Erasmus University - Master's thesis

Smart contracts: how smart are they?

An investigation into the implications of smart contracts on moral hazard, hold-up and contracts with contingent control

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"We believe that man is essentially good. It is only his behaviour that lets him down.

This is the fault of society. Society is the fault of conditions. Conditions are the fault of society."

Creed, by Steve Turner

Preface

Gouda, 21 March 2018

Dear reader,

After several months, the writing of my master thesis has come to an end. I am glad to provide you the result.

I want to thank my supervisor, Bauke Visser, for willing to supervise this project and guiding me along the way. In finding a good topic, you helped me get started. During the process, your help and questions provided me with new insights.

Writing my thesis was not always fun. The concept of smart contracts is relatively new, and this made it sometimes challenging to get to the core of the problem. I am curious how smart contracts can help us in the future.

There were times when it was hard to focus, because my girlfriend and I had to do work in our new home, and we were arranging the things for our wedding. Lizadine, my girlfriend and future wife, I want to thank you as well for your unconditional support. Week after week, you were -after long days of working- always willing to help me with my thesis process.

Also, I want to thank my father, who gave me meaningful tips for writing the research, and my mother for all the cups of coffee she gave to me, which provided me with new energy to go on.

Lastly, I am grateful for all the knowledge I gained at the Erasmus School of Economics, and I am looking forward to my career start at Laudame Financials.

Lars Rijkse

Summary

An unanswered question in the literature is whether smart contracts really can make contracts more complete. The aim of this paper is to show whether smart contracts can change contracting and add surplus, specifically in the field of moral hazard, hold-up and contracts with contingent control.

Smart contracts are digital, tamper-proof and self-enforcing contracts running on the blockchain technology. Smart contracts can save on writing, enforcement and renegotiation costs, and hence they make contracts more complete. However, it seems that they can do nothing to unforeseen contingencies. Thus, smart contracts make many contracts more complete, but not necessarily all contracts.

Table of Contents

Preface 2
Summary 3
Table of Contents 4
1. Introduction 6
1.1 Towards a new world? 6
1.2 Research question and thesis outline 6
2. Smart contracts 8
2.1 Blockchain, the underlying technology 8
2.2 What are smart contracts? 9
2.3 The scope of smart contracts 10
2.4 Some contract theory 11
2.4.1 Complete and incomplete contracts 12
2.4.2 Writing costs and enforcement costs 12
2.4.3 Unforeseen contingencies and renegotiation 12
3. Moral hazard 14
3.1 In principal-agent theory 14
3.1.1 Paying for performance 14
3.1.2 Allocation of decision rights 14
3.2 Information-asymmetry 15
3.3 The impact of smart contracts on moral hazard 15
3.3.1 Improving performance-based contracts 15
3.3.2 Effectively allocating decision rights 16
3.3.3 Reducing information-asymmetry 16
4. Hold-up 19
4.1 A hold-up model 19
4.2 A hold-up example: Apple & Corning 19
4.3 Traditional solutions for hold-up without smart contracts 20
4.3.1 Renegotiation-design mechanisms 21
4.3.2 Revelation mechanisms 21
4.4 The impact of smart contracts on hold-up 21
4.4.1 Observable and verifiable information 22

4.4.2 Bringing hold-up protection mechanisms into practice 22
4.4.3 Commitment 23
5. Contracts with contingent control 25
5.1 Decision rights and property rights 25
5.2 A real-world example: Coal Mine 25
5.3 Contracts with contingent control 25
5.4 The impact of smart contracts on contingent control contracting 28
5.4.1 An abstract model 28
5.4.2 Contingent control allocation in practice 28
6. Conclusion 31
6.1 Main findings 31
6.2 Answer to research question 32
7. Discussion 33
7.1 Research review 33
7.2 Practical implications 33
7.3 Suggestions for further analysis 34
8. Bibliography 35
9. Appendix 38

1. Introduction

1.1 Towards a new world?

Today, more and more rumours promise that the blockchain technology will deliver a new world. Many companies and banks are giving attention to the blockchain, by exploring the possibilities of this new technology and making substantial investments in it (Browne, 2017) (Bajpai, 2017). Although it seems that blockchain promises a lot for the future, there is a lot of overhyping going hand-in-hand with this new technology. On several websites and platforms, rumours are heard that smart contracts will replace lawyers in the future. Another conclusion that is quickly drawn, comes from Hewlett-Packard (HP), a large information technology company. HP published an article on the disruptive potential of smart contracts, by stating that *"if innovators in the blockchain space succeed, credit card companies, payments processors, and legions of accounting and law firms would be devastated* (Kastelein, 2015)*."*

But, one might ask: what exactly is the blockchain technology, and will smart contracts really change the way we manage our transactions, and replace laywers? The attempt of this thesis is to find more grasp on these questions. Specifically, the focus in this thesis lies on smart contracts and their influence on contracting and economic life. As we will see, the scope of smart contracts applications is very broad. Still, one might ask how smart contracts will be adopted in the economy and what value they really bring. Will smart contracts reduce opportunistic behaviour? And will smart contracts -according to the hyping in the media- really disrupt intermediaries, third parties and lawyers, so that those will go the way of the blacksmith?

For this, we would have to consider the nature of contracts. Economists distinguish between complete and incomplete contracts. Contracts are complete when *"for any contingency, parties can specify those actions that would create most value, fully compensate the party that incur cost, and distribute the rents that arise."* In short, complete contracts *"specify, for every possible contingency, exactly what parties should do and what they get."* (Delfgaauw, 2016)[1] In this context, courts would have no reason to allow renegotiation. (Holden & Malani, 2018) Incomplete contracts lack the above mentioned characteristics. Hart (1995) mentions that incomplete contracts have "*gaps, missing provisions, and ambiguities and have to be completed (by renegotiation or by the courts) with strictly positive probability in some states of the world" (Hart, 1995).*

1.2 Research question and thesis outline

With the aim of investigating the characteristics of smart contracts, the research question of this thesis is:

Will smart contracts make contracts more complete?

In asking the question, our assumption is that complete contracts are in general more desirable than incomplete contracts, because contractual incompleteness can often lead to

[1] Source from Blackboard (not publicly accessible)

opportunistic behaviour, which is harmful for society. However, there are cases where incomplete contracts are more desirable than complete contracts. For example, Baker, Gibbons & Murphy (1994) showed that using subjective performance measures (basically an incomplete contract) can provide better incentives than using objective performance measures (a complete contract) alone. Therefore, if smart contracts make contracts more complete, they do not provide the optimal incentives in those kind of scenarios.

Several chapters are composed to answer the research question. The second chapter will explore on the fundamentals of the blockchain technology, smart contracts and its applications, and contract theory. In the third chapter, the concept moral hazard will be described. Subsequently, the ability of smart contracts is linked with moral hazard, to gain insight in the impact of smart contracts in this field. In the fourth chapter, the concept hold-up will be described, and we will see how smart contracts might overcome or prevent hold-up scenarios. In the fifth chapter, contracts with contingent control are illustrated, and after that we elaborate on whether smart contracts can improve contingent control allocation in practice. Then, chapter 6 answers the research question, after having summed up the main findings. Lastly, chapter 7 provides a discussion, with a research review, practical implications, and suggestions for further research.

2. Smart contracts

2.1 Blockchain, the underlying technology

In 2008, Satoshi Nakamoto proposed blockchains as a method of validating ownership for bitcoin, a cryptocurrency. After several years, it became clear that the blockchain technology can impact a wider environment: they can remove traditional double-entry accounting, that is used for decades by accounting firms and banks.

In short, a blockchain is a cryptographically secure decentralized (or: distributed) ledger[2] upon which can be placed *"any information requiring public validation, e.g. money, contracts, property titles, identity, etc"* (Davidson, De Filippi, & Potts, 2016). This decentralized ledger verifies that transactions[3] are intended, feasible and executed, records transactions in a public way and ensures transactions are irreversible (Nakatomo, 2008). As a result, trusting centralized authorities for verifying transactions is no longer necessary.

To illustrate, the decentralized database is compared with the (traditionally used) centralized database below. In figure 1, a client-server network architecture is shown. Most traditional, centralized databases on the web use this architecture, for example Wikipedia. Here, clients (users) can make changes to entries stored on the centralized server. The users can change the 'master copy', which is the latest version of the database entry. However, only the administrators have full control of the database. Access and permissions are thus only given by a central power (Bauerle, 2018).

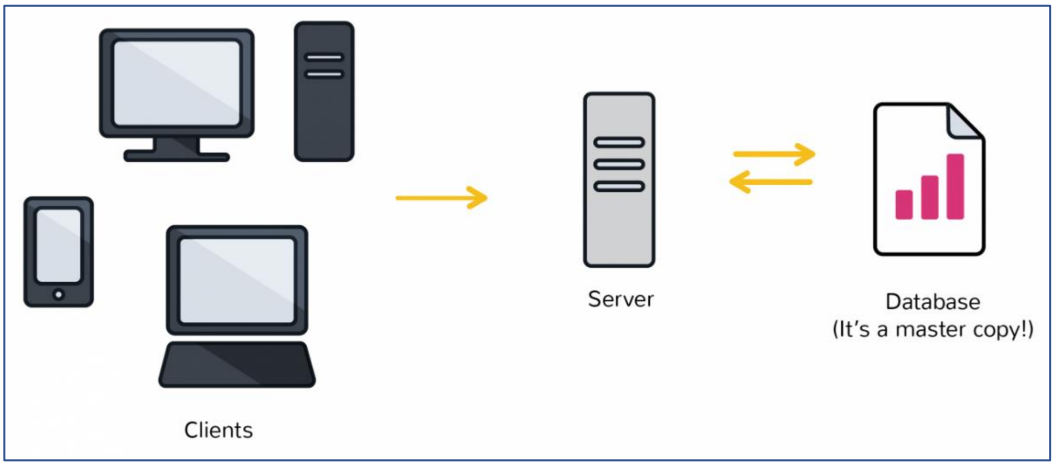

Figure 1 – a centralized client-server network architecture. Source: Coindesk

In contrast, in a blockchain database, *"each participant maintains, calculates and updates new entries into the database"*, which is shown in figure 2 (Bauerle, 2018). The transactions in the blockchain network are witnessed by nodes[4], that transform transaction messages

[2] The definition of a ledger is usually a 'collection of financial accounts'. In this context, a ledger could be considered broader (as a database), since not just financial information can be placed upon the ledger.
[3] Although Nakamoto (2008) initially used the term 'transaction' to indicate a monetary transfer, a transaction recorded in the blockchain can be any set of promises, i.e., a contract, or indeed any statement.
[4] Computers in the blockchain network

into “hashes”. A hash is simply a validation that some transaction was indeed announced. *“All nodes collaborate to ensure they are all coming to the same conclusions, providing in-built security for the network”* (Bauerle, 2018). After the hashes are produced, they are added to the previously witnessed transactions: the blockchain.

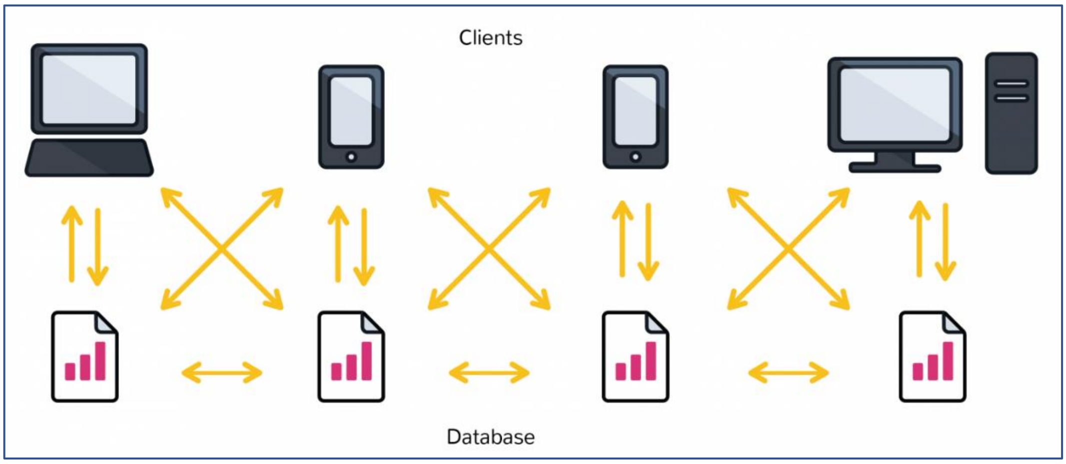

Figure 2 - a decentralized blockchain database. Source: Coindesk

In the business and legal field, blockchains can facilitate contracting: through smart contracts, firms will be able to automate the terms of agreement. In the next paragraph, we will see how these smart contracts work.

2.2 What are smart contracts?

Although the concept of smart contracts was originally devised by Szabo in 1994, the development of blockchain technology has rapidly facilitated the creation of smart contracts. The difference with a traditional contract is that smart contracts are generated by computers, and hence coding explain obligations of the parties.

According to Cong & He (2017), the primary notion of smart contracts lies in *“contracting on contingencies on a decentralized consensus, and on low-cost, algorithmic execution. To achieve decentralized consensus, a distributed ledger is needed, which also has to be self-executing.”*

The so-called *“contingencies (including allocation of property and control rights) in a smart contract should be codified, so that automated execution is feasible* (Cong & He, 2017)*”.* This clearly reduces enforcement costs. Cong & He (2017) mention that *“this could make smart contracts tamper proof, and more efficient than traditional third parties as the court or an arbitrator, where high degrees of human intervention are involved that are less algorithmic.*”

In their blockchain paper, Cong & He (2017) compare the self-enforcing functioning of smart contracts with a vending machine. Traditionally one would go to a lawyer or a notary, then pay them and then wait till the document is received. Smart contracts function like a vending machine, where *“one drops a coin into the vending machine (i.e. satisfies the contingency), and the escrow, driver’s license, or money drops into one’s account”* (Cong & He, 2017).

Smart contracts do not just define rules and penalties in agreement in the same way as a traditional contract is composed. Smart contracts also automatically enforce the rules and penalties in the contract. Many institutions, platforms and governments around the world are already utilizing smart contracts. In Ghana, a blockchain secured information database (called Benben) provides governments, financial institutions, realtors and the general public instant access to trusted property information. In the future, crowdfunding can happen without trusting intermediaries and having to pay them fees. Nowadays, people have to trust platforms like Kickstarter that their invested money will sent back, if some goal is not reached. Smart contracts do not require this trust: when people send money in a smart contract, they can be assured that if some condition is not reached, the amount will be returned to their account.

2.3 The scope of smart contracts

The tamper-proof nature and the power to automate bureaucratic, monetary transfers make smart contracts mainly attractive for the financial and trading sector.

Bartoletti & Pompianu (2017) analysed 834 smart contracts sampled from Bitcoin and Ethereum[5] and find five main categories of use (financial, notary, games, wallet and library). Of these five categories, three are related to monetary transfers and transactions. Also, more than two-thirds of the uses are on managing, gathering, or distributing money. In figure 3, a smart contract is shown (Bartoletti & Pompianu, 2017).

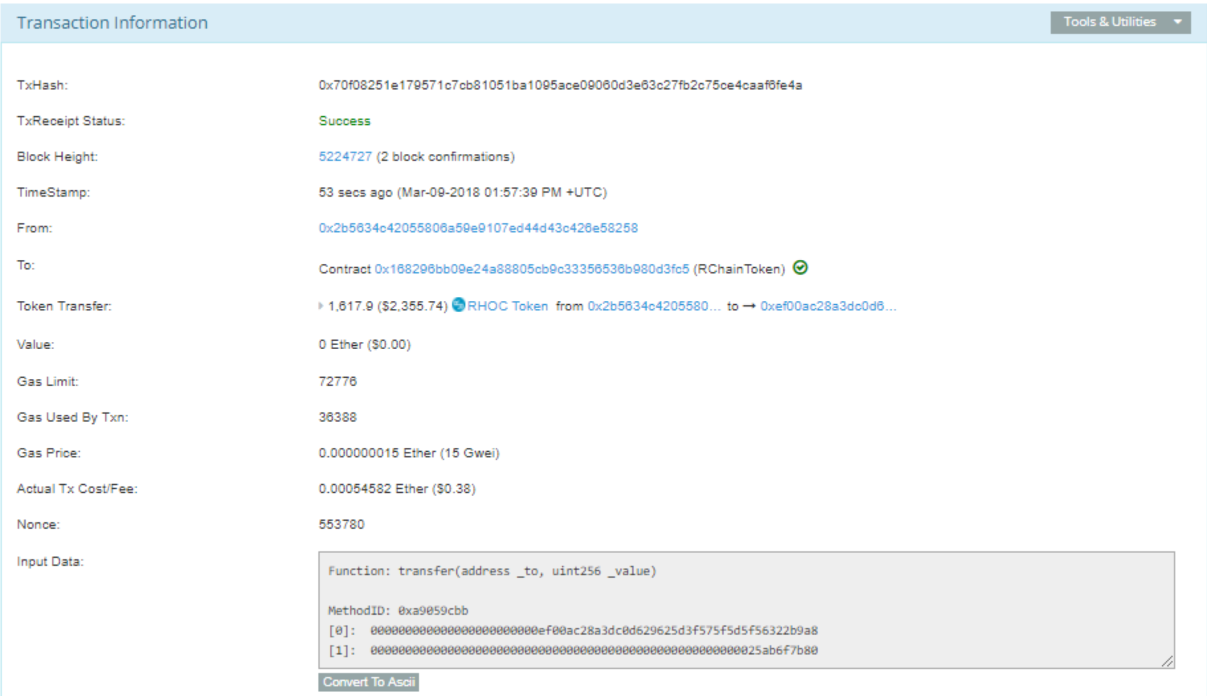

Figure 3 – an example of a verified transaction on etherscan.io

[5] Until now, Bitcoin and Ethereum are the largest existing blockchain platforms. Although Bitcoin has a higher market capitalization, Ethereum is a platform that is built specifically for creating smart contracts. In contrast to Bitcoin, Ethereum is written in a Turing Complete Language, which means anything can be done with it given enough time and enough computing power. Also, Ethereum's block time (15 seconds) is shorter than Bitcoin's block time (10 minutes), which allows for faster transaction times.

Ream, Chu, & Schatsky (2016) from Deloitte have analysed high-impact areas of potential smart contract use cases. In their research, they considered factors like a sizable market opportunity; the presence of active, relatively well-funded start-ups targeting the opportunity; the participation of prominent investors; technical feasibility and ease of implementation; and evidence of multiple pilots or adoption by corporations. According to the authors, *“the lowest-hanging fruits today are applications in which contracts are narrow, objective, and mechanical, with straightforward clauses and clearly defined outcomes”* (Ream, Chu, & Schatsky, 2016). They highlight two use cases that stand out for their immediacy to market, namely i) trade clearing and settlement and ii) supply chain and trade finance. First, they say that *“the opportunity to streamline clearing and settlement processes with smart contracts is immense since smart contracts can automate approval workflows and clearing calculations that are prone to lag and error, which reduces errors, cost, and the time to settlement”* (Ream, Chu, & Schatsky, 2016). This is reflected in the amounts of investments spent by start-ups, venture- and innovation funds and banks.[6] Second, they argue that “*blockchains make supply chain and trade finance documentation more efficient by streamlining processes previously spread across multiple parties and databases on a single shared ledger.*” A blockchain can provide “*secure, accessible digital versions to all parties in a transaction, and smart contracts can be used to manage the workflow of approvals and automatically transfer payment upon all signatures being collected*” (Ream, Chu, & Schatsky, 2016).

Although current attention is particularly paid to the financial services industry, the future scope for smart contracts is often considered to be broader. For instance, a legacy can get recorded on a smart contract. If someone dies, a smart contract can assign the inheritance to the right persons, for example by an input from a death registration. Another example would be a football bet that takes place on a smart contract. In this case, a football result will provide the input from the smart contract. For firms, smart contracts provide added value by entering into the smart contract that they will be paid upon completion of a project, or upon delivering a product or service. Also, a pizza delivery can be organized within a smart contract. If a customer puts his money in escrow, this money can be received by the pizzeria if some pizza is delivered within 40 minutes. However, if the pizza is delivered too late, the money can be returned to the customer. Smart contracts can thus be helpful in many different industries and activities where contracts, trust and security are needed.

2.4 Some contract theory

As we have seen, smart contracts could be applied in many situations. Yet, it is unclear whether smart contracts only bring efficiency gains, or that they fundamentally change contracting and hence economic life. Since the aim of this thesis is to learn whether smart contracts are also more complete contracts, we first study some contract theory to see which elements actually cause contractual incompleteness.

[6] As an example, (Ream, Chu, & Schatsky, 2016) notice that *“more than 40 global banks within the R3 consortium participated in testing that included clearing and settlement activity, and many of those banks have pursued further trials individually.”*

2.4.1 Complete and incomplete contracts

As described in paragraph 1.1, many contracts are incomplete because there are gaps, missing provisions, and ambiguities involved.

Tirole (1999) mentioned that in the contracting literature, there are four main justifications for contractual incompleteness, namely: i) unforeseen contingencies, ii) writing costs, iii) enforcement costs and iv) renegotiation.

Unforeseen contingencies are a crucial ingredient of incomplete contracts according to Tirole (1999): *''Parties cannot define ex ante the contingencies that may occur or actions that may be feasible later on. So, they must content themselves with signing a contract such as an authority or ownership relationship that does not explicitly mention those contingencies, or with signing no contract at all.''* Then, Tirole (1999) mentions the writing costs of a contract, by stating that "*even if one could foresee all contingencies, they might be so numerous that it would be too costly to describe them in a contract."* Besides the writing costs of a contract are relevant, the costs of enforcing a contract are not less relevant. *'Courts must understand the terms of the contract and verify the contracted upon contingencies and actions in order to enforce the contract"* (Tirole, 1999). Enforcement costs require an elaborate system consisting of courts, laws and police forces to be set up. Lastly, the possibility of renegotiation is an important reason to let contracts incomplete.

Now, the question remains whether and which parts of contractual incompleteness will be affected when smart contracts are fully developed. To find an answer to this question, paragraphs 2.4.2 and 2.4.3 elaborate on whether smart contracts could let shrink the incomplete parts of a contract.

2.4.2 Writing costs and enforcement costs

Clearly, when it comes to writing costs, they are expected to shrink since algorithms used in smart contracts will be more efficient than traditional third parties. Also, enforcement costs will go down if contingencies in a smart contract could be codified and automation execution will take place. Instead of calling for third parties, computer programming will directly enforce the pre-determined rules. But what about unforeseen contingencies and renegotiation?

2.4.3 Unforeseen contingencies and renegotiation

When we compare the definition of complete contracts with Cong & He's (2017) definition of smart contracts, i.e. "*digital contracts allowing terms contingent on decentralized consensus which are self-enforcing and tamper-proof through automated execution"*, we can imagine that writing a smart contract on decentralized consensus will only work without problems when all possible contingencies are known by the parties at the time of writing the contract. This is often not the case: for example, when both parties face a complex transaction, it would require them to make an excessively lengthy contract. What's more, bounded rationality implies that people cannot foresee every possible contingency and hence not every possible contingency is included in the contract. Consequence of this is that many contracts are by nature incomplete, and as a result, events may arise for which the contract does not specify what to do. In other words: some events or actions are not verifiable so that any contractual agreement cannot be enforced by courts. This creates room for ex post renegotiations as parties can renege, reopen bargaining about division of rents. This may sound intuitively positive, but as we will see in paragraph 2.2.3, new problems emerge here. The possibility of unverifiable events/actions and room for negotiation respectively lead to moral hazard and the hold-up problem. Both situations will be discussed, in chapter 3 and 4 respectively. Since smart contracts are said to have the biggest impact in the financial industry, it is also interesting to have a look at financial contract theory in chapter 5. We will especially consider the model of Aghion & Bolton (1992).

3. Moral hazard

As stated before, the possibility of unverifiable events/actions and room for negotiation respectively may lead to moral hazard. According to Hart & Holmström (2016), moral hazard occurs when *"a party may take actions that increase its own payoff but that reduce the overall surplus of the relationship*."

3.1 In principal-agent theory

In principal-agent theory, a classic example from moral hazard is a principal that engages an agent to take certain actions on the principal's behalf. However, the principal cannot directly observe the agent's actions. The principal could be a shareholder of a firm, whereas the agent could be the firm's manager. In this case, there is a separation of ownership and control in the firm. Hence, the manager might make decisions that conflict with the the interests of shareholders. In another setting, the principal-agent relationship could be a relation between an employer and employee. In the latter case, the employee can choose to shirk during working time when the principal cannot directly observe his employee's actions, which is clearly costly for the employer (Hart & Holmström, Contract Theory, 2016).

As the examples mentioned above are clearly threats to the principal, the question is how he should react to the moral hazard problem. For instance, the principal could alleviate moral hazard by investing in loyalty or by monitoring the agent. However, implementing one of these measures may be too costly for him.

3.1.1 Paying for performance

Hart & Holmström (2016) give another helping hand to the principal in order to cope with the moral hazard problem, namely tying the agent's income to some (observable and verifiable) performance measure. Paying for performance has its drawbacks. Frequently used performance measures are the company's profit or the stock market value, but they obviously depend on factors beyond the agent's control, so that they would be rewarded for luck. Hart & Holmström notice that *"any performance measure is likely to be imprecise and noisy, so in the end the optimal compensation schedule must trade off incentive-provision against risk-sharing* (Hart & Holmström, 2016)."

Another drawback of paying for performance is that it is often hard to write sufficiently detailed contracts ex ante. Also, it is hard to measure and verify performance ex post. Hart & Holmström (2016) describe a researcher (agent) whose task it is to develop a new technology for the principal's company. From the start, it may be hard to determine ex ante how the innovation should look like, due to all the uncertainties that are in the process. Moreover, the quality or impact on the principal's profit may be unverifiable ex post.

3.1.2 Allocation of decision rights

Therefore, according to Hart & Holmström (2016), an alternative attempt to alleviate moral hazard is the allocation of decision rights, which has proved to be a central insight in the incomplete contracts literature. Consider here the R&D example, where the principal could reward the researcher a fixed salary and let the agent have no ex post bargaining power, after he has developed a specific innovation. Another possibility that Hart & Holmström

(2016) present is that the researcher independently owns all his developed innovations, so that he either can deny the principal to use the new technology, or sell it to him at a price determined by some bargaining process. Both solutions have their pros and cons. In the latter case, probably the agent can set a higher price if the technology is of high quality. That implies that the agent has higher incentives as an independent researcher than as an employee to deliver an innovation of high quality. On the other hand, it may be risky for the principal to give full bargaining power to the agent, because his bargaining power will be much greater if the innovation has many alternative uses. Hart & Holmström (2016) conclude by saying that *"carefully allocated decision rights may produce good incentives and thus substitute for contractually specified rewards when performance-based contracts are hard to write or hard to enforce (Hart & Holmström, Contract Theory, 2016)."*

3.2 Information-asymmetry

The preceding part described situations of moral hazard in a principal-agent relation. However, the moral hazard problem is not limited to this relation, but it generally occurs in situations where there is information asymmetry between different parties. When a party has more information about its actions and its intentions than another party, it may have a tendency or incentive to behave inappropriately at the expense of the party with less information. Often here, the more 'informed' party is the risk-taking party and the less 'informed' party pays the consequences of the risk (Arrow, 1970). A famous example here is the insurance industry, where the insured party behaves riskier so that it raises costs for the insurer. The insured party only bears a (small) fraction of the raised costs. Not only the insurance industry, but a large part of the financial industry faces moral hazard, as contracts are made between a borrower and a lender.

3.3 The impact of smart contracts on moral hazard

It would be a bit naïve to think that moral hazard will at some time suddenly disappear by the coming of smart contracts. There may be debate about the idea of a "homo oeconomicus", but there will always be people that maximize their own payoff at the expense of others. In the real world, moral hazard has been a major theme in banking, insurance and organizations in general over the last decades. There are several measures that can alleviate the moral hazard problem, namely: investing in loyalty, monitoring agents, paying for performance and allocation of decision rights. Two of these measures, performance pay and the allocation of decision rights, were highlighted in paragraph 3.1, because they can be better organized by smart contracts. Smart contracts will also impact information asymmetry, which is often a crucial cause for moral hazard problem.

3.3.1 Improving performance-based contracts

As we have seen in paragraph 3.1.1, it is currently often hard to write detailed performance-based contracts. If it were easier to write and enforce performance-based contracts, we would expect firms to be more willing to apply performance pay. With algorithms in smart contracts, conditions can be created that make salary bonuses dependent on, say "good states" (high productivity) or "bad states" (low productivity). For organizations, this all can be done in a more efficient way, as computer programming will directly enforce the pre-determined rules. "*Smart contracts can be said "smart" to the extent they offer the efficiency* *of automated contractual performance and reduce the risk of human error and prospects of a dispute* (Adlerstein, 2017)*.”* Maybe more importantly, many more complex states can be captured within code language. This is relevant since risk-averse agents may experience disutility in their original bonus pay, since there may be external shocks outside their control that influence their productivity.[7] However, although computer coding can make performance pay more attractive, the problem of imprecise and noisy performance measures is still there.

Also, the blockchain technology can be beneficial in relative performance evaluation systems, in which the manager is awarded equity pay that is benchmarked against a market or industry index. This relative performance evaluation essentially gives the manager a *“short position in the benchmark index”* (he benefits when the benchmark index is falling) (Yermack, 2017). However, he can offset such a contract by privately taking a long position in the same benchmark, so that he hedges his risk. According to Yermack (2017), this could be restricted if boards could monitor these practices. He mentions that *“ordinarily, trading in shares of a competitor is not visible to the board of directors or to regulators, since it lies beyond the boundaries of insider trading disclosure requirements”* and that with the blockchain technology, more visibility can be provided.

3.3.2 Effectively allocating decision rights

In paragraph 3.1.2, we have seen how decision rights can deliver the right incentives in the scenario that performance-based contracts are hard to write or enforce. With the coming of smart contracts, allocating decision rights can be a more effective means for the principal as a goal to incentivise agents. Cong & He (2017) mention that *“the allocation of property and control rights in a smart contract can be codified, so that automated execution is feasible, which reduces enforcement costs.”* Thus, in the R&D example from paragraph 3.1.2, the decision for the principal to give bargaining power to the agent, can be made dependent on algorithms in the smart contract.

In chapter 4, more attention is given to this topic, since the field of decision rights is closely intertwined with the contingent control contracts. In any case, the extent to which smart contracts will improve either performance-based contracts or the allocation of decision rights, will change the cost-benefit analysis for firms in choosing the prior or the latter measure.

3.3.3 Reducing information-asymmetry

In paragraph 3.2, we saw that moral hazard not only occurs in principal-agent relationships. Generally, moral hazard generally happens when some party has more information about its actions and its intentions than another party, and behaves inappropriately at the expense of the party with less information. Therefore, there must be a sufficient amount of transparency within and between organizations to prevent information asymmetry and, as a result, moral hazard.

[7] For example, a sales person’s productivity can be very dependent on the weather. Hence, if algorithms in smart contracts are based on detailed weather data, the risk for a sales person to “lose” salary can be protected.

In many articles and reports, the blockchain technology is praised for its transparency and traceability. As an example, a recent Deloitte report speaks about this transparency by calling a blockchain a "chain" of information-storing "blocks," where each block contains information such as transactions made, amounts, and parties involved. This chain contains the entire history of all assets and instructions made in the past, hence it brings visibility in organization processes or supply chains. Therefore, the blockchain and smart contracts allow people who do not know each other to trust a shared record of events. The system of information-storing blocks can be very functional in that it requires both organizations and customers to reveal their information in transactions. This is especially helpful for the financial and insurance industry, since there are a lot of relatively simple transactions involved, with organizations and customers that all have different (risk) profiles. It could be that firms are hesitant to disclose specific information, but they could encouraged (or required) to do so, if the benefits from preventing moral hazard exceed these costs.

Cuccuru (2017) argues that the blockchain technology is ideal to experiment with in the banking world, because: *"1) financial bodies almost always deal with highly standardized terms and measurable variables, 2) financial activities depend on complex, bureaucratic accounting systems that compare and transfer a huge amount of data every day, 3) financial actors operate in an environment where inter-institutional operations are frequent and interdependence is high."* With lots of information within and between organizations, especially in the financial industry, there is room to reduce information-asymmetry using by smart contracts. Also, smart contracts could overcome strategic default (Gerardi, Goette, & Meier, 2013): this happens when a borrower decides to stop executing his obligations/payments, while he does have the financial ability to execute them.

In other industries, smart contracts can reduce information-asymmetry in supply chains. The longer the supply chain, the more impact smart contracts can achieve. In a Food & Agribusiness report from Rabobank, the second largest bank in the Netherlands, mentioned is that "trust in a product will become less dependent on the trust in the supplier, but more dependent on the information available in the blockchain (Rabobank, 2017).

From an industrial organization perspective, Cong & He (2017) consider information asymmetry as an entry barrier, and in their model they explain why smart contracts can create more competition and improve welfare and consumer surplus.

The authors mention that *"blockchains facilitate agents to contract on service outcome and enforce contingent transfers".* Therefore, they argue, *"a fraudulent type gains nothing from mimicking because he knows that he can never deliver the service and hence receive a payment. This enables the authentic entrant to signal his authenticity fully and enter the market."* If the service quality of some entrant is higher than its competitors, she can steal customers and hence she will enter. In this way, smart contracts facilitate entry. If entry will be facilitated, competition in the economy will enhance. (Cong & He, 2017)

On the other hand, Cong & He (2017) mention that *"generating decentralized consensus also inevitably leads to greater observability and contractibility of aggregate service activity recorded on the blockchain."* The authors argue that sellers can turn this expanded contractibility to their own favour by forming cartels. Even when explicit smart contracts among sellers are infeasible, blockchain technology can still foster tacit collusion among sellers, which is a clear downside. Thus, Cong & He’s model shows a trade-off: on the one hand, smart contracts lead to enhanced competition, while on the other hand they lead to worse collusion.

4. Hold-up

Another important problem in the field of incomplete contracting is the hold-up problem, which causes parties to be reluctant to make specific investments. Parties may refuse to invest ex ante because they fear to be held up ex post, so that they do not get a sufficient return on their investment. Also, since in at least some states of the world, parties have to renegotiate their contractual agreements later, they can today[8] lack the incentives to make relationship-specific investments.

4.1 A hold-up model

This can be illustrated in a simple model where a buyer B and a seller S trade some product. The buyer has valuation v for the product, whereas the seller incurs a cost of c to make the product. The joint surplus is v - c, and some price must be set to split that surplus. However, the surplus can be increased, as the buyer can make an investment that increases its valuation to $v' > v$, while the seller can also make an investment to reduce his cost c. The investments may look attractive, in the case that they increase the joint surplus less than they cost. However, after one party invests, the other party can withhold performance to obtain a better price.

4.2 A hold-up example: Apple & Corning

Holden & Malani (2018) provide a modern example in a trade relationship between Apple, a famous original equipment manufacturer and Corning, an important component manufacturer that produces "Gorilla Glass". Apple buys 1 unit of a glass from Corning at price p per unit. The joint surplus generated by trade depends on Apple's valuation for the glass, v and Corning's cost of producing the glass c (Holden & Malani, 2018).

First, the parties contract. At this time, the precise values of v and c are not known since they depend on investments made by both parties. Suppose that v can be either \$40 or \$32 and correspondingly c can be \$16 or \$10. Second, both parties make their investments non-cooperatively and simultaneously. Corning can invest to customize those components for Apple's unique phone design, and Apple can invest by designing and marketing features enabled by properties of Corning's glass.[9] Third, both parties learn v and c. After either Apple or Corning invests, the other party can try to renegotiate their contract to its own advantage.

Apple's investment affects the probability that v is high and Corning's investment affects the probability that c is high. Both investments come at a private cost: for Apple \$5 and for Corning \$5.

The parties do not write fully state-contingent contracts that specify p and the probability of trade q for each combination of v and c and they only invest after they contract because in

[8] or, at t=0

[9] Apple's investment could for example be the marketing of the iPhone, Corning's investment could be improving the strength of the glass, or lowering the cost of production etc.

reality, there are unanticipated innovations, opportunities or challenges that arise after contracting but before delivery. (Holden & Malani, 2018)

In the example of Holden & Malani (2018), the socially efficient thing to do is for Apple and Corning to make an investment, since both investments have their marginal value above their marginal cost, ($8 gain above $5 cost for Apple's investment and $6 gain above $5 cost for Corning's). After both investments are made, the joint surplus is $40 − $10 − $5 − $5 = $20. The essence of the hold-up problem, however, is that Apple and Corning will underinvest in the absence of the ability to contract on the investments (or values/costs) if they cannot prevent renegotiation.

To see this, consider Corning making their privately costly investment. Once Apple's value for the glass and Corning's cost of producing is realized, the parties will renegotiate the price, since contracting was incomplete at the start of the relationship. Assuming, for simplicity, that the parties evenly split the incremental surplus generated) then the price will be adjusted so that Corning only gets half of the $6 that it increased total surplus by, that is $3. Corning anticipates this at the investment stage and will not invest, since the $3 benefit is lower than the $5 cost. Similarly, Apple will not invest since their $8/2=$4 benefit is lower than its $5 cost. Hence, in the presence of hold up, neither party will invest so that Apple's valuation will be low and Corning's cost high. The joint surplus will be $32-$16=$16. As we have seen, hold-up reduces economic surplus, and therefore economists have spent considerable effort exploring how its impact can be mitigated (Holden & Malani, 2018).

4.3 Traditional solutions for hold-up without smart contracts

There are some ways in which parties can try to protect themselves from the hold-up problem.

First, if all the facts were verifiable by courts, then Apple and Corning could simply write a contract that stipulated payoffs for each possible set of facts (basically, a complete contract). However, this requires a great deal of information and is not feasible as courts have imperfect fact-finding and -interpretive capacity.

Second, Apple and Corning could merge and conduct the transaction internally within a single firm. However, hold-up problems could be replaced by internal agency problems in this way.

Third, Apple and Corning could rely on repeat play and reputation. Parties could be hesitant to hold-up each other, because (beneficial) future deals between them can be foregone.

Fourth, courts could enforce original contracts which contain provisions that bar renegotiation.

Fifth, renegotiation could be structured differently so that the social optimum could be obtained despite hold-up. In the paragraphs 4.3.1 and 4.3.2, several mechanisms are described.

4.3.1 Renegotiation-design mechanisms

Renegotiation-design mechanisms have been designed to structure renegotiation in such a way that despite the presence of a hold up, the social optimum can be reached.

Chung (1991) and Aghion, Dewatripont & Rey (1994) have worked on this, and central in their approach is that the renegotiation-design mechanism consists of two components. The first component is a default trade that can always be requested by one party, even in a situation of a hold-up. Therefore, that party (say the seller) always receives a full return to its investment for sure. The second component gives all the bargaining power in renegotiation to the other party (say the buyer) by letting the buyer make a take-it-or-leave-it offer. The timing of this renegotiation game is as follows: 1) parties decide how much they invest, 2) the buyer makes a take-it-or-leave-it offer, and 3) the seller can decide between accepting the offer (so that trade takes place on those terms), and triggering the default trade. With this two-stage mechanism, the socially optimal level of investment can be achieved. The seller has no bargaining power at the offer stage, but still has appropriate incentives to invest optimally. This is because the seller still is the residual claimant on his investment, due to his access to the default opinion in the last stage of the game. By backward induction, the buyer knows that the seller has incentives to invest optimally, and similarly has incentives to invest optimally.

4.3.2 Revelation mechanisms

In the above example, Apple and Corning make relation-specific investments. However, also in the absence of relation-specific investments, there may be important ex-post inefficiencies that arise from the inability to write complete contracts.

Aghion and Holden (2011) noted this by saying:

> *"A basic premise of property rights theory is that there is some information that is observable to the contracting parties but not verifiable by a court, so that contracts are necessarily incomplete and property rights matter. This premise was sharply questioned by Maskin and Tirole (1999), who suggested that observable information can be made verifiable by the use of cleverly designed revelation mechanisms. That is, the contracting parties can agree in advance to play a game where they have the appropriate incentives to reveal truthfully their private information in equilibrium" (Aghion and Holden, 2011).*

A large literature has explored how mechanisms that require players to make announcements, may be able to cause information observable to players but not to outsiders to become observable and thus verifiable by outsiders. In case of a hold-up, this is particularly useful, because once the parties know that the true state will be revealed then, then they can ex ante contract on v or c, even if they cannot contract on relationship specific investments per se. Aghion and Holden (2011) provide an example of such a revelation mechanism.

4.4 The impact of smart contracts on hold-up

In general, smart contracts can reduce the parties' likelihood to be held up. Moreover, they can stimulate the functioning of mechanisms that can protect against holdup.

4.4.1 Observable and verifiable information

The distinguishing part between verifiable and observable information is that verifiable information can be checked by third parties (e.g. a judge) and that it can be part of formal contract, whereas observable information can only be observed by parties in a transaction. Observable information cannot be part of a formal contract, as disputes cannot be settled in court. The difference between observable and verifiable information can become vaguer through smart contracts, because the observable information placed in smart contracts can become directly verifiable, not by courts but by the coding and automatic enforcing (because of the nodes witnessing the transactions in the blockchain, see paragraph 2.1). If smart contracts can make observable information verifiable, this will clearly negatively affect the size of the possible holdup situations, as the share of verifiable information in the whole economy gets larger. However, how smart contracts will be adopted in the economy, and how regulations will be designed is still unknown.

4.4.2 Bringing hold-up protection mechanisms into practice

In paragraph 4.3, the renegotiation-design mechanisms and revelation mechanisms are described as a restructuring of the renegotiation process and hence a protection against holdup. Therefore, one might ask: how can smart contracts protect against holdup?

Holden & Malani (2018) note that in real-life, the above-mentioned mechanisms do not have a foothold in the market yet:

"Rarely, if ever, are the renegotiation design or the revelation mechanisms described above seen in practice. This begs the question: why not?"

The authors explain three reasons why, namely because of:

1) <u>uncertainty</u>**:** the cost and payoffs to the investments of both parties are often uncertain. As a result, the mechanism cannot be precisely structured.
2) <u>information asymmetry</u>**:** even when the state of nature is observable to the contracting parties, there can be no common knowledge among both parties. The mechanisms assume that Apple and Corning not only observe v and c, but also agree on what v and c are. This assumption is often a strict one. For example, parties may obtain unbiased information about v and c, but not precise; i.e. there may be random noise. Therefore, they might not agree on the same values for v and c.
3) <u>commitment:</u> main weakness of these mechanisms is that they each require a strong form of commitment, which is a significant barrier to their usefulness. Holden & Malani (2018) note this because there is a possibility that the stronger party would still trade in the case that the weaker party refuses the take-it-or-leave-it offer. In this scenario, the ultimatum is not credible. Also, parties can agree to split the penalty payment to the third party rather than handing it over to that party.

Smart contracts can positively affect the three factors above:

First, smart contracts can reduce uncertainty about promises (counterparty risk) and uncertainty about interpretation (legal risk). Counterparty risk can be reduced because automated smart contracts gives counterparties confidence that promises will be fulfilled.

Legal risk can be reduced because computers executing a smart contract may be more predictable than an uncertain court's interpretive methodology. Also, executing a smart contract under many parameter values for contract inputs can be cheaper and quicker.

Second, they reduce information asymmetry, by requiring both organizations and customers to reveal their information in transactions (as also described in paragraph 3.3.3). Not just this, experimental evidence from Aghion, Fehr, Holden and Wilkening (2017) shows that revelation mechanisms underperform due to asymmetric information, but that the degree of underperformance is proportional to degree of asymmetric information. Revelation mechanisms are thus likely to perform better when there is less information asymmetry.

Third, they can deliver the necessary commitment in holdup situations, which will be described below.

4.4.3 Commitment

In order to have commitment, Apple and Corning could use penalty clauses to ensure commitment in the renegotiation-design mechanism context or even in the original contract. Penalty clauses are liquidated damages that are greater than the real economic damages. They are used to create additional sanctions if some party breaches the contract.

But, courts frown upon penalty clauses, though they may be more permissive to enforce penalty clauses in cases where both parties are sophisticated businesses rather than cases involving small businesses or individual consumers. If courts won't enforce the penalty clause, it will not incent parties to commit to their roles in the mechanisms or to their original contract terms.

Even if courts would enforce the penalty clause, it can skew the incentives of the two parties. Such clauses act like reliance damages, which are known to risk overinvestment by the protected parties. The solution to overinvestment is to pay the penalties to a third party rather than the party making an investment. Yet both contractual parties have a mutual incentive to negotiate around that third-party payment, as they did in the revelation mechanism. The only way to obtain commitment without skewing investment incentives then is to have an automatic payment to a third party that cannot be undone by the contractual parties (Holden & Malani, 2018).

Smart contracts have the capabilities do transfer this automatic payment. The future transactions envisioned in the smart contract are automatically executed and, because of the inalterability of the blockchain, cannot practically be stopped. Therefore, smart contracts can impose liquidated damages that cannot be renegotiated, or commanded, or reversed by courts. This allows the parties either to commit to the original contract or to renegotiation mechanisms that both protect against holdup while allowing for mutually-preferred modifications due to changed circumstances (Holden & Malani, 2018).

Thus, smart contracts might better enable the contractual commitment required, either to stop renegotiation or to enable the use of renegotiation design or revelation mechanisms. When both renegotiation design and revelation mechanisms are better brought into practice, the risk of renegotiation will shrink. And if there is less risk of negotiation, there will be less holdup scenarios, which is socially desirable.

In theory, it is possible that the government or courts will ban smart contracts. But if the government will understand that it has enough value, then collateral costs will deter the government from banning our solution. Also, specific applications of smart contracts and blockchain could be prohibited, for example the stopping automation of future promises or certain contract penalty provisions. But this is unlikely as both parties to a contract want these terms ex ante. It is only ex post that one party does not prefer them.

5. Contracts with contingent control

5.1 Decision rights and property rights

In the incomplete contracts literature, an important insight has been the use of allocating decision rights. By providing ownership, decision rights can replace rewards.[10] Hart & Holmström explain why this is the case: *"ownership of an asset goes together with the possession of residual rights of control over the asset. The owner has the right to use the asset in any way not inconsistent with a prior contract, custom, or any law (Hart & Holmström, 2016)."*

A contract that cannot explicitly specify what the parties should do in future eventualities, must instead specify who has the right to decide what to do when the parties cannot agree. The party with this decision right will have more bargaining power, and will be able to get a better deal once output has materialised. In turn, this will strengthen incentives for the party with more decision rights to take certain decisions, such as investing, while weakening incentives for the party with fewer decision rights. In complex contracting situations, allocating decision rights therefore becomes an alternative to paying for performance.

5.2 A real-world example: Coal Mine

Consider a coal mine that needs money to expand their business. The coal mine approaches an investor and promises him a substantial share of future profit to persuade him to invest. To capture the terms, a financial contract is made between an investor and a coal mine. This contract is incomplete, since events will occur that the parties could not fully foresee when they started out. Therefore, the investor is worried about possible opportunistic behaviour (e.g. hold-up) by the manager of the coal mine. For example, the manager could pay himself a big salary or reinvest profits rather than paying back the investor.

The investor could be protected against opportunism by giving him the residual control rights. If the investor would become the owner of the coal mine, then he would have the power to control the manager's salary or even fire him and replace him by someone else. However, one important downside here is that the incentives of the manager of the coal mine may be reduced.[11]

Aghion and Bolton (1992) showed that these opposite effects could be balanced by making the contract control state contingent. In other words: the manager has control in some states of the world, whereas the investor has control in other states of the world. (Aghion & Bolton, 1992) Their model will be discussed in the next paragraph.

5.3 Contracts with contingent control

For their model, Aghion and Bolton (1992) use the incomplete-contracts approach from Grossman & Hart (1986) to explain financial contracting, by describing a manager with limited wealth who asks an investor for capital. Hart (2001) brings the Aghion & Bolton-

[10] In the form of fixed salary or incentive pay

[11] e.g. incentives to have ideas, create profits, etc.

model to the attention, and shows that the venture capital sector corresponds quite well with this model. We will summarize his elaboration below.

Hart (2001) considers a model where some project yields \$V cashflows and \$B private benefits.[12] The investor only cares about cashflows, while the manager cares about both cashflows and private benefits. These different interests can create a conflict between the manager and the investor.

In the model, the manager is allocated a fraction θ of the project cashflows, and the investor receives the remaining (1-θ) Suppose that the project is set up at date t and all decisions are taken and benefits earned at date t+1. The utility functions of the manager and investor are as follows:

Manager: Max $B + \theta V$,
Investor: Max $(1 - \theta)V$ = Max V

Let us know add a "social planner" in the game, i.e. someone concerned with achieving a social optimum.[13] His goal would be to maximize the sum of both payoffs, B + V.

Social Planner: Max $B + V$

According to Hart (2001), the three utility functions are clearly diverse; therefore, it is relevant whether the manager or the investor makes ex post decisions. Suppose that at date t+1, the parties must decide whether the project should be finished or continued.[14] Also, suppose that the manager's private benefit from finishing the project is \$100, while \$200 in resources can be saved if the project is finished now rather than later. Also assume $\theta = 0.1$.

Hart (2001) goes on to say that, from a social surplus perspective, the project should be finished (\$200 loss > \$100 private benefit) Obviously, the project will be finished if the investor decides, since she does not care about private benefits, but not if the manager decides: given his stake of 10%, he gains only \$20 from avoiding losses, but loses his full private benefit of \$100.

If the losses from continuation (L) would be e.g. \$80 instead of \$200, it would be socially optimal to continue the project. Here, continuation will be achieved if the manager has the authority to decide, while continuation will not occur if the investor decides.

Suppose that the parties contract at date t. Both parties are risk-neutral and have two instruments which they can share: the allocation of cashflow rights, represented by θ, and the allocation of decision rights. At the contract-signing stage, the manager hands a take-it-or-leave-it offer to the investor.

[12] Examples of private benefits are personal satisfaction and reputational enhancement, since they are enjoyed by the manager but not the investor. It is likely that – above the cashflows received - the manager gets some personal satisfaction from working on the project, or from the project succeeding. Also, if the project succeeds, the manager's reputation is enhanced and he will do better in the future.
[13] Note that the planner does not have decision-making authority
[14] Note that this is the only decision to be made

Hart (2001) notices here that *"the manager will choose the contract to maximize his expected payoff subject to the investor breaking even, i.e., recovering her investment cost C (on average). Since the investor's gross expected return is fixed at C, an optimal contract will also maximize the sum of the manager and investor's payoffs, i.e., (expected) social surplus, B + V, subject to the investor breaking even."*

We can compare two polar contracts that can be made. At one extreme, the manager could be granted all the cashflow rights (θ = 1) and all the decision rights. In this scenario, the manager's utility function and the social planner's utility function are the same: both parties want to maximize B + V. This would guarantee an efficient outcome. Unfortunately, the investor gets none of his money back, which makes the contract not very feasible. At the other extreme, the investor could be granted all the cashflow rights (θ = 0) and all the decision-making rights. In this scenario, the investor will maximize his own payoff and he will receive at least or more than break-even, because otherwise the project can never start at all. Unfortunately, this contract could destroy significant private benefits since the investor only cares about cash flows.

The question Hart (2001) then asks is, "*where between these two extremes does the optimal contract lie?"* He presents one case where the answer is simple. Suppose that, whatever decision was made at date t+1, the project yields a cashflow that is at least C (discounted back to date t). Then the investor can be given a riskless debt of C and the manager can be allocated all the equity, i.e., he is the residual income claimant and has all the decision rights. This contract is feasible because the investor breaks even and optimal because there is no inefficiency: the entrepreneur maximizes B + V. However, we live in a world of uncertainty, so it is unlikely that the cashflows will be large enough to support a riskless debt of value C.

This problem makes Hart (2001) refer to the core of contingent control contracting, by saying: *"In order to understand what is optimal then, imagine that the parties can anticipate-and contract on-certain events at date t+1 (they are verifiable). An example of an event might be a situation where the firm has low earnings and its product is not selling; in another event the opposite may be true-the firm has high earnings and its product is selling."*

Hart (2001) notes that *"the advantage of allocating cashflow and control rights to one party or the other will typically differ across these events. For example, in one event it may be the case that a ruthless strategy of value (cash flow) maximization leads to an approximately efficient outcome because private benefits aren't very important."*

In the prior example where some amount $L was saved and $100 private benefits were wasted when the firm was closed, the control -and cashflow rights can be allocated depending on the magnitude of the amount $L.

Recall the example where closing the firm down saved $L and wasted a private benefit of $100. Aghion and Bolton (1992) show that the investor should have control-and cash flow rights if L=200, where cashflow maximization generates an efficient outcome. If L=$80, private benefits get relatively more weight, and cashflow maximization will reduce social surplus. Hence, the manager should have control- and cashflow rights here.

Roughly summarized, Aghion-Bolton's presumption is as follows: the investor should have control in the events where cashflow maximization is the least inefficient, and the manager should have control in events where cashflow maximization is (pretty much) inefficient. The cut-off should be chosen so that the investor breaks even.

By practicing this 'rule', the investor receives protection against large losses in the bad state, while the manager has the security of keeping control in the good state (Aghion & Holden, 2011). It can happen that some events are not (fully) verifiable, but still the allocation can approach first-best if some verifiable signal correlates strongly with the state of the world.

5.4 The impact of smart contracts on contingent control contracting

The question in this paragraph is whether smart contracts can reduce contractual incompleteness in contingent control contracting. There are reasons to think so, as will be described below.

5.4.1 An abstract model

Bolton (2013) himself concluded about his contingent control model: *"the model remains in many ways too abstract and general to be an operationally useful analytical tool. Part of the difficulty lies in the somewhat vague notion of private benefits. The other difficulty is that the enforcement limits on financial contracts are exogenously imposed in a somewhat arbitrary fashion. There is also the conceptual difficulty revealed by Maskin and Tirole (1999) that when an action or state of the world is observable to the contracting parties but not to a court (or judge) it can still be made verifiable through a suitable revelation mechanism."*

In practice, smart contracts can make the enforcement limits less arbitrary by objective, automatic coding. Also, smart contracts can make revelation mechanisms perform better, which has been described in paragraph 4.4.2.

5.4.2 Contingent control allocation in practice

In paragraph 5.3, we have seen that the contingent control allocation can be exercised through debt financing, whereby the investor has control in the event of default and otherwise the manager retains control. Bolton (2013) mentions that contingent control allocation can also be implemented through staged transfers of control under a venture capital (VC) contract.[15]

Bolton (2013) mentions that *"several empirical studies show that the contingent allocation of control rights through debt covenants is a common practice that has significant effects on corporate investment and financing decisions."* [16] Covenants can be used to restrict the management's actions. Also, they function to align the interests of both debt holders and shareholders. As covenants are often contingent on accounting performance measures, they have the ability to limit e.g. dividend payouts, capital expenditures, asset sales, or the issuance of additional debt (Christensen et. al, 2015). However, firms often have private

[15] Kaplan & Strömberg (2000) show that Aghion & Bolton's (1992) model corresponds quite well with real-life venture capital contracts. They show that venture capital contracts typically separate cashflow and control rights. Also, venture capital contracts make control rights contingent on (accounting) performance measures.

[16] Roberts and Sufi (2009), Chava and Roberts (2008), Nini, Smith and Sufi (2009), and Bienz, Faure-Grimaud, and Fluck (2012)

information about their realized earnings. Therefore, Bolton and Scharfstein (1990) and Hart and Moore (1994; 1998) explored models of limited commitment where a distinction was laid between liquidity and strategic defaults. A liquidity default happens *"when a firm is forced to default due to a cash shortage"* (Bolton, 2013). A strategic default happens when *"a firm chooses to default and force a debt restructuring because it is in its interest even though it is able to service the existing debt*." (Bolton, 2013) In general, smart contracts can reduce the threat of strategic default, simply because they limit borrowers to undo the automatically enforced clauses, once the pre-programmed conditions are satisfied. (Gerardi, Goette, & Meier, 2013). Since the automatic payments are permanent and cannot be undone by the borrower, his money/property will be transferred to the lender, according to the agreed terms.

Nowadays, the phenomenon of strategic default explains why there are so many protections that creditors require. One could think of seniority, collateral, security interests, and covenants. These protections are invented to increase the probability that firms will repay their creditors. The latter can be achieved when it is made more difficult to strategically default, and when the bargaining position of creditors is improved for future debt renogiations. (Bolton, 2013)

According to Bolton (2013), limited commitment models of debt point to the relevance of debt renegotiation, and indeed, empirical studies confirm that debt renegotiation is a relevant phenomenon today. For instance, Roberts and Sufi (2009) have found that *"the vast majority of corporate long-term debt (more than 90%) is renegotiated before maturity in response to changes in the firm's environment."* The authors also show that debt design reflects the firm's anticipation of future renegotiation, and attempts to allocate bargaining power on a state-contingent basis.

Furthermore, Roberts and Sufi (2009) show that new information (such as changes in credit quality, investment opportunities or the borrower's collateral) leads both firms to make changes to the terms of the original contract. Lastly, they find that renegotiation is pro-cyclical with the macro-economic environment: it is *"driven by changes in credit market liquidity and the financial health of commercial banks"* (Roberts & Sufi, 2009).

If the "new information" that Roberts and Sufi (2009) talk about is automatically and permanently absorbed in smart contracts, then both the "manager" and the "investor" can prevent costly writing and renegotiation. Yermack (2017) claimed more or less the same: *"with self-executing smart contracts, many costly negotiating strategies involving brinksmanship and risk-shifting might be precluded, generating net savings that could be shared ex ante by the borrower and lender."* When the cashflow and control rights are based on measurable changes, the contracting is organized in a more efficient and dynamic way (Yermack, 2017).

Smart contracts do not only prevent costly writing and renegotiation, they can play a role in enforcing the protections against defaults. Bolton (2013) mentioned that *"debt covenants are costly to enforce because they require continuous monitoring of the borrower by the* *lender"* (Bolton, 2013). According to Christensen et. al (2015), *"accounting information plays an important role within incomplete contract theory because the optimal allocation of control rights is contingent on contractible signals that reflects the underlying economics of the borrower."* Hence, accounting systems produce *"summary measures of firm performance, hence accounting signals are primary candidates for improving the efficiency the state-contingent allocation of control rights"* (Christensen et. al, 2015). Through computer algorithms, accounting systems can be matched with the smart contracts, so that continuous monitoring will be a lot clearer and easier for the creditor. If financial information (e.g. investment numbers, or invoices and payment receipts) is stored on the distributed ledger, this can be shared with counterparties, which allows creditors to verify that the borrower the value chain is using true information.

The necessary monitoring will also be facilitated by triple entry accounting, a technique that the blockchain technology brings. For decades, double entry accounting has been the norm, whereby e.g. cashflows are booked on a debit- and a credit side. The downside of double-entry accounting is that the balance between debit and credit does not change when some purchase or sale remains unregistered. Triple entry accounting can minimalize fraud, because one booking is placed in one system, instead of three bookings in three different systems.

If the costs of monitoring debt covenants will be much lower for creditors, they will probably agree faster with providing loans. Serhal (2017) confirms this by noting: *"the blockchain technology can help creditors in their quest for securing their investment. The decentralised shared ledger will provide valuable information for the lenders, which will contribute to the reduction of information asymmetry and consequently reduce the cost of debt"* (Serhal, 2017).

At the same time, debtors know that they are monitored and that they will be "punished" after a default, for example the instant transfer of collateral. Obviously, this incentivises them to avoid a default. Aghion et. al (2016) already noticed that the threat of asset liquidations motivates debtors to avoid default. Consistent with theoretical models, he mentions in his review several empirical papers that prove that collateral liquidation values determine the ex post strategic behaviour of borrowers, as well as the ex ante pricing of these contracts, their maturity structure, debt capacity, and number of creditors. Consequently, only the "good" debtors will ask for loans. In this way, the blockchain technology reduces opportunism and delivers more mutual trust between parties. Another important benefit seen by Yermack (2017) is that *"important side effects might spill over to the real economy, as changing incentives for informed investors to trade might lead to more reliable signals about the value of individual firms"*.

In sum, the objective and dynamic nature of smart contracts (mainly the absorbing of many different future contingencies) makes it possible to allocate control rights more efficiently, so that a higher social optimum can be reached.

6. Conclusion

In the previous chapters, several economic models and articles are highlighted with the attempt to get a better grasp on smart contracts. Below, our main findings are highlighted, and an answer is given to the research question: *"Will smart contracts make contracts more complete?"*

6.1 Main findings

Smart contracts are digital contracts on the blockchain technology, based on decentralized consensus, and are self-enforcing and tamper-proof through automated execution. Complete contracts specify for every possible contingency exactly what parties should do and what they get. In contrast, incomplete contracts have gaps, missing provisions and ambiguities and have to be completed by renegotiation or courts. Ingredients for contractual incompleteness are i) unforeseen contingencies, ii) writing costs, iii) enforcement costs and iv) renegotiation.

The moral hazard problem occurs in many situations where actions cannot be observed, or where there is information-asymmetry between parties. Paying for performance and allocating decision rights are ways to provide the right incentives so that moral hazard can be reduced. With self-enforcing algorithms in smart contracts, it will be easier to write and enforce performance-based contracts, and to allocate decision rights. Blockchain's visibility can strengthen relative performance evaluation systems. Also, smart contracts require parties to make information public on the blockchain. This drastically reduces information-asymmetry between parties, which benefits the financial and insurance industry the most. From an IO perspective, smart contracts' ability to contract on service outcome can be an entry barrier, leading to more competition. However, this expanded contractibility can also foster tacit collusion.

The hold-up problem takes place when parties have insufficient incentives to invest ex ante, because they fear to be held up ex post. This reduces economic surplus. One of the current protections are renegotiation-design mechanisms and revelation mechanisms, but they do not work properly yet. Smart contracts can stimulate the functioning of the protections because they reduce counterparty risk, legal risk, and information asymmetry. Also, they deliver the contractual commitment needed. In general, smart contracts can reduce hold-up scenarios because observable information can become verifiable, not by courts but by automatic enforcing.

In financial contracting, contracts with contingent control can deliver higher social surplus by granting entrepreneurs control in some (good) states of the world, and investors in other (bad) states of the world. Smart contracts can prevent costly writing and renegotiation in state contingent contracting by automatically absorbing in the contract changes in e.g. the borrower's liquidity or changes within the macro-economic environment. Also, smart contracts can make the allocation of control rights better contingent on accounting signals. This makes continuous monitoring easier and a lot cheaper for the creditor. Also, it incentives borrowers to reduce strategic default, so that a higher social optimum can be reached.

6.2 Answer to research question

After having summed up the main findings of our research, we can now turn back to our research question to argue whether smart contracts make contracts more complete.

Smart contracts make contracts more complete when one or more of the following elements of contractual incompleteness can be reduced: i) unforeseen contingencies, ii) writing costs, iii) enforcement costs and iv) renegotiation. As we have seen, smart contracts do have the ability to reduce contractual incompleteness because they can significantly save on three of the above elements: writing, enforcement and renegotiation costs. Here we must notice that is hard to empirically measure the reduction of contractual incompleteness due to smart contracts.

Writing costs let contracts incomplete when there are so many contingencies that it is too costly to describe them all in a contract. Smart contracts can alleviate this problem, because algorithms in smart contracts can save much time and money in the writing of contracts.

Enforcement costs can be reduced since automated execution is possible after decentralized consensus is made and contingencies are codified. In relatively easy contracts, there is a lot to gain here when coding is based on objective (accounting) numbers. The distributed ledger technology removes the need to trust centralized authorities, which enables firms or agents can to save on legal costs. However, in the more complex contracts, enforcement costs will not directly drastically shrink as human involvement is still needed to interpret disputable terms.

Renegotiation costs will shrink because smart contracts reduce hold-up scenarios and provide better protections against hold-up, which prevents costly renegotiation. Also, many renegotiation costs can be saved in state-contingent contracting, as investors and entrepreneurs can ex ante include future contingencies in the smart contracts, so that the shift in cashflow or control rights directly happens after changes in e.g. liquidity.

Still, smart contracts can do nothing to unforeseen contingencies, simply because smart contracts are not all-knowing. There may always arise events for which the smart contract does not specify what to do, and it may already be a challenge to capture complex events in code language. The conclusion of this paper is therefore that smart contracts make many contracts more complete, but not necessarily all contracts.

7. Discussion

In paragraph 7.1, we will review our research and findings. Afterwards, some practical implications of our findings are mentioned in paragraph 7.2. Lastly, in paragraph 7.3, suggestions for further analysis will be given.

7.1 Research review

In the introduction, the question was asked what value smart contracts will bring. After consulting contract theory and economic models, we have shown that smart contracts can reduce contractual incompleteness by reducing writing, enforcement and renegotiation costs. The models that are discussed are of course simplifications of reality, but it is evident that both moral hazard, hold up and contracts with contingent control happen in real life. Therefore, the prediction that smart contracts make many contracts more complete in real life, is not farfetched. However, there is more to say about smart contracts. Their immutability for example, can lead to new problems if contingencies are multi-interpretable. Also, firms or consumers need to be empowered to manage their own rights and obligations without trusted intermediaries. This clearly comes at a cost, especially since today's institutions work quite well because they are built on centuries of accumulated knowledge. This cost must be accounted when experimenting with smart contracts is done through pilot projects. The blockchain technology is still in early stages, therefore a lot is unknown. Like other new technologies, smart contracts may be misunderstood and create new problems. Still, the point of this thesis remains that in situations where moral hazard, hold up and contingent control allocation occur frequently, there is lot to "gain" with smart contracts.

7.2 Practical implications

Firms and governments must reflect on the blockchain technology, as smart contracts reduce moral hazard, holdup and state-contingent contracts can make financial contracting more effective. For economic life, this is very relevant as this will lead to more investments, more collaboration between firms, more security for financial lenders, less opportunism and hence a higher social welfare.

Especially for the financial industry, smart contracts can offer a lot of benefits. Banks, notaries and insurance companies must stay informed about the latest developments and possibilities, and invent new business models. Less human activity will be needed when drawing up relatively easy contracts. Also, IT knowledge becomes more and more relevant for lawyers and middleman that will work with smart contracts.

The introduction of smart contracts brings new challenges, and it is highly important that healthy regulations are set up in case things could go wrong. As an example, the immutable nature of smart contracts makes them tamper-resistant, but this also means that they cannot be reversed if something goes awry. What will happen then is still the question. Also, it is yet unknown whether special provisions are needed, in case that some event happens that is not included in the smart contract.

Today's markets are still in the beginning stages of discovering the potentials and pitfalls of smart contracts. Therefore, a lot is yet unknown and this could change some assumptions about the ability of smart contracts. Often, with the coming of a new technology, the focus lies mainly on the benefits while new problems may emerge later. Therefore, it is desirable that researchers, developers and governments keep track of how the blockchain technology develops, to know better and better what the benefits and boundaries of smart contracts are. Also, an important barrier at the moment is that smart contracts are not accessible for those without programming knowledge. Hence, many people (except programmers) cannot use them yet. Time will tell how this develops.

7.3 Suggestions for further analysis

Suggestions for further study could be: A) a study to the benefits of smart contracts for a specific industry, for example the banking or insurance business, B) the role of governance in smart contracts, C) theoretical models wherein two worlds are described, one without and one with smart contracts, D) empirical studies that examine the impact of smart contracts, e.g. if there are less defaults in debt financing.

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9. Appendix

Table 1. Range of use case applications for smart contracts

Use case		What the smart contract can do
Financial services	Trade clearing and settlement	Manages approval workflows between counterparties, calculates trade settlement amounts, and transfers funds automatically
Financial services	Coupon payments	Automatically calculates and pays periodic coupon payments and returns principal upon bond expiration
Financial services	Insurance claim processing	Performs error checking, routing, and approval workflows, and calculates payout based on the type of claim and underlying policy
Financial services	Micro-insurance	Calculates and transfers micropayments based on usage data from an Internet of Things-enabled device (example: pay-as-you-go automotive insurance)
Life sciences and health care	Electronic medical records	Provides transfer and/or access to medical health records upon multi-signature approvals between patients and providers
Life sciences and health care	Population health data access	Grants health researchers access to certain personal health information; micropayments are automatically transferred to the patient for participation
Life sciences and health care	Personal health tracking	Tracks patients' health-related actions through IoT devices and automatically generates rewards based on specific milestones
Technology, media, and telecom	Royalty distribution	Calculates and distributes royalty payments to artists and other associated parties according to the contract
Energy and resources	Autonomous electric vehicle charging stations	Processes a deposit, enables the charging station, and returns remaining funds when complete
Public sector	Record-keeping	Updates private company share registries and capitalization table records, and distributes shareholder communications
Cross-industry	Supply chain and trade finance documentation	Transfers payments upon multi-signature approval for letters of credit and issues port payments upon custody change for bills of lading
Cross-industry	Product provenance and history	Facilitates chain-of custody process for products in the supply chain where the party in custody is able to log evidence about the product
Cross-industry	Peer-to-peer transacting	Matches parties and transfers payments automatically for various peer-to-peer applications: lending, insurance, energy credits, etc.
Cross-industry	Voting	Validates voter criteria, logs vote to the blockchain, and initiates specific actions as a result of the majority vote