-order extension of LTL is decidable. In (Damaggio *et al.* 2011) decidability results are provided for verification with arithmetic constraints on infinite domains. Our (decidable) language is less expressive, not allowing for explicit quantification and assuming finite domains for variables.

In (Montali *et al.* 2010) the Abductive Logic Programming framework SCIFF (Alberti *et al.* 2008) is exploited in the declarative specification of business processes as well as in the verification of their properties. CLP is used for constraints on the timing of events. In (Alberti *et al.* 2005) expectations are used for modelling obligations and prohibitions and norms are formalized by abductive integrity constraints.

In (Roman and Kifer 2008) Concurrent Transaction Logic (CTR) is used to model and reason about general service choreographies. Service choreographies and

https://doi.org/10.1017/S1471068413000409 Published online by Cambridge University Press

contract requirements are represented in CTR. The paper addresses the problem of deciding if there is an execution of the service choreography that complies both with the service policies and the client contract requirements.

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