Smart Contract Generation for Inter-Organizational Process Collaboration

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Abstract-Currently, inter-organizational process collaboration (IOPC) has been widely used in the design and development of distributed systems that support business process execution. Blockchain-based IOPC can establish trusted data sharing among participants, attracting more and more attention. The core of such study is to translate the graphical model (e.g., BPMN) into program code called smart contract that can be executed in the blockchain environment. In this context, a proper smart contract plays a vital role in the correct implementation of block-chainbased IOPC. In fact, the quality of graphical model affects the smart con-tract generation. Problematic models (e.g., deadlock) will result in incorrect contracts (causing unexpected behaviours). To avoid this undesired implementation, this paper explores to generate smart contracts by using the verified formal model as input instead of graphical model. Specifically, we introduce a prototype framework that supports the automatic generation of smart contracts, providing an end-to-end solution from modeling, verification, translation to implementation. One of the cores of this framework is to provide a CSP#-based formalization for the BPMN collaboration model from the perspective of message interaction. This formalization provides precise execution semantics and model verification for graphical models, and a verified formal model for smart contract generation. Another novelty is that it introduces a syntax tree-based translation algorithm to directly map the formal model into a smart contract. The required formalism, verification and translation techniques are transparent to users without imposing additional burdens. Finally, a set of experiments shows the effectiveness of the framework.

Index Terms—Inter-Organizational Process Collaboration, Blockchain, BPMN, Smart Contract, Verification

I. INTRODUCTION

At present, inter-organizational process collaboration (IOPC), as a distributed para-digm, has been widely used

in the design and development of software systems that support business process execution [1]. Furthermore, because of its powerful modeling ability, Business Process Model and Notation 2.0 (BPMN for short) [2] has become one of the most commonly used proposals when defining process models, supporting the design and implementation of IOPC from the perspective of model-driven development.

Blockchain is an emerging decentralized technology for establishing trusted data sharing among participants [3]. Since it is tamper-proof, the executed log records will not be disputed by possible forgery by participants or third parties. This enables it to provide a full process audit trail of transactional data. Benefiting from the above features, IOPC combined with blockchain has attracted more and more attention, and has been explored in many fields, e.g., supply chain [4, 5], government service [4], e-commerce [5] and others [8-10]. This type of study usually translates the model (e.g., BPMN) into program code called smart contract that can be executed in the blockchain environment, and coordinates and records the task execution and interaction of the participants. In this context, a smart contract that meets expectations plays a vital role in the correct implementation of blockchain-based IOPC.

In fact, the generation of smart contract (as object code) is directly affected by the graphical model of IOPC (as source code). Although BPMN has been widely used as a de facto modeling standard, semiformal definition and natural text description sometimes contain misleading information in model description [6]. This may become more serious in industrial environment, because model designers are usually not familiar with formalism and verification technology, but are used to standard graphical symbols. In this context, the quality of the graphical models may be uneven. The low-quality models (e.g., deadlock) may result in incorrect contracts that cause undesirable behaviours, and more importantly, it is hard to repair the contracts after implementation.

To avoid undesired implementation, this paper proposes an automated framework support the smart contract generation for IOPC. It covers the complete life cycle of IOPC from modeling, verification, translation to implementation. One of its core is to propose a suitable formal model as the source code for smart contract generation. As we all know, a formal model has clear execution semantics, can accurately describe the behavior specification, and avoid the ambiguity caused by semiformal and text description. In particular, it can identify problematic models in advance through model checking, which enhances the confidence of quality of models and software systems. These are particularly important for IOPC involving a large number of message interactions, because the graphical model is prone to deadlock due to message congestion, and its corresponding smart contract is difficult to repair in real time [7].

Specifically, the framework first uses BPMN collaboration model to represent IOPC. In practice, BPMN collaboration can intuitively representing the boundaries and business responsibilities of participants, focusing on interaction in collaboration [3, p. 317]. Furthermore, due to the advantages of Communicating Sequential Programs (CSP#) [8] in message communication and structured representation, we give a structured formalization for the BPMN model and the corresponding automatic translation algorithm, that is, the model elements are mapped to the corresponding composition of CSP# processes. This facilitates the subsequent smart contract generation.

Another key is the translation from CSP# model to smart contract. The formal model is parsed into a syntax tree structure, in which all internal nodes are non-terminal symbols, and each leaf node is a terminal symbol, representing a component element of the CSP# model. Based on the syntax tree, a two-stage translation algorithm is given, with a formal model as input instead of a semiformal graphical model. It first traverses the relationships among the formal model elements to determine the logical execution order, and then translates each element in turn into the smart contract codes written in Solidity. Finally, a set of experiments shows the effectiveness of prototype framework.

In summary, the main contributions of this paper include the followings:

- We propose a prototype framework for automatic smart contract generation for IOPC, which provides an end-to-end solution integrating "modeling-verificationtranslation-implementation". The required formalism and translation technology are transparent to users, so the framework does not impose additional user burden while achieving the expected goal.
- We give a CSP# formalization of BPMN collaboration model and the corresponding translation algorithm from BPMN model to formal CSP# model. Different from the existing proposals, it is structured and focuses on message communication, ignoring internal elements that do not

participate in interaction. This structured formalization is particularly suitable for mapping to smart contract, reducing the complexity of translation.

• We develop a translation algorithm from CSP# model to smart contract. It starts with defining the association relationships between model elements, and then generates contract code by parsing the syntax tree of formal model. This algorithm employs the knowledge of compilation principles (lexical and syntax analysis), which is conducive to accurate understanding and translation of smart contract.

The rest of this paper is organized as follows. Section 2 briefly describes a running example to illustrate the context and motivation of this work. Section 3 introduces the framework and Section 4 describes the core methods in detail. Section 5 shows a set of experiments and discusses some observations obtained in the experiments. After reviewing the related work in Section 6, Section 7 summarizes the paper.

II. RUNNING EXAMPLE

This section introduces a supply chain process collaboration scenario as an example throughout this paper, which is convenient to explain the context and motivation of our work.

In the collaboration scenario, the participants come from different organizations and assume different business responsibilities. Each participant has its own BPMS and establishes interaction with each other through the blockchain-based collaboration service (agent). The internal processes of participants are implemented on its own BPMS to ensure privacy, while the collaboration process is translated into a Solidity smart contract deployed in the blockchain environment, which stores transaction information and controls the interaction order to provide mutual trust.

The supply chain example adapted from literature [9] describes the manufacturing and delivery process of product order, involving 5 participants: *Wholesaler*, *Manufacturer*, *Broker*, *Supplier* and *Carrier*. The collaboration model is shown in Fig. 1. We don't provide a detailed description of the model here, because the meaning of each task should be intuitive.

This collaboration scenario needs to fully consider the model design of multiple participants and a large number of message interactions among participants. Indeed, complex model design and message flow configuration is an error prone task. For example, in the collaboration between *Carrier* and *Supplier*, messages are blocked due to the wrong configuration of tasks and messages in the gateways, resulting in deadlock. Once this model is translated and deployed directly, blockchain may lose its essential meaning, that is, it cannot achieve accurate collaboration with this supply chain scenario. More detailed knowledge about BPMN, CSP# and blockchain is provided in the technical report of the repository¹.

¹https://github.com/xthHub/SCG4IOPC



Fig. 1. BPMN Collaboration model of supply chain scenario.



Fig. 2. The overview of integrated framework.

III. FRAMEWORK

The framework provides an end-to-end solution from modeling to implementation for smart contract generation for IPOC. It consists of 5 parts: Modeling, Translation (translate BPMN to CSP# model), Verification, Generation (translate CSP# model to smart contract), and Implementation. Fig. 2 shows the internal components of the framework and the user interfaces/operations related to the system designers.

The special feature of framework is that the system designers only need to focus on the modeling, optimization (e.g., adjusting the model according to the counter examples) and monitoring, without mastering the formal language, verification and parsing techniques. The framework is developed as a stand-alone solution, but it can also be integrated as a service accessed through RESTful interface or as a plug-in in existing tools.

The modeling environment integrates a graphical modeling tool Camunda_bpmn.io [10] that supports BPMN standard. Furthermore, considering the diversity of existing modeling tools, the framework does not impose any restrictions on the source of the graphical models. Input models (.bpmn file format) can be created by system designers using different BPMN modeling tools, or retrieved from a common repository. In this regard, the framework is not limited to specific modeling tools, and is easy to use by system designers from different business fields.

The framework provides an implementation environment, as shown in the right part of Fig. 2. Workflow engines (BPMS) are logically aggregated and physically dispersed. They perform the internal processes of participants and interact with the Blockchain environment through Agents. The Solidity smart contract deployed in blockchain is used to record transaction data and control the order of interaction among participants. Here, workflow engine extends the open source engine Zeebe² to support the instantiation of BPMN model. Blockchain environment is based on Ganache³ that is a node emulator of Ethereum. The agent based on the interoperability protocol Wf-XML 2.0 [11], is responsible for monitoring the state

²https://github.com/camunda-cloud/zeebe

³https://www.trufflesuite.com/ganache

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\begin{split} C &::= \operatorname{pool}(p, P) \mid C1 \parallel C2 \\ P &::= \operatorname{start} \mid \operatorname{end} \mid \operatorname{andGate}(T1, T2 \dots Tn) \mid \operatorname{xorGate}(T1, T2 \dots Tn) \mid \operatorname{eventbaseGate}(T1, T2 \dots Tn) \mid \operatorname{task} \\ \mid \operatorname{sndTask}(M) \mid \operatorname{rcvTask}(M) \mid \operatorname{sndInter}(M) \mid \operatorname{rcvInter}(M) \mid P1 \mid P2 \\ T &::= \operatorname{task} \mid \operatorname{sndTask} \mid \operatorname{rcvTask} \mid \operatorname{andGate} \mid \operatorname{xorGate} \mid \operatorname{eventbaseGate} \mid T1, T2 \\ M &::= (\operatorname{ch}(P1, P2), m) \mid M1, M2 \end{split}
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Fig. 3. The overview of integrated framework.

changes, initiating or receiving (actively subscribing) external requests, and triggering task or event execution. The Frontend UI provides a user-friendly web interface and supports the complete data display.

IV. METHODS

This section introduces CSP# model translation and smart contract generation in detail.

A. Translation from BPMN to CSP# Model and Formal Verification

This sub section describes the translation of BPMN to CSP# model, and the property verification. To simplify CSP# formalization, inspired by literature [6], we apply the general syntax notation BNF to textual BPMN model.

a) Translation: The BNF syntax definition of the core elements of the collaboration model is given, as shown in Fig. 3. It maps model elements to structured text descriptions to facilitate subsequent formalization. In this syntax, C, P, T and M represent collaboration structure, participant structure, element list and message list respectively.

A collaboration *C* represents a model composition that associates *pool* (p, P) with the parallel operator "||". In the pool, *p* is the name of the pool and *P* is the encapsulated participant model (process). To simplify formalization, we assume that each pool contains only one participant, and treat the gateway as a structured whole containing split and join mode, with unique input and output sequence flow. For example, andGate (T1, T2...Tn) captures all the elements it affects, where T1, T2...Tn respectively represent the element list on each inner parallel edge. The message list *M* contains a series of triple (ch(P1, P2), m), where *ch* is the channel, *P1* is the sender, *P2* is the receiver, and m is the designated unique message name.

The above BNF syntax only provides a structured description. To describe the semantics, we employ the features of structured representation supported by CSP#. Each graphical model element is mapped to a structured CSP# process consisting of alphabet, operators and keywords, as shown in Table 1. In task element, $event_{work}$ represents the work of the task (i.e., $event_{work} -> Skip$;). We assume that the send and receive tasks (i.e., sndTask and rcvTask) are only responsible for message interaction. According to task types, $event_{work}$ can be mapped to channel operations (i.e., ch!m and ch?m, respectively). Note that the channel can be seen as a FIFO queue here.

A part of Translation Algorithm from BPMN to CSP# model			
Input info: BPMN node			
Output info: target_code			
1: for each $m \in messageFlow // processing message flow, message channel$	for each $m \in messageFlow //$ processing message flow, message channel		
2: define a new message			
3: if channel_list[messageFlow] is new	if channel_list[messageFlow] is new		
4: define a new channel	define a new channel		
5: end if			
6: end for			
7: for each $p \in participant // processing participants with unique start and end events$	for each $p \in participant // processing participants with unique start and end events$		
8: find <i>startEvent</i> \in <i>p</i>			
9: $target_code \leftarrow return_temp_code;$			
10: end for			
11: return target_code			
12: Function return_temp_code //all branches are stopped at the corresponding			
//gateway or end event			
13: if type(node, startEvent) type(node, task) type(node, endEvent) type(node, startEvent) type(node, startEve	gate)		
14: then			
15: do conversion according to node type and mapping rules in Tables 1			
16: return temp_code			
17: end function			

The gateway affects multiple elements. These elements (e.g., multiple tasks) are associated by the sequential, parallel or choice operators. Thus, according to the covered elements, the gateway is represented as a composition of elements. For example, the CSP# process of *Broker* participant (see Fig. 1) is a composite process that contains three task elements.

 $Broker() = (event_{e1} \rightarrow Skip; cMB?SupplierOrder \rightarrow Skip; event_{e2} \rightarrow Skip); ((event_{e2} \rightarrow Skip; cBS!TurnSupplierOrder \rightarrow Skip; event_{e3} \rightarrow Skip) || (event_{e2} \rightarrow Skip; cBC!TransportOrder \rightarrow Skip; event_{e3} \rightarrow Skip)).$

This means that the *Broker* first receives message *SupplierOrder* through channel *cMB*, and then it will perform the parallel operation, sending messages *TurnSupplierOrder* and *TransportOrder* through channels *cBS* and *cBC*, respectively.

The corresponding translation algorithm first reads the BPMN model and stores the elements in the corresponding nodes. Then it traverses the model and constructs NextElements. Finally, it adopts depth first traversal method to recursively maps elements to CSP# process according to the rules in Table 1. Limited by space, only part of the algorithm is shown below.

b) Formal Verification: This paper focuses on the soundness verification of collaboration model. It is a fundamental requirement for IOPC [12]. The IOPC is sound if all participants are sound and there are no undelivered messages among participants. The soundness of participants means that it is terminable, there is no deadlock, and each task is reachable

 TABLE I

 A CSP# FORMALIZATION FOR CORE COLLABORATION MODEL ELEMENTS

Elements	BPMN Syntax	CSP#
	$task(e_i, e_o)$	$event_{ei}$ ->Skip; $event_{work}$ ->Skip; $event_{eo}$ ->Skip
Tasks	$sndTask(e_i, M, e_o)$	$event_{ei}$ ->Skip; ch!m ->Skip; $event_{eo}$ ->Skip
	$rcvTask(e_i, M, e_o)$	$event_{ei}$ ->Skip; ch?m ->Skip; $event_{eo}$ ->Skip
	andGate $(e_i, (T1,T2Tn), e_o)$	$event_{ei}$ ->Skip; (T1 T2 Tn); $event_{eo}$ ->Skip
Gateways	$\operatorname{xorGate}(e_i, (T1, T2Tn), e_o)$	$event_{ei} \rightarrow Skip;$ (T1 [] T2 [] [] Tn)); $event_{eo} \rightarrow Skip$
	eventbaseGate(e_i , (T1,T2Tn), e_o)	event _{ei} ->Skip; (T1 [*] T2 [*] [*] Tn)); event _{eo} ->Skip

(executable). The formal definition is given below.

Formally, Soundness: \forall participant \in P: deadlock-free(participant) $\land <> (\forall participant \in P: participant reaches end <math>\land \forall ch \in$ channel: |ch|=0), where deadlockfree, nonterminating and reaches are CSP# based attribute assertions, end is a given conditional proposition and "|ch| = 0" indicates that there is no message in the channel ch.

In fact, besides soundness, user-defined property verification is also supported. For example, given a participant, the following assertion asks whether participant satisfies the LTL formula. Formally, #assert *participant* |= F, where F is the LTL formula.

According to the selected properties, the framework automatically completes formal verification. Once the verification fails, it will feedback a counter example.

B. Translation from CSP# Model to Smart Contract

This section introduces the translation algorithm of mapping CSP# model to Solidity smart contract. Inspired by the knowledge of lexical and syntax analysis, a two-stage algorithm is given. Firstly, a set of association relationships is defined to specify the logical order among the elements within the participants and among the participants. Secondly, the syntax tree of the formal model is given, and a traversal algorithm is used to capture the set of association relationships based on the syntax tree.

a) Association relationships between CSP# Processes: Association relationships describe the interaction (execution order) among different model elements within participants and among participants. These relationships are the basis of automatic generation of smart contracts. Here we defines 6 kinds of relationships, including Next, End, Init, And, Xor and Enable. The first five of them indicates the interaction among the CSP# processes within the participants, while the last one specifies the interaction logic constraints among the participants. The 6 relationships are essentially the analysis of process structure. They cover sequence, branch, parallel and loop, and can combine any single entry and single exit process structure.

- Next describes the sequential relationship between CSP# processes within a participant. If CSP# process *P1* ends, then CSP# process *P2*[] will start. That is, Next (*P1*) = [*P2*[]] where *P2*[] is a CSP# process array.
- End describes the end relationship between CSP# processes within a participant. When a process ends, it triggers other processes to end. If P1 ends, then P2[] will end. Namely, End (P1) = [P2[]].

- Init describes the initialization relationship between CSP# processes within a participant. If *P1* begin, then *P2*[] begins first. That is, Init (*P1*) = [*P2*[]].
- And describes the relationship among CSP# processes involved in parallel gateway. If And (*P1*) = [*P2*[]], then *P1* ends only if *P2*[] ends.
- Xor describes the relationship among CSP# processes involved in exclusive gateway. If P2 ∈ Xor (P1) is executing, ∀ P3 ∈ Xor (P1) is disabled.
- Enable describes the enabling relationship of message interaction between participants. The message flow M specifies the enabling relationship between sender and receiver. If M = (ch(P1, P2), m), Enable (P1) = [P2].

Fig. 4 shows the relationships of *Broker* participant in the supply chain example. *Broker* is a **composite process**, so is *P2*, which is composed of more than one **atomic process** like *P1*, *P3* and *P4*.

Init (Broker) = [P1], which means that when the *Broker* is started, *P1* will execute first. Next (P1) = [P2], which means that when *P1* is completed, *P2* can start. End (P2) = [Broker], which means that when *P2* is completed, it triggers the *Broker* to end. In addition to complying with the internal relationships in *Broker*, whether *P1* (responsible for receiving *SupplierOrder* message) can be executed also depends on the Enable relationship of the external participant (i.e., Enable (external participant) = [P1]), because it requires the external participant to complete the sending of the message first. Because the focus of this paper is process collaboration, in order to facilitate a clear analysis of the collaboration model, here we ignore the internal events that do not participate in the interaction.



Fig. 4. The relationships of Broker participant.



Fig. 5. The syntax tree of Broker participant.

b) Relationship traversal algorithm: The relationship traversal algorithm is based on syntax tree. To facilitate the traversal and display of relationships, an syntax analysis tool ANTLR (Another Tool for Language Recognition) [13] is used to obtain the syntax tree of CSP# model. For example, Fig. 5 shows the syntax tree of the Broker participant, in which the leaf nodes form its CSP# process from left to right, i.e., Broker() = cMB?SupplierOrder -> Skip; (cBS!TurnSupplierOrder-> Skip || cBC!TransportOrder -> Skip). The spec, definition, simpleDefinition, definitionLeft, defnCallLeft are the default reserved words. A part of the algorithm is given here as an example. It traverses the syntax tree to get the logical association relationships in the CSP# processes.

A part of Relationship Traversal Algorithm					
Input info: S	Input info: Syntax tree node with 3 subtrees // Traverse the node with 3				
subtrees ///	subtrees //Node.LeftS: process corresponding to the left subtree				
//Node.Ri	ightS: process corresponding to t	he right subtree			
1: if IsSe	micolon (Node.MiddleS) then	//";"operator, sequential execution			
2:	add Node.RightS to Next[Node	.LeftS];			
3:	add Node to End[Node.RightS];			
4:	add Node.LeftS to Init[Node];				
5: if IsPa	arllel(Node.MiddleS) then	//" " operator, parallel execution			
6:	add Node to End[Node.LeftS];				
7:	add Node to End[Node.RightS];			
8:	add Node.LeftS and Node.Righ	tS to Init[Node];			
9:	add Node.LeftS and Node.Right	S to And[Node];			
10: if IsE:	xclusive(Node.MiddleS) then	// "[]"operator, exclusive execution			
11:	add Node to End[Node.LeftS];				
12:	add Node to End[Node.RightS];				
13:	add Node.LeftS and Node.RightS	S to Init[Node];			
14: a	dd Node.LeftS and Node.RightS	to Xor[Node];			
15: return	n Next. End. Init. And. Xor				

c) Reduction: Our goal is to generate smart contracts, and the content of the contracts will affect the cost to execute them, so we take some measures to reduce the cost as much as possible. Note that the relationships defined above are used

to describe the association of **all nodes** in the syntax tree, which contains many non-leaf nodes, corresponding to the CSP# composite processes. However, leaf nodes are enough to form the whole CSP CSP# composite process like *Broker()*. So our strategy is to concentrate on the CSP# **atomic processes** (leaf nodes in the syntax trees), and the relationships between them. Here we define three new relationships to achieve our reduction: Activate, Inactivate, Parallel.

- Activate describes the sequential relationship between CSP# atomic processes within a participant. If atomic process *P1* finishes its execution, atomic processes in *P2*[] will start, then we have Activate (*P1*) = [*P2*[]] where *P2*[] is a atomic process array.
- Inactivate describes the inactivate relationship between CSP# atomic processes within a participant. If atomic process P1 finishes its execution, atomic processes in P2[] can't be executed in this business process instance, then we have Inactivate (P1) = [P2[]]
- Parallel describes the relationship among CSP# atomic processes involved in parallel gateway. If Parallel (*P1*) = [*P2*[]], then the process must wait for atomic processes *P1* and *P2*[] finishing their execution to continue.

As mentioned above, the new relationships only concern about atomic processes. The Reduction Algorithm helps us to get the new relationships by removing the state transitions involving the non-leaf nodes in the syntax trees. Now, we use Activate, Inactivate, Parallel and Enable to describe the interaction within and among participants. Fig. 6 shows the new relationships of *Broker* participant. It can be observed that, compared with Fig. 4, the state transition is more simple, and composite processes like *P2* have been removed.



Fig. 6. New relationships of Broker participant.

A part of the Reduction Algorithm is given here as an example. It starts with the CSP# processes and the old relationships, ending with the new relationships.

d) Smart Contract Generation: Smart contract refers to the program code running in the blockchain environment. It controls the execution of the collaboration model in the order specified in advance. Specifically, it drives the change of process state by receiving external requests, judging the

A pa	A part of Relationship Reduction Algorithm			
Inpu	Input info: CSP# proc of the participant			
	Relationships: Next, End, Init, And, Xor:			
1:	for proc in AtomicProcesses			
2:	search up with End[] recusively until find p that Next[End[p]] exists;			
	// End[p] refers to an ancenstor of proc in the syntax tree			
3:	s = Next[End[p]];			
4:	for child in <i>Init[s]</i>			
5:	<pre>aps = FindAtomicProcessesWithInit(child);</pre>			
	// find atomic processes in the subtree with Init			
6:	add aps to Activate[proc];			
7:	for proc in ExclusiveGatewayProcesses			
	// find the first atomic processes in every outgoing path			
8:	LeftAtomicProcesses = FindAtomicProcessesWithInit(Xor[proc][1]);			
	RightAtomicProcesses = FindAtomicProcessesWithInit(Xor[proc][2]);			
9:	for left in LeftAtomicProcesses			
10:	add RightAtomicProcess to Inactivate[left];			
11:	for right in RightAtomicProcesses			
12:	add LeftAtomicProcess to Inactivate[right];			
13:	for proc in ParallelGatewayProcesses			
	// find the last atomic processes in every outgoing path			
14:	LeftAtomicProcesses = FindTheLastAtomicProcesses(And [proc][1]);			
	RightAtomicProcesses = FindTheLastAtomicProcesses (And [proc][2]);			
15:	for left in LeftAtomicProcesses	1		
16:	add RightAtomicProcess to Parallel[left];			
17:	for right in RightAtomicProcesses	2		
18:	add LeftAtomicProcess to Parallel[right];	(
19:	return Activate, Inactivate, Parallel	I		

legitimacy of the request (e.g., whether the task can be executed), and sending requests to other participants. Here, we introduce the automatic generation method for Solidity smart contract that is widely used Ethereum environment.

The core of smart contract generation is to respond to the corresponding requests according to the states of CSP# process and the relationships between CSP# processes. These requests trigger changes in the states of CSP# process.

The states of CSP# process are defined as follows. *Disabled* indicates that the process is silent and execution is not allowed. *Waiting* indicates that the process is enabled and waiting to be executed. *Executing* indicates that the process is executing. *Done* indicates that the execution of the process is completed and the process exits the executing state.

In this paper, the smart contracts generated are composed of many functions used to handle external request. The external request is responsible for handling message interaction and event trigger. It checks the state of the CSP# process and trigger the state change of other CSP# processes according to the association relationships At the same time, it forwards the message to the receiver (listening), and activates the receiving condition of the receiver. The external request algorithm is shown below.

V. EXPERIMENTS

This section tests a case set including 5 application cases to illustrate the effectiveness of the framework. These cases

Exte	ExternalRequest Algorithm			
Inp	Input info: CSP# atomic proc			
1:	if State(proc) is not Waiting then			
	return false;			
2:	if Type(proc) is sender then // proc is a send task			
3:	stateChange(proc, Executing); //change the state to Executing			
4:	emit message event of rcvProc; // rcvProc = Enable[proc]			
5:	set RcvActivated[rcvProc] as true; // the receive condition is triggered			
6:	if Type(proc) is receiver and RcvActivated [proc] is true then			
7:	// proc is a receive task and the receive condition is triggered			
8:	<pre>stateChange(proc, Executing);</pre>			
9:	if Inactivate[proc] exists then // inactivate the xor procs			
10:	for $xorProc \in Inactivate[proc]$			
11:	<pre>stateChange(xorProc, Disabled);</pre>			
12:	stateChange(proc, Done); ////change the state of proc to Executing			
13:	if Activate[proc] exists then			
14:	if Parallel[proc] exists then // deal with the parallel procs			
15:	if all procs in Parallel[proc] is Done			
16:	for $nextProc \in Activate[proc] // activate the next procs$			
17:	<pre>stateChange(nextProc, Waiting);</pre>			
18:	else			
19:	for $nextProc \in Activate[proc]$			
20:	stateChange(nextProc, Waiting);			

are from the existing literature [9], BPMN sample library and BPMAI [14], covering different application scenarios, namely supply chain (SC), booking travel (BT), online education (OE), paper review (PR) and pastry cook (PC). Here, we test each case (1) with smart contracts generated by our method(labelled as A). Besides, we conduct a comparative experiment (2) with contracts generated by the method of [9](labelled as B) and manually contracts written in the way inspired by [15](labelled as C). Note that B is a classic method of smart contract automatic generation in the field of IOPC. This mainly considers the following reasons: Firstly, we want to observe whether the proposed framework meets our expected objectives (for (1)); Secondly, by quantitatively comparing the differences among the methods, we expect for a feasible direction for subsequent optimization (for (2)). Moreover, we provide a detailed analysis from the perspective of methodology in Section 6.

Table 2 shows the statistics of the experiments. Note that we have tested all the execution paths (branches) of each model and report the transaction data with the longest execution path in the order of message interaction.

One of advantages of our framework is that it provides model verification by introducing a formal model. Considering the Verification, the framework automatically performs model checking according to the selected properties. Once the verification fails, the framework will give corresponding counter examples to help users correct the problematic model. In these 5 cases, SC and BT are detected not to meet the soundness requirements, where Round 1 and Round 2 in the table represent their first round verification (failed) and modified verification (passed) respectively. If the verification fails, the model designers need to modify the model according to the prompt of counter example.

Only when the verification is passed, the framework gen-

Casa	Verification	Contract Execution			
Case	Soundness(Y/N)	Item	Our Method(A)	B	С
Supply Chain (SC) (Round 1)	Ν		_	_	—
	Y	Total Gas Cost	1472682	1374716	1091035
Supply Chain (SC)		Compared with C	135%	126%	100%
(Round 2)		Initialization Gas Cost	1099479	1016856	767555
		Initialization Gas Ratio	74.66%	73.97%	70.35%
Booking Travel (BT) (Round 1)	N	_	_	_	_
	Y	Total Gas Cost	673808	653868	505198
Booking Travel (BT)		Compared with C	133%	129%	100%
(Round 2)		Initialization Gas Cost	566762	548688	401313
		Initialization Gas Ratio	84.11%	83.91%	79.44%
	Y	Total Gas Cost	612334	567097	505198
Online Education (OE)		Compared with C	127%	118%	100%
Olimie Education (OE)		Initialization Gas Cost	474703	434975	346800
		Initialization Gas Ratio	77.52%	76.70%	72.21%
	Y	Total Gas Cost	580467	600144	450903
Dopar Daviaw (DD)		Compared with C	128%	133%	100%
Paper Review (PR)		Initialization Gas Cost	475029	494899	347062
		Initializations Gas Ratio	81.84%	82.46%	76.97%
	Y	Total Gas Cost	837937	741897	689443
Pastry Cook (PC)		Compared with C	121%	107%	100%
Tastry COOK (FC)		Initialization Gas Cost	628723	543578	460708
		Initialization Gas Ratio	75.03%	73.27%	66.82%

TABLE II Statistics of experiments

erates the smart contract based on the formal model. After manual inspection one by one, all smart contracts comply with the original model specifications and can be executed correctly. The APPENDIX shows a segment of the smart contract code of the supply chain scenario. However, in the comparative experiments, we find that it is not easy for experimenters to find abnormalities (because both methods don't include verification phase), and most of them still convert the problematic model directly into a smart contract. This reminds us that a formal model is necessary and meaningful as the input of smart contract generation. In this way, the verified formal model can not only provide clear execution semantics for the graphical model and eliminate ambiguity for the accurate generation of smart contracts, but also identify unqualified models in advance through model checking to avoid undesired contract implementation.

It can be observed that in terms of Gas Cost, smart contracts generated by automation method cost more gas than manual written contracts. Both A (our method) and B bring more gas consumption than C, because smart contracts in A and B need to deal with more complex state transition conditions, leading to a lot of data recording costs and data update costs.

From the perspective of contract auto-generation, our method costs slightly more gas than B. However, our method could detect flaws of the graphic models in advance, which helps to avoid contract generation in the wrong base. Specifically, our method includes verification phase, and take as input the formal models that have passed the verification, rather than the manually designed graphic models that have a potential for flaws. In general, though our method costs 4%-9% more than B, we could save a lot of work of contract test, contract deploy and contract revision.

Furthermore, when we compare the gas cost details of the contracts, we find that in all groups of our experiments, contract initialization, as the first transaction, is the most expensive one, always taking up more than 70%. Taking the SC in the experiment A as an example, the gas cost of its first transaction is 1099479, which is much higher than the cost of subsequent transactions (the gas used is among 34019 and 56952). From this point of view, the main cost of the contract execution is contract initialization, while the gas cost caused by message interaction is relatively small. This reminds us that we should pay more attention to contract initialization in smart contract generation and optimization, so as to further reduce the cost.

VI. RELATED WORK

This section reviews the current work on smart contract generation and formalization of BPMN collaboration model.

A. Researches on Translation of BPMN Model to Smart Contract Generation

The existing work mainly focuses on two different technical methods, namely the direct translation of BPMN models into smart contracts and the translation of BPMN models into smart contracts through intermediate formalisms.

Due to the difference of input model types and framework configurations, it is difficult to provide a quantitative experimental analysis for different methods from time or cost. Here we make a comparative analysis from the aspects of method, formalism, input model and intention. We add reference [7] because it is the latest representative on smart contract generation and is most relevant to ours in terms of intention. Considering direct translation, Weber et al. [9] for the first time propose the implementation and monitoring solution of IOPC based on blockchain to deal with the problem of mutual distrust among participants. To this end, it provides a translation algorithm and tool implemented in [16] to map BPMN choreography elements to the corresponding smart contract. López-Pintado et al. [17] combine the advantages of BPMS and blockchain platform to design a business process engine Caterpillar that can be executed on Ethereum. Different from other methods, it is a complete block-chain collaboration platform. Besides the smart contract of the collaboration model, other BPMS components such as work item are also embedded in the blockchain environment.

Furthermore, the work of Ladleif et al. [4] is an extension of [9]. It points out the shortcomings of BPMN choreography model in terms of ownership and local observability according to the technical characteristics of blockchain (such as shared data and smart contract). Then the authors provide an extension and refinement of BPMN 2.0 choreography, and propose a proof of concept framework to fill the gap between modeling and implementation. From a model-driven perspective, Corradini et al. [5] try to provide a bridge between the graphical model description and the low-level code executed on the blockchain. To this aim, the authors propose an implementation framework based on blockchain, as an infrastructure to support model management and Solidity smart contract generation.

In fact, compared with graphical models, formal models have advantages in accurately describing model behavior specifications. More importantly, it can use model checking to identify problematic models. These features help to avoid the generation of undesired smart contracts and enhance the confidence of blockchain-based IOPC (distributed systems) in software quality. Thus, some studies try to explore the indirect translation method through formal models to help optimize and improve the implementation of IOPC. With respect to indirect translation, Zupan et al. [7] point that smart contract is very error-prone, and it is difficult to repair the contract after implementation, and the formal model helps in advance discovery of threats that cause insecurity. The authors introduce Petri net into the smart contract generation to avoid unexpected problems.

García-Bañuelos [18] introduce Petri net as the intermediate carrier of translation. This work focuses on how to reduce the gas cost of transaction as much as possible while generating smart contract. It proposes an optimization method for contract initialization cost, execution cost and component throughput to reduce the impact of data volume and data update frequency on cost. It maps the BPMN model to a Petri net, and then simplifies the model by eliminating invisible transitions and redundant places.

It is worth mentioning that Nakamura et al. [15] introduce statechart into the automatic generation of smart contracts. It transforms a BPMN process with swimlanes into multiple statecharts. In this way, the statecharts can be simplified conveniently, thereby reducing the need for data exchange with the blockchain in collaboration. Then the statecharts as input are translated into the smart contracts.

The work [18] and [15] are different from ours in terms of input model type and intention. Their focus is to reduce the cost of contract generation and execution by using the reduction technology of formal models, rather than focusing on the possible impact of problematic models. Furthermore, our work uses BPMN collaboration model to show the boundaries and roles of different participants. Meanwhile, in the formal method, we give a structured CSP# formalization that considers message communication and process interaction, which simplifies the formal model and contract generation.

B. Researches on CSP Formalization and Verification of BPMN Collaboration Model

The formalization of BPMN model, and on a wider scale the formal study of IOPC, is a hot research field. Many works have explored from the perspective of formal language, e.g., PN/WF-net, Process algebra (Pi calculus), LTS, and First-Order Logic (FOL) and so on. As described in Section 2.2, CSP# has advantages in process communication and structured representation, which help to reduce the complexity of smart contract generation. Here we focus on the existing CSP formalization and verification of BPMN collaboration related to our work.

As far as BPMN is concerned, both BPMN choreography and collaboration models could be used to model IOPC. The former is widely regarded as purely descriptive from a global point of view [4], while the latter has more advantages in intuitively representing the boundaries and business responsibilities of participants [3, p. 317]. More importantly, the BPMN collaboration has been widely used in the development of supporting software systems and serves as a starting point for model-driven development of distributed systems [1]. Thus, we here choose the collaboration model to describe the participants and their interactions.

Wong et al. [19] believe that a formal semantics for BPMN can ensure accurate specification and help designers to implement business processes correctly. To this end, the authors introduce Z syntax to describe BPMN structures. In particular, it employs the classic CSP and FOL to provide formalization for a subset of BPMN1.1. This formalization contains a lot of FOL and judgments (a lot of logic codes). This makes the formal models too complex and increases the complexity of smart contract generation.

Then, Corradini et al. [20] focuses on specific e-Government digital service requirements, using CSP to represent collaboration model of BPMN 1.1. In this work, a task is considered to be an element that may directly associate multiple input and output sequence flows. Its corresponding formalization maps multiple parallel flow events (sequence flows) into a CSP process. This way may make the generated formalization too bloated. In our method, tasks, including sending and receiving types, focus on the task itself and ignore the internal flow that does not participate in the interaction, which helps to reduce the complexity of formalization. Furthermore, the work of Capel et al. [21] can be regarded as an extension of [19]. It uses Z syntax and CSP + Time to provide the formalization of Timed BPMN 2.0. Each model element is attached with time constraints or rules, which is mapped to the corresponding CSP process. This work focuses on specific time constraints and cannot be directly applied to smart contract generation.

VII. CONCLUSION

This paper proposes a prototype framework to automatically generate smart contracts for IOPC. It provides an end-toend solution from modeling, verification, translation to implementation. As one of the cores, a CSP# formalization for BPMN collaboration model bridges the graphical model with the smart contract. Another novelty is the translation algorithm of smart contract. It takes the verified formal model as input instead of graphical model, and translates it into Solidity smart contract based on syntax tree. The proposed framework identifies the abnormal model in advance through model checking, preventing undesired contract generation and implementation. In addition, the required formalism, verification and translation techniques are transparent to users without imposing additional burdens. In this regard, this reduces the complexity of studying blockchain-based distributed systems and model-driven software development.

Some observations on gas cost are obtained from the experiment. Contract initialization is the most expensive, and its gas cost accounts for a high proportion of the total execution cost. This means that contract initialization should be an important optimization point when considering gas cost. In fact, as a hot topic, the combination of blockchain and IOPC is a systematic work involving many aspects, such as privacy, data storage, security and so on. This paper mainly discusses the relationship between IOPC described by BPMN collaboration models and smart contracts, and adopts the formal models to avoid the undesired contract implementations caused by lowquality models.

In the future, reducing the cost of smart contract generation and execution is one of the directions we are interested in. In addition, we plan to optimize the framework architecture, providing more interfaces for external integration. And we also seek support for more complex elements, such as complex gateway and subprocesses.

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REFERENCES

- O. Pastor, "Model-driven development in practice: from requirements to code," in *International Conference on Current Trends in Theory and Practice of Informatics*. Springer, 2017, pp. 405–410.
- [2] OMG, Business Process Model and Notation (BPMN), Version 2.0.2, Object Management Group Std., Rev. 2.0.2, Dec. 2013. [Online]. Available: http://www.omg.org/spec/BPMN/2.0.2
- [3] J. Mendling, I. Weber, W. V. D. Aalst, J. V. Brocke, C. Cabanillas, F. Daniel, S. Debois, C. D. Ciccio, M. Dumas, S. Dustdar *et al.*, "Blockchains for business process management-challenges and opportunities," *ACM Transactions on Management Information Systems (TMIS)*, vol. 9, no. 1, pp. 1–16, 2018.
- [4] J. Ladleif, M. Weske, and I. Weber, "Modeling and enforcing blockchain-based choreographies," in *International Conference on Business Process Management*. Springer, 2019, pp. 69–85.
- [5] F. Corradini, A. Marcelletti, A. Morichetta, A. Polini, B. Re, and F. Tiezzi, "Engineering trustable choreography-based systems using blockchain," in *Proceedings of the 35th Annual ACM Symposium on Applied Computing*, 2020, pp. 1470–1479.
- [6] F. Corradini, C. Muzi, B. Re, L. Rossi, and F. Tiezzi, "Animating multiple instances in bpmn collaborations: from formal semantics to tool support," in *International Conference on Business Process Management*. Springer, 2018, pp. 83–101.
- [7] N. Zupan, P. Kasinathan, J. Cuellar, and M. Sauer, "Secure smart contract generation based on petri nets," in *Blockchain Technology for Industry* 4.0. Springer, 2020, pp. 73–98.
- [8] J. Sun, Y. Liu, J. S. Dong, and C. Chen, "Integrating specification and programs for system modeling and verification," in 2009 Third IEEE International Symposium on Theoretical Aspects of Software Engineering. IEEE, 2009, pp. 127–135.
- [9] I. Weber, X. Xu, R. Riveret, G. Governatori, A. Ponomarev, and J. Mendling, "Untrusted business process monitoring and execution using blockchain," in *International conference on business process* management. Springer, 2016, pp. 329–347.
- [10] N. Rehwaldt, "Bpmn editor," https://bpmn.io/.
- [11] K. D. Swenson, S. Pradhan, M. D. Gilger, M. Zukowski, and P. Cappelaere, "Wf-xml 2.0 xml based protocol for run-time integration of process engines," *Workflow Management Coalition*, 2004.
- [12] S. Houhou, S. Baarir, P. Poizat, and P. Quéinnec, "A first-order logic semantics for communication-parametric bpmn collaborations," in *International Conference on Business Process Management*. Springer, 2019, pp. 52–68.
- [13] T. J. Parr and R. W. Quong, "Antlr: A predicated-ll (k) parser generator," Software: Practice and Experience, vol. 25, no. 7, pp. 789–810, 1995.
- [14] M. Kunze, P. Berger, M. Weske, N. Lohmann, and S. Moser, "Bpm academic initiative-fostering empirical research." in *BPM (Demos)*. Citeseer, 2012, pp. 1–5.
- [15] H. Nakamura, K. Miyamoto, and M. Kudo, "Inter-organizational business processes managed by blockchain," in *International Conference on Web Information Systems Engineering*. Springer, 2018, pp. 3–17.
- [16] A. B. Tran, Q. Lu, and I. Weber, "Lorikeet: A model-driven engineering tool for blockchain-based business process execution and asset management." in *BPM (Dissertation/Demos/Industry)*, 2018, pp. 56–60.
- [17] O. Lòpez-Pintado, L. García-Bañuelos, M. Dumas, I. Weber, and A. Ponomarev, "Caterpillar: a business process execution engine on the ethereum blockchain," *Software: Practice and Experience*, vol. 49, no. 7, pp. 1162–1193, 2019.
- [18] L. García-Bañuelos, A. Ponomarev, M. Dumas, and I. Weber, "Optimized execution of business processes on blockchain," in *International conference on business process management*. Springer, 2017, pp. 130– 146.
- [19] P. Y. Wong and J. Gibbons, "A process semantics for bpmn," in International Conference on Formal Engineering Methods. Springer, 2008, pp. 355–374.
- [20] F. Corradini, A. Polini, A. Polzonetti, and B. Re, "Business processes verification for e-government service delivery," *Information Systems Management*, vol. 27, no. 4, pp. 293–308, 2010.
- [21] M. I. Capel and L. E. Mendoza, "Automating the transformation from bpmn models to csp+ t specifications," in 2012 35th annual IEEE software engineering workshop. IEEE, 2012, pp. 100–109.

```
// SPDX-License-Identifier: MIT
                                                            function ReceiveProductOrder() public {
pragma solidity >=0.4.24;
                                                                 if (isEnabledReceiveProductOrder) {
                                                                      emit next("", "", "ReceiveProductOrder");
contract ServiceRegistry {
                                                                 }
  event next(bytes from, bytes to, bytes activity);
                                                                        isActiveSendSupplierOrder = true;
  string public version;
                                                               }
  bool isActiveSendProductOrder = false;
  constructor(string memory _version) public {
                                                            bool isActiveReceiveReceipt = false;
    version = version;
                                                            bool isEnabledReceiveSupplierOrder = false;
    isActiveSendProductOrder = true;
                                                            function SendSupplierOrder() external {
                                                                 if (isActiveSendSupplierOrder) {
  }
                                                                        isEnabledReceiveSupplierOrder = true;
  bool isEnabledReceiveProductOrder = false;
                                                                        ReceiveSupplierOrder();
  bool isActiveReceiveProductStatus = false;
                                                                 }
  function SendProductOrder() external {
                                                                        isActiveReceiveReceipt = true;
    if (isActiveSendProductOrder) {
                                                               }
            isEnabledReceiveProductOrder = true;
                                                               function ReceiveReceipt() public {
            ReceiveProductOrder();
                                                                 if (isEnabledReceiveReceipt) {
                                                                      emit next("", "", "ReceiveReceipt");
    }
            isActiveReceiveProductStatus = true;
                                                                 }
                                                                        isActiveSendProductStatus = true;
  }
bool isActiveSendSupplierOrder = false;
                                                               }
```

APPENDIX

A. This shows a part code of smart contract in the supply chain scenario