Dynamic Role Binding in Blockchain-Based Collaborative Business Processes

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Abstract. Blockchain technology enables the execution of collaborative business processes involving mutually untrusted parties. Existing platforms allow such processes to be modeled using high-level notations and compiled into smart contracts that can be deployed on blockchain platforms. However, these platforms brush aside the question of who is allowed to execute which tasks in the process, either by deferring the question altogether or by adopting a static approach where all actors are bound to roles upon process instantiation. Yet, a key advantage of blockchains is their ability to support dynamic sets of actors. This paper presents a model for dynamic binding of actors to roles in collaborative processes and an associated binding policy specification language. The proposed language is endowed with a Petri net semantics, thus enabling policy consistency verification. The paper also outlines an approach to compile policy specifications into smart contracts for enforcement. An experimental evaluation shows that the cost of policy enforcement increases linearly with the number of roles and constraints.

1 Introduction

Access control is an essential aspect in the design and execution of business processes. Mainstream Business Process Management Systems (BPMSs) rely on static Role-Based Access Control (RBAC) models. In these models, any worker who plays a role is allowed to perform any task associated to this role in any instance of the process, modulo additional constraints such as separation of duties [13]. This approach is unsuitable for collaborative inter-organizational processes involving untrusted actors. For example, a buyer may trust a given carrier but not others, even though they all play the same role.

Blockchain technology enables the execution of collaborative business processes involving untrusted actors [8]. Existing tools such as Caterpillar [6] and Lorikeet [14], support the definition of collaborative processes using high-level notations and their execution on top of blockchain platforms. However, these tools either do not support access control or they adopt a static role binding approach wherein all actors are bound to roles upon process instantiation.

The characteristics of blockchain technology shift the role binding problem in two ways. First, rather than groups or individual users being bound to roles, we
need to bind blockchain accounts (or identities) to roles, as shown in Fig. 1. These accounts, in turn, are controlled by users, groups, systems, or (IoT) devices. Second and more significantly, in open blockchain networks, instances of a collaborative process are created by different actors, and each of these actors trusts one subset of actors but not others. Moreover, the set of actors changes dynamically and so do the trust relations. For example, a buyer may initially trust a carrier and agree to its appointment together with the supplier. But later, the buyer may lose this trust (e.g. if the carrier misses a deadline). Thereafter, the buyer may wish to re-bind the transportation task to another carrier, but this re-binding must be endorsed by the supplier. This example illustrates the need to support dynamic binding and un-binding of actors to roles and collaborative binding of actors to roles (buyer and supplier both need to agree on the carrier).

This paper proposes a role binding model and a binding policy specification language designed to support collaborative business processes in such open and untrusted environments, as well as an approach to compile policies into executable code. The semantics of the policy specification language is defined via a mapping to Petri nets, which enables the static verification of policies prior to their compilation. The proposed method has been implemented in Caterpillar [6] – a blockchain-based execution engine that supports the Business Process Model and Notation (BPMN). The paper reports on an experimental evaluation aimed at assessing the cost of policy enforcement on the Ethereum blockchain.

The rest of the paper is structured as follows. Section 2 discusses basic concepts of blockchain technology and the limitations of existing role binding models for collaborative processes. Section 3 describes the role binding model and policy language. Section 4 presents the semantics of the policy language and the policy verification approach. Finally, Section 5 discusses the implementation and evaluation, while Section 6 draws conclusions and sketches future work.

2 Background and Related Work

2.1 Blockchain Technology and Collaborative Processes

A blockchain is a distributed append-only store of transactions distributed across computational nodes and structured as a linked list of blocks, each containing a set of transactions [16]. A blockchain network is made up of nodes, a subset of which holds a replica of the data structure. Clients use a blockchain system (a concrete network) by reading data from and submitting transactions to it. Submitted transactions are grouped into blocks, which are broadcast across the network to be appended to the blockchain. A consensus mechanism ensures tamper-proofness without assuming mutual trust between participants.
A smart contract is a program deployed on the blockchain, which may be invoked via a transaction [10]. In Ethereum, smart contracts are written in the Solidity language, which is compiled into bytecode and executed on the Ethereum Virtual Machine. The computational and data storage consumption of a transaction are measured in gas, which translates to monetary costs for the transaction’s sender. Each block has a gas limit and hence gas directly impacts throughput.

Existing blockchain-based process management tools support the specification of collaborative processes using BPMN [6,14] or domain-specific languages [4], and their execution via smart contracts. These systems focus mainly on the control-flow perspective. Lorikeet [14] implements a static access control mechanism, where roles are bound to accounts upon process instantiation. A method proposed in [11] allows dynamic handoffs of process instances between actors, but does not support the specification and enforcement of permitted handoffs.

2.2 Binding and Delegation Models for Collaborative Processes

The question of dynamic role binding has been considered in the context of Web service composition, e.g. in the Business Process Execution Language (BPEL) [1] where role binding is supported via “partner links”. A partner link is a variable that holds a reference to a service endpoint (i.e. a concrete address). This variable can be modified anytime during the execution of a process instance. This approach assumes that the whole process is orchestrated by a single entity and that this entity unilaterally decides which actor (i.e. endpoint) should be bound or re-bound to a role (i.e. a partner link). The same assumption is made in BPEL4People [5] (which extends BPEL to support human actors), in Pautasso et al. [10] and Lu et al. [7]. These approaches are not applicable in settings where the binding of actors to roles is not determined by a single actor.

Other work studies the problem of dynamic role binding in settings where the process is not orchestrated by a single actor. [12] extracts dynamic authorization policies from service choreographies. These policies are enforced locally by each party, but they rely on a centralized authority to specify the role bindings. BPEL4Chor [3] allows an actor to bind other actors to the roles it has control over. But each role is controlled by a single actor – in other words, collaborative role binding is not supported, e.g. this approach does not support the scenario where both the buyer and seller must agree on the actor who plays the role of carrier. Also, BPEL4Chor does not support role re-binding. In [15,2], dynamic role bindings in decentralized processes are captured via a delegation and revocation scheme. This approach supports un-binding (revocation) but does not support collaborative binding (each actor decides on the roles it has control over).

In summary, none of the above studies has addressed the problem of dynamic role binding and un-binding in decentralized processes, where multiple actors must collaboratively agree on each role binding and un-binding decision.

3 Role Binding Model

The starting point of the proposed approach is a (collaborative) business process model where each task is associated with a role. For a given process instance (herein called a case), each role may be assigned to at most one actor. An actor
has an identity (e.g. a blockchain account) and may represent a user, a group, an organization, a system or a device (cf. Fig. 1). As a running example, Fig. 2 shows a BPMN model of an order-to-cash process. There are six roles represented by numbers below each task label: (1) Customer, (2) Supplier, (3) CarrierCandidate, (4) Carrier, (5) Invoicer and (6) Invoicee. Initially, a customer submits a purchase order (PO) to a supplier. If the PO is rejected the process terminates. Otherwise, the execution continues with the SHIPMENT sub-process, where a supplier requests quotes from multiple carrier candidates (cf. the multi-instance task). Once the shipment completes, two parallel paths are taken to handle the payments. These payments are encapsulated in sub-process INVOICING. This sub-process is called twice: for the supplier’s invoice and for the carrier’s invoice.

Fig. 2. Running example: (2a) An Order-to-cash process linked, via call activities, to two reusable sub-processes: (2b) Shipment and (2c) Invoicing.

The act of assigning an actor to a role within a case is called binding. When a role is not assigned to an actor within a case, we say that the role is unbound. The binding of an actor to a role can be performed anytime during the execution of a case. Actors can also be unbound from a role – an operation called release.

A task is performed by the actor bound to the task’s role. If a task is enabled when its associated role is unbound, the task waits until the role is bound.

Actors may nominate themselves or other actors to play a role in a case, or they may request to release themselves or other actors from a role. Given the lack of trust, the nomination/release of an actor to/from a role may require the endorsement of actors playing other roles. If an actor is nominated to play a role in a case, this nomination only leads to the role’s binding if the required endorsements are granted. A binding policy associated to a process model determines which role(s) are allowed to nominate an actor to a role, to request the release an actor from a role, and to endorse a nomination or a release request.

3.1 Binding Policy Specification Language

A policy consists of a set of roles and a set of statements restricting how an actor may be nominated/released to/from a role. A statement is formed by a nominator, a nominee, and optionally a binding and/or an endorsement constraint. The
nominator is a role that nominates/releases the actors of another role, namely the nominee. A binding constraint is a boolean expression stipulating that the nominee must be bound to an actor who is also bound to some other role(s). An endorsement constraint is a boolean expression that determines which roles need to endorse a nomination/release request. A role may be associated with the case-creator, implying that the role is bound upon case creation and does not need a nomination or endorsement. A policy statement applies by default to the root process, but it can be scoped to a sub-process call activity. Fig. 3 shows an extract of the grammar of the policy language in Backus Naur form (BNF).

Fig. 3. BNF grammar describing the basic statement syntax of a binding policy.

Listing 1 shows a policy for the model in Fig. 2. The policy states that the case creator is automatically bound to the Customer role. The Customer nominates the Supplier (no endorsement needed here). The Supplier, in turn, nominates the Candidate (i.e. the carrier candidate) and the Carrier. The Carrier must be among the actors bound to the Candidate role (cf. binding constraint “Carrier in Candidate”). Note that Candidate is a role associated to a multi-instance task (Submit Quotes), implying that multiple actors may be bound to this role. The Customer must endorse the nomination of the Carrier. Under the Carrier Invoicing call activity, the Invoicer is nominated by the Carrier with endorsement from the Supplier and Customer, and reciprocally for the Invoicee. Meanwhile, under the Supplier Invoicing activity, the Supplier nominates the Invoicer with Customer endorsement, and reciprocally for the Invoicee.

Listing 1. Binding Policy to control the execution of the processes modeled in Fig. 2

1 { Customer is case-creator;
2  Customer nominates Supplier;
3  Under Shipment, Supplier nominates Candidate;
4  Under Shipment, Supplier nominates Carrier in Candidate endorsed-by Customer;
5  Under Carrier Invoicing, Carrier nominates Invoicer endorsed-by Supplier and Customer;
6  Under Carrier Invoicing, Customer nominates Invoicee endorsed-by Carrier;
7  Under Supplier Invoicing, Supplier nominates Invoicee endorsed-by Customer;
8  Under Supplier Invoicing, Supplier nominates Invoicee endorsed by Customer;
9 }

3 Some details (e.g. path expressions to refer to nested subprocesses) are omitted for space reasons and can be found at [http://git.io/caterpillar](http://git.io/caterpillar)
This example illustrates the possibilities offered by the policy language to deal with lack of trust. For example, dishonest suppliers could try to derive benefits by not selecting the best carrier candidate but their preferred one. However, the customer would be able to reject such nominations. Also, the policy prevents the supplier from selecting a carrier that has not been a carrier candidate before.

The policy language also allows us to state that the set of actors who endorse a nomination request must fulfill a boolean expression. For instance, the above policy requires that the Invoicer of the carrier services must be endorsed by both the buyer and the supplier. This scenario is relevant in the context of international trade, where both buyers and suppliers need to ensure that they do not deal with black-listed entities or entities in countries banned from trading. The boolean expressions in the endorsement constraint may contain arbitrary combinations of conjunctions and disjunctions. They may not however contain negation, e.g. it is not possible to state that the nomination is approved if a given actor refuses to endorse it. Such scenarios are not applicable in this setting.

3.2 Runtime Binding Operations

The role binding model relies on three operations. The nominate operation allows an actor to request that another actor (or itself) be bound to a role within a process instance (herein called a case). Inversely, a release operation allows an actor to request that another actor (or itself) be unbound from a role. The vote operation allows an actor to accept/reject a nomination or release request.

These operations trigger transitions in the role lifecycle depicted in Fig. 4. Within a case, a role is initially unbound. After a nominate operation, the role changes to nominated if it requires to be endorsed, otherwise is considered bound. A role in nominated state, can transition to the bound state after a vote operation where the endorser accepts the nomination if, as a result of it, the endorsement constraint of this role is satisfied. On the contrary, a vote operation where the endorser rejects the nomination and by doing so makes the role’s endorsement constraint unsatisfiable, triggers a transition to the unbound state. If after a vote operation, the endorsement constraint remains satisfiable, then the role remains in the nominated state. Symmetrically, a role can transit from bound to unbound as a result of a release operation, via a releasing state, which is specular to the nominated state. If the endorsement constraint associated to a release request becomes unsatisfiable, the role goes back to the bound state, and if it becomes satisfied, the role moves to the unbound state.

4 Policy Consistency Verification

Nomination and release statements in a policy implicitly induce precedence dependencies in the binding of roles. A statement R1 nominates R2 endorsed-by R3 implies that for R2 to be bound, R1 and R3 must be bound before. Circular and unresolvable dependencies induced in this way may lead to deadlocks. Accordingly, we define a notion of policy consistency as follows. A policy is consistent if, starting from the state where only the roles associated with case-creator
are \textsc{Bound} and after executing any allowed sequence of nomination, release and endorse operations, we always reach a state where all roles will reach the \textsc{Bound} state via some (other) sequence of nomination, release and endorse operations.

To verify policy consistency, we define a mapping from a policy to a Petri net, herein called a \textit{nomination net}. Given the nomination net of a policy, we map the problem of checking policy consistency to a problem of reachability analysis over Petri nets. Algorithm\textsuperscript{1} maps a policy to a nomination net. For the sake of conciseness, this algorithm focuses on nomination statements, leaving aside release statements. The mapping of release statements follows a similar structure. For the same reason, the algorithm leaves aside binding constraints.

To illustrate the algorithm, we consider the binding policy in Fig. 5. The algorithm takes as input a symbolic representation of a policy consisting of a structure. For the same reason, the algorithm leaves aside binding constraints. The mapping of release statements follows a similar structure.

The algorithm proceeds as follows. After initializing variable \texttt{R Nets} in line 2, the algorithm builds a Petri net for each node in lines 3-4 (Step 1). Let us consider that we are building the Petri net for role \texttt{A}, which is shown in color blue in Fig. 4. In line 4, the algorithm creates such a Petri net with three places, namely \texttt{nA}, \texttt{nA} and \texttt{bA}, which represent the states of the role’s lifecycle \textsc{Unbound}, \textsc{Nominated} and \textsc{Bound}, respectively. Similarly, two transitions are added to the Petri net, namely \texttt{nmA} and \texttt{enA}, representing the operations ‘nominate’ and ‘endorse’. Finally, four arcs added to complete the Petri net, by connecting the places and transitions. The Petri nets for all the other nodes are created in a similar way. Every Petri net thus created is added to \texttt{R Nets} that serves as a map that associates a role to its corresponding Petri net.

In lines 5-9 (Step 2), all the role (Petri) nets are merged to form the initial nomination net, which is held in variable \texttt{NNet}. This is done by taking the union of the elements in the role nets. Also, the initial marking is set to the empty set.

In lines 11-14 (Step 3), the algorithm adds double-headed arcs to the Petri net to synchronize the transition that represents the nomination of roles. To illustrate the idea of nomination, consider the double-headed arc connecting the place \texttt{bA} and the transition \texttt{nmB} in Fig. 4, highlighted in red. Simply put, role \texttt{A} will be able to nominate role \texttt{B} when role \texttt{B} is \textsc{Unbound} and role \texttt{A} is \textsc{Bound} (\texttt{bA} must hold a token). The firing of transition \texttt{nmB}, that is ‘nominate \texttt{B}’, will

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4}
\caption{Lifecycle of a role within a case.}
\end{figure}
Algorithm 1 Construction of the Nomination Net for a given Binding Policy

1: function CONSTRUCTNOMINATIONNET(R, BP)
2: \( \text{RNets} \leftarrow \emptyset \)
3: \( \text{Step 1: Build a Petri net for each role} \)
4: for each role \( r \in R \) do
5: \( \text{RNets} \leftarrow \text{RNets} \cup \{ r \mapsto \{ u_r, n_r, b_r \} \mapsto \{ nm_r, en_r \}, \{ (u_r, nm_r), (n_m, n_r), (en_r, b_r) \} \mapsto \{ F_r \} \} \)
6: \( \text{Step 2: Merge all role nets to form the nomination net} \)
7: \( M_0 = \langle P, T, F, M_0 \rangle \)
8: \( P \leftarrow \bigcup_{r \in R} P(\text{RNets}[r]) \)
9: \( T \leftarrow \bigcup_{r \in R} T(\text{RNets}[r]) \)
10: \( F \leftarrow \bigcup_{r \in R} F(\text{RNets}[r]) \)
11: \( M_0 \leftarrow \emptyset \)
12: \( \text{Step 3: Wire up operation NOMINATE} \)
13: for each \( (r_{nr}, r_{ne}, _) \in \text{BP} \) do
14: select \( b_{nr} \in P(\text{RNets}[nr]) \)
15: select \( nm_{ne} \in T(\text{RNets}[ne]) \)
16: \( F(NNet) \leftarrow F(NNet) \cup \{ (b_{nr}, nm_{ne}), (nm_{ne}, b_{nr}) \} \)
17: \( \text{Step 4: Wire up operation ENDORSE} \)
18: for each \( (r_{nr}, r_{ne}, eex) \in \text{BP such that } eex \neq \bot \) do
19: \( P(NNet) \leftarrow P(NNet) \cup \{ disj_{ne}, eex_{ne} \} \)
20: \( F(NNet) \leftarrow F(NNet) \cup \{ (nm_{ne}, disj_{ne}), (eex_{ne}, en_{ne}) \} \)
21: for each \( \text{conj} \in eex \) do
22: \( T(NNet) \leftarrow T(NNet) \cup \{ eex_{conj} \} \)
23: \( F(NNet) \leftarrow F(NNet) \cup \{ \{ b_{nr}, eex_{conj} \}, \{ eex_{conj}, b_{nr} \}, \} \)
24: \( \text{Step 5: Update NNet’s initial marking} \)
25: let \( r_{cc} \in R: r_{cc} \text{ be case creator in} \)
26: \( Ps \leftarrow \{ u_r | r \in R \setminus \{ r_{cc} \} \land u_r \in P(NNet[r]) \} \cup \{ b_{cc} | b_{cc} \in P(NNet[r_{cc}]) \} \)
27: \( M_0(NNet)(p) = \begin{cases} 1 & \text{if } p \in Ps \\ 0 & \text{Otherwise} \end{cases} \)
28: return \( NNet \)

change the state of role \( B \) from UNBOUND to NOMINATED. The double-headed arc will keep a token in \( b_A \) after the nomination of role \( B \).

The encoding of endorsement conditions is handled in lines 15-20 (Step 4). Without loss of generality, we assume that the endorsement conditions are expressed in disjunctive normal form, meaning that there is only one disjunction that relates several conjunctions. We consider two additional cases: (1) no endorsement condition is specified (represented by \( \bot \)), meaning that no endorsement is required, and (2) only one conjunction is specified. To illustrate this step of the construction of the nomination net, consider the binding policy:

\[ D \text{ nominates } E, \text{ endorsed-by (A and B) or (B and C);} \]
\{ A \text{ is case-creator;} \\
A \text{ nominates } B; \\
A \text{ nominates } C; \\
C \text{ nominates } D, \text{ endorsed-by } A \text{ and } B; \}

\[ R = \{ A, B, C, D \} \]

\[ BP = \{ \langle A, B, \perp \rangle, \langle A, C, \perp \rangle, \langle C, D, A \land B \rangle \} \]

**Fig. 5.** Sample binding policy

\[ R = \{ A, B, C, D \} \]

\[ BP = \{ \langle A, B, \perp \rangle, \langle A, C, \perp \rangle, \langle C, D, A \land B \rangle \} \]

**Fig. 6.** Symbolic representation of the binding policy in Fig. 5

**Fig. 7.** Nomination net for binding policy in Fig. 5

The Petri net in Fig. 8 encodes the endorsement condition in the above policy: \((A \land B) \lor (B \land C)\). The latter is bound to variable \textit{eeex} in line 15. In line 16, the algorithm adds two new places: \textit{disj} which encodes the disjunction, and \textit{eeex}, which collects the outcome of the endorsement (i.e. it holds a token when one of the endorsement conditions is met). In line 17, these are connected to the transitions of the role: from the nomination \textit{nm} to \textit{disj}, and from the outcome \textit{eeex} to the endorsement \textit{en} (not shown in Fig. 8). Then, in line 18, the algorithm iterates over each one of the conjunctions. In line 19, a new transition, representing the underlying conjunction is added to the net, and the corresponding arc in line 20. For instance, the net in Fig. 8 has transition \textit{eeex}_{A\land B} representing conjunction \(A \land B\), and \textit{eeex}_{B\land C} representing \(B \land C\). Only \textit{eeex}_{A\land B} or \textit{eeex}_{B\land C} will be able to consume the token held by \textit{disj}, which prevents the generation of an arbitrary number of tokens in \(NNet\). \textit{disj} receives a token when \textit{nm} fires, i.e., when \(D\) nominates \(E\). The disjunction expressed in this way means that role \(E\) can be endorsed if at least one of the conjunctions holds true, which corresponds to the firing of one of the transitions \textit{eeex}_{A\land B} and \textit{eeex}_{B\land C}. Returning to the example in Figures 5-7, we observe that role \(D\) is endorsed if and only if both roles \(A\) and \(B\) are BOUND. The subnet implementing the endorsement condition is shown in green in Fig. 7.

Finally, lines 21-23 set the initial marking for the nomination net. Briefly, line 21 will add a token to the place representing the state UNBOUND of every single role, except for the “case creator”. In the latter case, we add a token to the place representing the state BOUND.

To verify policy consistency, we use reachability analysis to check if the marking where all roles are bound is always reachable starting from the initial mark-
\{ 
  J is case-creator;
  J nominates K, endorsed-by L;
  J nominates L, endorsed-by K;
\}

Fig. 9. Binding policy with circular dependency and its nomination net

In other words, there is no deadlock preventing a role from being bound. Fig. 9 shows a binding policy with a circular dependency, leading to a deadlock in the corresponding nomination net. Fig. 9 shows the marking where the deadlock occurs. Both roles K and L have been nominated by role J. Hence, disjK has a token, but transition eexL cannot fire until bL has also a token. In order for bL to have a token, however, transition eexK needs to fire because it requires bK to have a token.

5 Implementation and Evaluation

To demonstrate the proposal’s feasibility, we developed a compiler that takes as input a policy specification and produces Solidity smart contracts to enforce the policy. This policy compiler is designed to be used in conjunction with the CATERPILLAR BPMN-to-Solidity compiler [6]. The smart contracts generated by the policy compiler manage the association between roles and actors (represented as blockchain accounts), while the smart contracts generated by the BPMN-to-Solidity compiler enforce the control-flow constraints in the process model. When a task is enabled, the worklist handler smart contract of CATERPILLAR, checks if the corresponding role is bound to an actor within the current case, and ensures that only this actor can execute the task. The source code of CATERPILLAR, including the binding policy compiler and the examples used in this paper, are available at http://git.io/caterpillar. Below we discuss the generation of smart contracts and evaluate the costs generated by these contracts.

5.1 Compiling Binding Policies into Smart Contracts

Given a process model and a policy specification, the policy compiler generates a smart contract (named BINDINGPOLICY) to encode the policy and a smart contract (TASKROLEMAP) to encode the task-role relations in the process model. The BINDINGPOLICY contract encodes the logic of who can nominate and release each role and the binding and endorsement constraints for each role. A third contract (BINDINGACCESSCONTROL) implements the runtime operations sketched in Section 3. BINDINGPOLICY and TASKROLEMAP are singleton contracts – only one instance of each of them is created since these contracts only
maintain schema-level data. Meanwhile, the BindingAccessControl contract is instantiated once per case. The BindingAccessControl contract instance of a given case maintains the state of each role, as per the lifecycle in Fig. 4. When a nomination, release, or vote operation is invoked, the BindingAccessControl contract invokes the BindingPolicy contract. The latter checks if this operation is allowed in the current state and computes the new state.

The class diagram in Fig 10 captures the functionality of the generated smart contracts. Input parameters with no type specification are by default uint. As stated above, contract BindingAccessControl implements the runtime operations for nomination, release and voting. Since this contract does not encode anything about a particular policy, it is not generated by the policy compiler, but instead it is hard-coded and deployed once on the target Ethereum blockchain. This contract maintains the state of the role bindings for a given case in a variable called BindingState. Given that the cost of a smart contract depends on the amount of data it maintains, we encode the BindingState using bitmaps. Similarly, the endorsement constraints are represented as bit arrays. Specifically, we first put these constraints in disjunctive normal form, e.g., \((A \text{ and } B \text{ and } \ldots) \text{ or } (D \text{ and } \ldots)\). Then we implement each conjunction set as a bit array and encode it as a 256-bits unsigned integer – the default word size in Ethereum.

![Class diagram of the smart contracts derived from the policies.](image)

Contract TaskRoleMap is generated from the process model. This contract is straightforward (it maps tasks to roles), so we do not discuss it further.

The policy specification is compiled into the BindingPolicy contract. Below we discuss how the role binding functions are generated (functions canNominate, assertNConstraint and assertNVote). The generation of the release functions (canRelease, assertRConstraint and assertRVote) is done in a similar way.

To generate function canNominate, for each distinct nominator in the policy a conditional and bit array, namely nmask, is created with one bit per role such that the presence of a nominee is represented with a one and the absence with a zero. For example, a nominator with index 3 and nmask = 6 is translated into:
```solidity
function canNominate(uint rNominator, uint rNominee) returns (bool) {
    ...
    if (rNominator == 3)
        return 6 & (1 << rNominee) != 0;
    ...
}
```

Function `assertNConstraint` verifies if the roles held by a nominee do not contradict the binding constraint. Thus, a conditional instruction per nomination statement including a binding constraint is added. A statement is identified by the union of nominator and nominee, i.e., \( (1 << rNominator) | (1 << rNominee) \). Variable `nomineeRoles` is the bit array encoding the nominee’s current roles. Given a constraint of the form \((A \land B) \lor (C) \lor \ldots\), the constraint is fulfilled if at least one of the conjunction sets is fully included in `nomineeRoles`. This is encoded as follows:

```solidity
if ((1 << rNominator) | (1 << rNominee))
    return nomineeRoles & ((1 << A) | (1 << B)) == ((1 << A) | (1 << B))
        || nomineeRoles & (1 << C) == (1 << C) || ...;
```

Function `assertNVote` checks if an endorser can vote for a nomination and determines the state after this vote. Given the input parameters `endorsedBy` and `rejectedBy`, which are bit arrays encoding the roles that already accepted and rejected the nomination, this function determines the resulting state as follows:

1. **Bound** if all the roles in at least a conjunction set, namely `CS`, endorsed the nomination, i.e., \((endorsedBy | endorserRole) & CS == CS\),
2. **Unbound** if in each conjunction set contains at least one role rejected the nomination, i.e., for each `CS`, \((rejectedBy | endorserRole) & CS != 0\),
3. **Nominated** if none of the conditions 1. and 2. are fulfilled yet, i.e., there is at least a conjunction set with no rejections and with roles pending to vote.

### 5.2 Experimental Setup

We conducted an evaluation to answer the following question: How does the cost (in gas/ether) of enforcing a binding policy increase depending on the size and complexity of the policy statements? We decompose this question into three: (Q1) How do the costs of deploying the generated smart contracts vary with the size of the policy? (Q2) How do the costs of executing the runtime operations vary with the size of the policy? (3) How does the combined cost of enforcing a process model and a binding policy varies with the size of the model?

It follows from Section 5.1 that the costs depend on the number of roles to nominate and the number of conjunction sets in the binding/endorsement constraints. Thus, we designed the following experiments: (E1) We varied the number of nomination statements in a policy from 1 to 40, without any binding or endorsement constraints. (E2) We fixed the number of statements to 40, selected one statement, and gradually increased the size of its conjunction set from 1 to 4

In Ethereum, gas is linearly related to throughput, see Section 2.1. So by answering this question we also indirectly answer the related throughput question.
40. (E3) We fixed the number of statements to 40, and gradually added a binding constraint with one conjunction set to each of the 40 statements. (E4,E5) The experiments E3 and E4 were repeated for the endorsement constraint (instead of the binding constraint). (E6) We generated a policy with 40 roles such that each statement includes a binding constraint stipulating that the nominated actor must belong to the role in the previous statement and that the nomination must be endorsed by all actors nominated in previous statements. (E7) Starting from a BPMN model with only one task, we iteratively expanded it by one task at a time (up to 40) and assigned each task to a different role. In this latter experiment, once a role was bound to an actor, we checked that the corresponding task could be performed. Note that the evaluation focuses on nomination statements, but the release statements are symmetric.

We implemented a replayer in Java that generates the policies, triggers their compilation and deployment, and executes the runtime operations via CATERPILLAR’s REST API. For each transaction included in the blockchain, Caterpillar sends some meta-data that includes block number, consumed gas, transaction hash which is collected and assessed by the replayer. For the experimentation we run a Node.js based Ethereum client named ganache-cli which is widely used to simulate a full client for developing and testing purposes on Ethereum.

5.3 Experimental Results

Deployment costs for experiments E1-E5 are plotted in Fig. 11. It can be seen that deployment costs increase quasi-linearly with the size and complexity of the policy. The simplest contract (with a single role bound to case-creator) costs 154,167 gas. As expected, the most pronounced growth in cost occurs for endorsement constraints (E4-E5) as they produce more instructions during code generation. We observe an increase of around 16.0 – 19.0% when adding a new endorsement constraint and 5.0 – 6.5% when adding a conjunction set to a constraint. Experiments E2-E3 show that adding a binding constraint increases cost by 4.0 – 5.7%, while adding a conjunction to a constraint adds 2.4 – 3.5% overhead. E1 shows that adding one unrestricted statement to nominate a role adds 4.0 – 4.5% overhead.

![Fig. 11. Growth of deployment costs with size of binding policy.](https://github.com/trufflesuite/ganache-cli)
For the runtime operations, we observed that costs vary depending on the number and the order of statements and conjunction sets in the constraints. The cost to nominate a role is higher when the corresponding policy statement is at the end of the policy. Similar behavior was observed for binding and endorsement constraints. This is because in Ethereum, the gas depends on the number of bytecode instructions executed. Hence, in a function with if-else-if instructions, the cost increases with the number of evaluated conditions. Table 1 shows the min, max, and average costs to perform the nominate and vote operations in experiments E1-E5. Note that voting is less costly than nominating and nomination costs are lower when restricted by binding constraints compared to endorsement constraints.

The combined cost of executing a process model with an associated policy (experiment E6) has several components. First, the contract BINDINGACCESSCONTROL must be deployed at a fixed cost of 1,340,098 gas, entailing a transaction fee of 0.0067 ether (ETH). Next, the contracts generated from the policy must be deployed, with gas ranging from 154,167 (simplest) to 1,803,898 gas (largest policy), corresponding to 0.0007 ETH to 0.0090 ETH. The smart contracts derived from the policies are deployed once and then reused, while the contracts handling the process execution are deployed for each case. Thus the policy deployment costs are amortized as more cases are executed. At runtime, roles have to be bound to actors. The costs of executing one nominate operation ranged from 111,407 (0.0005 ETH) to 168,270 (0.0008 ETH), while the vote operations cost between 76,845 (0.0003 ETH) and 78,184 (0.0003 ETH). Finally, when an actor performs a task, function canPerform is called to check if the actor is bound to the task’s role. This function invokes the TASKROLEMAP smart contract to retrieve the task-role relation. We observed a linear growth in the deployment cost of this contract as the number of tasks increased, from 129,539 gas (0.0006 ETH) to 241,114 (0.0012 ETH). The cost of function canPerform also grew linearly from 31,693 (0.0001 ETH) to 33,066 (0.0001 ETH).

### Table 1. Cost of nominations and votes

|   | E1 | E2 | E3 | E4 | E5 |
|---|---|---|---|---|---|
| Nom. | Min. | Max. | Ave. | Min. | Max. | Ave. | Min. | Max. | Ave. |
|     | 151,586 | 152,638 | 151,948 | 151,586 | 152,638 | 151,948 |
|     | 112,476 | 152,790 | 151,270 | 76,845 | 78,136 | 77,463 |
| Max. | 111,407 | 113,447 | 112,277 | 77,184 | 78,184 | 77,541 |
| Ave. | 132,417 | 152,746 | 151,738 | 131,493 | 153,800 | 142,660 |

6 Conclusion

Motivated by the possibilities opened by blockchain-based collaborative process execution, this paper presented a role binding model and a binding policy language that support collaborative binding and unbinding of actors to roles at runtime. The proposal includes a method to verify the consistency of policies defined in the proposed language and an approach to compile the policies into smart contracts. The proposal has been implemented on the CATERPILLAR blockchain-based collaborative process execution tool. We evaluated the

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6 Gas price: 5 Gwei, average from [https://ethgasstation.info](https://ethgasstation.info) on 30/11/2018.
costs (and therefore throughput) to deploy and execute smart contracts generated from binding policy statements, on the Ethereum platform. The evaluation shows that the deployment and runtime policy enforcement costs grow linearly with the number of roles and the complexity of the constraints. We acknowledge that the evaluation is limited in scope (only one business process and up to 40 roles) and focuses on evaluating cost. An avenue for future work is to further validate the approach via more thorough experiments and case studies.

While the proposed approach has been designed with the goal of supporting collaborative process execution on blockchain, its field of possible applications is wider. Another future work avenue is to study the applicability of this approach to other blockchain applications where dynamic role binding may be required, e.g. in crowdsourcing and computer-supported collaborative work scenarios.

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