Literature Review: Smart Contract Semantics

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Abstract

This review presents and evaluates various formalisms for the purpose of modelling the semantics of financial derivatives contracts. The formalism proposed by Lee [1] is selected as the best candidate among those initially reviewed. Further examination and evaluation of this formalism is done.

1 Introduction

1.1 Introduction to the Problem

Contracts are legally binding documents that govern agreements between some parties. Generally, they define obligations between parties, typically regarding the delivery of goods, the performance of services, or payments. Contracts are essential to business transactions across all industries, as well as private transactions amongst the general public. In this paper, the domain is limited strictly to financial derivatives contracts that have been generated from the International Swaps and Derivatives Association (ISDA) Master Agreement template.

Contracts are a crucial part of doing business. Consequently, businesses are heavily invested in the task of Contract Lifecycle Management (CLM). CLM encapsulates all the various processes and operations that go into supporting a contract throughout its life including: contract creation, negotiation, approval, execution, and analysis. A study [2] by the Aberdeen Group found that 80% of businesses were manually performing some or all of these tasks. They found that standardising, formalising, and ultimately automating these processes would result in cost savings from greater efficiency. In their analysis of the global financial derivatives industry, ISDA had similar findings [3]. Therefore, there is a clear need for a solution that would allow us to automate some or all of these CLM processes.

Smart contracts are a solution to this problem. Clack et al [4,5] offer this definition of a smart contract:

A smart contract is an automatable and enforceable agreement. Automatable by computer, although some parts may require human input and control. Enforceable either by legal enforcement of rights and obligations or via tamper-proof execution of computer code.

Smart contracts would allow us to automate and monitor the performance of legal agreements electronically. For example, smart contracts could standardise and automate the performance of actions that occur over the lifetime of a financial derivative contract, reducing infrastructure cost. To start with, only a small part of the legal agreement would be automated, but as technology improves these agreements would be increasingly automated, including automatic detection of non-performance. Additionally, the use of smart contract templates would simplify the task of generating complex legal agreements between parties.

The first step in developing smart contracts, and the problem that this paper examines, is formalisation. This is the conversion of a contract into a formal representation that is unambiguous and machine interpretable. This conversion must happen in a manner such that we can be assured that the semantics of the contract and that of the the formal representation are identical. Once a contract has been converted to this form, we could write computer code to automate its performance. This code could easily make reference to the features of the contract as specified in its formal representation.

1.2 Modelling the Semantics of Legal Agreements

We adopt the terminology of Hvitved [6] when discussing formalisms. A formalism consists of a formal model and a formal language. In this context, a formal model is a mathematical model, the components of which can be used to construct formal representations of contracts. A formal language is a syntactic representation of some model. There should exist some mapping between the syntactic elements of the language and the semantic elements of the model. Formalisms are necessary since legal texts in their original form contain complex vocabulary and language constructs (e.g. modal verbs, conditional futures, and complex temporal clauses). This makes it difficult for a smart contract engineer to write code to automate the performance of the
agreement directly from this form. Additionally, sometimes this language can be ambiguous and difficult to parse. On the other hand, the formal representation of this contract should be unambiguous and machine interpretable by definition. Finally, by having a formal model of the legal text, we can create automated validation tests for its smart contract code.

There are various aspects of legal text that we would like to model formally. An initial analysis yields three broad categories of things we would like to model:

**Deontic** These are aspects relating to rights, obligations, permissions, and prohibitions. Typically, parties to a contract do not spontaneously take action unless they have the right or an obligation to do so as specified by the contract. If a party does not perform or deliver on their obligations according to the constraints specified in the contract, they will typically be subject to some punitive action. This may be specified in detail in the contract, or it may be left to a court of law to decide and administer appropriate punishment for non-performance. When a party has not fulfilled its obligations or takes some prohibited action, it is said to be in a state of default. The deontic relationships defined in contracts are typically only "active" under some conditions. For example, in a contract governing the exchange of goods the Buyer may only be obligated to pay the Seller after the goods have been delivered. Another way to express this is that the Buyer’s obligation to pay is only activated after the Seller has fulfilled their obligation to deliver the goods.

**Temporal** The temporal aspects of a contract are aspects related to time. Temporal expressions in legal agreements are typically used to specify deadlines for obligations or the “life spans” of permissions and prohibitions. These deadlines may be absolute temporal expressions (e.g. *Party A must deliver the goods by 12:00 on Friday 4 November 2018*) or they may be relative temporal expressions (e.g. *Party B must pay Party A £400 within 7 days of receiving the goods.*) The “life spans” of permissions and prohibitions typically take the form of continuous time intervals.

**State, Events, and Actions** As discussed, contracts have some notion of state, since their semantics may change over time as parties make choices and perform actions. While the operational aspects of a contract covers state-modifying actions that are defined in the contract, we must also consider how changes in external state and actions that parties take outside of the domain of the contract might affect the state of the contract. One crucial and fundamental piece of external state that is relevant to most contracts is the current date and time. It is easy to see that the state of the contract could be affected by the current date and time, since many deontic commitments, prohibitions, and permissions are governed by time. More complex external state, such as market events, could also affect a contract’s state.

**Operational** As mentioned, contracts typically define obligations between parties to perform some actions. If we reuse the example from above: *Party A must deliver the goods by 12:00 on Friday 4 November 2018 and Party B must pay Party A £400 within 7 days of receiving the goods.* We can clearly identify two actions that these parties must carry out, the first being the delivery of some goods and the second being a payment. It is these actions that we would like to be able to automate. Before that can happen the actions in a contract must be identified, computer code must be written to automate their performance, and we must identify the conditions that must be satisfied in order for those actions to be allowed to take place.

1.3 Review of Formalisms

1.3.1 Event Condition Action

Goodchild et al. [7] propose a formalism for contracts in which obligations are specified as “policies” through actions and associated constraints. These constraints can be absolute temporal constraints, relative temporal constraints, or conditional constraints. Operationally, these policies would be defined using XML.

1.3.2 Normative Statements

Boulmakoul and Sallé [8] propose normative statements as a formalism for modelling contracts. Each
normative statement defines some obligation between parties. A normative statement has the following form:

\[ l : f \mapsto D_{i_1,i_2}(a < T) \]

Where \( l \) is a label, \( f \) is some predicate, \( D \) is some deontic relationship (either obligation, permission or prohibition), \( i_1 \) and \( i_2 \) are identities of parties, \( a \) is an action, and \( T \) is a temporal constraint. The statement reads as “when \( f \) holds, \( i_1 \) is obliged/permitted/prohibited (depending on \( D \)) \( i_2 \) to achieve/perform \( a \) before \( T \)”

1.3.3 Functional Programming

Peyton Jones and Eber [9] make use of the compositional and modular nature of functional programming and use it to model contracts. They design an algebraic data type to represent a contract which, in its most basic form, is an atomic obligation between parties. The definition is enhanced through more complex binary operators and predicates.

1.3.4 Finite State Machines

Molina-Jimenez et al. [10] propose a formalism that is similar to Lee’s [1] trans assertions which will be explored later. In this formalism, the life cycle of a contract is defined as a series of states. Progressions between states occur as a result of actions. Constrained obligations are represented by having transitions to a default state if some action is not performed within that constraint (i.e. some absolute temporal constraint). The system is unique in that the global state of a contract is not tracked by the machine. Instead, each party has a respective machine that tracks their progression through the contract from their perspective.

1.3.5 Business Contract Language

Milosevic et al. [11] [12] propose the Business Contract Language (BCL). The language consists of roles and policies. Policies encapsulate deontic semantics, as well as associated relative temporal and state based ordering, and absolute temporal constraints.

1.3.6 Process Algebra

Andersen et al. [13] propose an approach that is similar to that of Peyton Jones and Eber [9] in the sense that contracts are defined recursively. The base, atomic definition of a contract is either success, signifying that all obligations have been met, or failure, signifying that a party has defaulted.

1.3.7 Dynamic Logic

Prisacariu and Schneider [14] propose a contract language CL. CL is made up of elements of deontic, dynamic and temporal logics. An extension to CL was proposed by Fenech et al. [15] With this extension, they are able to specify obligations, permissions and prohibitions with state based constraints, and relative temporal constraints. The system also has support for reparations.

1.3.8 Defeasible Logic

Defeasible deontic logic of violation as proposed by Governatori [16] and later refined by Governatori and Pham [17] extends defeasible logic and adds deontic modalities. In its basic form, defeasible logic provides a method of reasoning about rules and precedence among those rules. Rules are similar to implications in that if we have

\[ r_1 : \alpha \mapsto \beta \]

Then if \( \alpha \) is known to be true, \( \beta \) is also known to be true. However, contradictory facts can defeat previously known facts. For example if we have

\[ r_2 : \alpha \mapsto \neg \beta \]

And \( r_2 > r_1 \), then \( r_2 \) has precedence over \( r_1 \) and therefore we know that \( \neg \beta \) must be true. The extension proposed by Governatori and Pham takes defeasible logic and introduces deontic predicates.

1.3.9 Lee’s Formalism and Recent Extensions

Lee [1] proposes a formalism for capturing contract semantics that brings together many different tools and frameworks into a single cohesive framework. Pithadia [19] identifies weaknesses in Lee’s formalism and proposes extensions to rectify these problems. Vance [20] does the same, and makes mean-
1.4 Evaluation of Reviewed Formalisms

Hvitved [6] identifies 16 requirements that a formalism must support or fulfil to be deemed adequate for modelling contracts. The requirements are listed below:

1. Contract model, contract language, and a formal semantics.
2. Contract participants.
3. (Conditional) commitments.
4. Absolute temporal constraints.
5. Relative temporal constraints.
6. Reparation clauses.
7. Instantaneous and continuous actions
8. Potentially infinite and repetitive
9. Time varying, external dependencies
10. History sensitive commitments
11. In-place expressions
12. Parametrised contracts
13. Isomorphic encoding
14. Run time monitoring
15. Blame assignment
16. Amenability to (compositional) analysis

Hvitved [6] reviews the formalisms described above and evaluates them according to his criteria. The results of this analysis are presented in Table 1.

|   | Lee | Goo | Bou | Pey | Mol | Mil | And | Pri |
|---|-----|-----|-----|-----|-----|-----|-----|-----|
| R1 |     |     |     |     | X   | X   |     |     |
| R2 | X   |     |     |     | X   | X   |     |     |
| R3 | X   | X   | X   | X   | X   | X   | X   |     |
| R4 | X   | X   | X   | (X) | X   |     |     |     |
| R5 | X   |     | X   | X   | X   |     |     |     |
| R6 |     |     |     | X   | X   | X   |     |     |
| R7 | X   |     |     |     |     |     |     |     |
| R8 | X   |     | X   |     |     |     |     | X   |
| R9 |     |     |     |     |     |     | X   |     |
| R10|     |     |     |     |     |     |     |     |
| R11| X   |     |     |     |     |     |     |     |
| R12| X   |     |     |     |     |     |     |     |
| R13| X   |     | (X) |     |     |     |     |     |
| R14| X   | X   |     |     |     |     |     | X   |
| R15| (X) |     |     |     |     |     |     |     |
| R16|     |     | X   | X   | X   | X   |     |     |

Table 1: Hvitved’s formalisms comparison matrix. The compared formalisms are the following: Lee is Lee’s formalism [1], Goo is Goodchild et al. [7], Bou is Boulmakoul and Salle [8], Pey is Peyton Jones and Eber [9], Mol is Molina-Jimenez et al [10], Mil is Milosevic et al. [11], And is Andersen et al [13], and Pri is Prisacariu and Schneider [14].

As noted by Vanca [20], the formalisms proposed by Andersen et al. [13] and Prisacariu et al. [14] are the only ones that consist of complete formal models, languages, and semantics. However, there is no proof that these formalisms can correctly replicate the semantics of contracts. Additionally, these formalisms fail to meet requirement 7: support for instantaneous and continuous actions. This would be render them unsuitable for modelling derivatives contracts as these contracts typically prescribe some long term, continuous obligations. While it does not satisfy all of the requirements, Lee’s framework [1] is the next best option.

The law firm King & Wood Mallesons published a report in collaboration with ISDA which highlights some further requirements that are specific to the finance industry [21]. Namely, smart contracts would have to be constructed with strict adherence to regulatory standards with an emphasis on safety and transparency, while still meeting the performance expectations of their users. The report also identifies a benefit of working in the domain of financial derivatives: the ISDA Common
Domain Model (CDM). The CDM is a dictionary of events and actions that can occur during the lifecycle of a derivatives contract. The data is accessible in an unambiguous and machine interpretable way, and can therefore be integrated into a formal model for derivatives contracts.

In the next section, different aspects of Lee’s framework are presented and assessed. The analysis is done by looking at how the formalism deals with the deontic, temporal, and operational aspects of contracts. Additionally, this analysis looks at how the separability problem makes it difficult to develop formalisms to exclusively model each individual aspect.

2 Review of Lee’s Framework

2.1 Introduction to the Framework

Lee [1] presents a combined framework that is designed to model the various features of contracts identified earlier. Clack [22] finds that the temporal aspects of a contract are very difficult to separate from the deontic aspects. He calls this the separability problem. Temporal expressions are rarely found in isolation. Discrete time values in contracts are typically used to express deadlines for obligations. Likewise, continuous time intervals are generally used to express the duration of a prohibition or permission.

The structure of Lee’s formalism is influenced by this issue. The components of the formalism simultaneously express both deontic and temporal semantics. Additionally, the notion of contract state and state transitions are also encapsulated by the formalism.

2.1.1 Summary of the Components of the Formalism

Deontic Logic: Deontic logic is used to model the obligations, prohibitions, and permissions that are stipulated in the contract. Lee’s formalism makes use of an extension of the deontic logic model proposed by Von Wright [23].

Petri Nets: Lee uses Petri Nets to visualise conditional state changes in the lifecycle of a contract. Changes in state are triggered by performance or non-performance of actions. Consequently, the Petri Net can be thought of as a way of modelling both deontic and relative temporal features of the contract.

Trans Predicate: The trans predicate is a syntactical representation of the states and transitions of a Petri Net. Lee uses this syntax in his “logic programming formulation” which is an attempt to implement a working prototype of his formalism.

Rescher Urquhart Calculus: Lee employs and extends the Rescher Urquhart calculus to model absolute temporal constraints. This tool is also somewhat inseparable from deontic features of the contract, since instances of single discrete time values or time spans are typically linked to some deontic relationship.

2.2 Analysis of the Components of Lee’s Framework

2.2.1 Deontic Logic

Contracts typically define obligations between two or more transacting parties. The ISDA Master Agreement defines many such relationships, where parties agree to fulfil obligations to each other such as payments or other actions. We require a formal model to be able to create representations of such relationships.

Deontic logic is a formal model for representing rights and obligations proposed by Von Wright [23]. This model contains an operator to denote obligation:

$$O\phi$$

Meaning that $\phi$ is obligatory. From this further operators are developed for the notion of permission:

$$P\phi \leftrightarrow \neg O\neg \phi$$

Meaning that something is permitted if there is no obligation not to do it. And finally for prohibition:

$$F\phi \leftrightarrow O\neg \phi$$

Meaning that something is prohibited if it is obligatory not to do it.

Lee [1] adopts deontic logic in developing his formal model for contracts. Lee also adopts a set of axioms to complete the model.
2.2.2 Petri Nets, T-Calculus, and the Trans Predicate

To address the issue described above, Lee [1] presents a system for reasoning about sequential orderings of events that may occur over the life of a legal agreement. Lee uses Petri nets to visualise the state changes that may occur over a time span. Through the concept of contracts “moving forward” through states, Petri nets can help to model the relative temporal order of events that may occur. Each state models a set of rights and obligations, and at each state, there may be a set of states that the system can progress to. Typically the choice of the next state is dependent on the performance of some action. In this sense, Petri nets simultaneously model temporal, operational, and deontic aspects of legal agreements.

Lee [1] extends Von Wright’s [23] T-Calculus and employs it as a syntactic representation of Petri Nets. This model allows us to specify the relative order of contract “states”. The key operator is $T$.

\[ \phi T \psi \]

means that $\psi$ follows $\phi$. We can also represent choices:

\[ \phi T (\psi \lor \theta) \]

Lee [1] extends this concept in his definition of the trans predicate. $\text{trans}(s_1, s_2, e)$ has the meaning: “we transition from state $s_1$ to state $s_2$ if event $e$ occurs”. This construct is equivalent to conditional state transitions in Petri nets.

Vanca [20] provides an example of the trans predicate being used to model the following pair of conditional obligations:

- Party $A$ will pay party $B$ a sum of 10,000,000
- In exchange, $B$ agrees to transfer Building $BC$ to $A$ on 10/09/2018.

\[ \text{trans}([s(0, 1), [s(1, 1)], A : \text{rb}(30\text{Aug}18) : \text{Pay}(B, 1000000))] \]
\[ \text{trans}([s(1, 1), [s(2, 1)], B : \text{rb}(10\text{Sep}18) : \text{Transfer}(\text{BuildingBC})]) \]

Notice that this example tackles an issue that has not yet been discussed: absolute time constraints. This is one of the limitations of the model as it stands: it can express relative temporal and conditional relationships between states, but not absolute temporal constraints. In the next section we will see how Lee models absolute temporal constraints using the RU Calculus.

Pithadia [19] extends the trans predicate further to express prohibitions and permissions. Vanca [20] finds basic issues with the way these constructs are presented and with the semantics for the representation of permissions.

2.2.3 Lee’s Adaptation of the RU Calculus

Lee’s [1] framework for modelling absolute temporal expressions is based on the Rescher and Urquhart temporal logic system. In this system we have the $R$ operator, with $R_t \phi$ meaning that $\phi$ is realised at time $t$. In addition, a total ordering of times is introduced, allowing for absolute time references. Lee expands on this system by introducing notation to allow for the representation of time spans, and to denote when an event is realised during a time span. This is crucial for use...
in smart contracts. In Lee’s model, this temporal framework is integrated with deontic logic to represent deadlines (i.e., obligations with some fixed due date) and ongoing prohibitions.

Lee acknowledges some shortcomings of this model. First, he notes that the model assumes that the base time units used are equal in length, which is problematic if months or years are desired as a basis. Second, the system cannot handle continuous time.

Clack and Vanca identify some issues with Lee’s framework. One criticism is that the system cannot handle all of the complex or nuanced temporal expressions that sometimes arise in the natural language of legal text. For example: in Lee’s framework, there is no way of expressing “business days”. Another example: it is difficult to express the set of dates corresponding to “the first Friday of every month” without directly specifying each day itself.

Vanca identifies one further issue with the model: the user is forced to choose some base unit of time for the system. This could prove problematic in cases where different contracts that use the same system are dealing with vastly different timescales. Vanca contrasts the example of a web hosting company that promises service uptimes with millisecond precision to derivatives contracts that deal with infrequent payments over many years.

2.3 Implementation of the Combined Formalism

Lee describes how his formalism would be implemented in practice. The key component of this implementation would be the trans predicate, as well as the syntax that Lee developed to describe relative and absolute temporal constraints. Obligations would be modelled as demonstrated in earlier examples. A key feature of Lee’s implementation is modularity and parameterisation. This allows the smart contract engineer to define reusable components that could be used in many different smart contract instances.

Earlier in this paper, the operational aspects of contracts were identified along with the deontic and temporal aspects as being something that should be modelled by a formalism. Furthermore, the automation of these operational aspects was identified as a defining feature of smart contracts. Lee does not go as far as describing how these operational aspects would be automated in this formalism. He instead describes a system by which performance of a contract could be monitored through a kind of simulation environment.

3 Summary and Future Work

3.1 Summary

This paper initially provided a brief introduction to the problem of contract formalisation. In doing so, the necessary components of smart contract formalisms were explained. Then, various different formalisms were briefly presented, along with an explanation of the criteria that would be used to evaluate them. Lee’s framework was selected as the best of those presented. This formalism was then described in depth and analysed with respect to the criteria identified earlier. Some issues with Lee’s framework were identified, however a formal gap analysis was not conducted.

3.2 Future Work

The requirements identified by this paper are informal and do not necessarily provide full coverage of the ISDA Master Agreement. What is needed is a formal specification of requirements for formalisms. Once this has been produced, a gap analysis must be conducted to test whether prospective formalisms meet the requirements. Once this is done, the gaps that have been identified must be resolved.

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