Smart Contracts, IoT Sensors, and Efficiency: Automated Execution *vs.* Better Information*

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Abstract

The increased attention to blockchain-related technologies has brought into focus "smart" contacts, whose key feature is the automated algorithmic execution based on mapping states of the world to corresponding contractual actions. Smart contracts require digital inputs that determine when such algorithmic execution should take place, often provided by connected "Internet of Things" (IoT) sensors, and as a result these two technologies are frequently confounded. In this paper we develop a model of smart contracts that distinguishes their impact from that of sensors. We analyze four possible regimes: (a) conventional contracting; (b) contracting with increased information from IoT sensors; (c) smart contracts that automate certain actions; and (d) the combination of smart contracts and IoT sensors.

We show that IoT sensors and smart contracts can have different impacts on contracting outcomes and efficiency, and thus should not be confounded. Smart contracts restrict the strategy space by allowing the contracting parties to commit not to hold-up each other; this typically increases the contracting region where trade occurs and thus increases efficiency, but for certain parameter values it surprisingly can decrease social welfare. IoT sensors expand the state space over which the contract can be specified by creating finer partitions of the verifiable states of nature. This typically leads to more efficient trades, but it is still not fully efficient. Finally, when applied together, smart contracts and IoT sensors enable all efficient trades, including certain trades that neither technology can enable individually; in that sense the two technologies can be complementary.

Keywords: smart contracts, connected sensors, IoT, blockchain

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1 Introduction

It is often argued that technology in general, and blockchain technology in particular, will improve the efficiency of contracting by enabling "smart" contracts, an idea whose introduction is often attributed to Nick Szabo (1996). The key characteristic of smart contracts is their automated algorithmic execution based on a mapping from certain detectable states of the world to corresponding actions. The increased attention to applications of blockchain-related technologies has brought in focus the potential economic role of smart contracts, and claims they would offer improvements in economic efficiency, while also potentially affecting firm boundaries and business models.[1]

In discussing the role of smart contracts, the literature draws on examples dating to Szabo's proposal for a "smart lien" on a car, which would automatically "return control of the car keys to the bank" if the borrower fails to make payments and thus "might be much cheaper and more effective than a repo man." More recent examples include using real-time transaction data to provide automated sales financing (Tinn 2018) and taking automatic actions when a transported good is subjected to certain events, which is one of the capabilities of TradeLens, the blockchain-enabled digital shipping platform by Maersk and IBM Blockchain Solutions. For instance, TradeLens can trigger automatic shipment of replacement for fruit that has not been properly refrigerated while in transit; notably this can take place as soon as the transported fruit is exposed to abnormal temperature, without waiting for it to be inspected upon delivery.

Smart contracts, however, critically depend on digital inputs that inform them that a certain state of the world has occurred, and the ability to trigger the corresponding actions. These inputs may already exist in digital form, such as digital notification of a delivery, or a trade execution, or a missed payment,[2] but some of the most promising proposals for smart contracts rely on new sources of digital information. In the smart lien example, the smart contract not only needs to be informed of the failure to make payments, but also connected sensors would be needed that can disable the car on the bank's command and can

[1] While smart contracts such as limit brokerage orders have existed for a long time without blockchain related technologies, the emergence of these technologies can broaden the scope and applicability of smart contracts by providing an infrastructure for their recording and execution, by helping certify the occurrence of contracted states of the world, and by enabling execution of certain actions "on the blockchain," such as a cryptocurrency transaction (e.g., see Holden and Malani 2018; Gans 2019).

[2] Technologies such as digital "oracles" can help with certification of these inputs and communication to the smart contract platform, as well as relaying of required actions to "off chain" platforms for execution.

communicate its location to the bank.

Predictions for the coming prevalence of smart contracts are thus predicated on the availability of connected sensors such as those that are part of the "Internet of Things" (IoT). These sensors increase the ability to identify states of the world with high accuracy and at a fine-grained level of discrimination, and frequently these states are rendered "verifiable" as the sensors provide evidence that can be shown to a court or an arbitrator in the event of a dispute.[3]

If most applications of smart contracts require employing new sensors, is the value really coming from smart contracts, or could most of this value be realized with just the sensors? Connected sensors enable increased detail in both "conventional" and "smart" contracts, and can add significant value on their own, yet popular accounts for the importance of smart contracts often confound the implications of the two technologies. For instance, in Szabo's foundational example of the smart lien, arguably most of the value is created by the ability to determine the location of the car and remotely disable it, rather than by the automatic execution provided by the smart contract.

Sensors can be implemented without smart contracts, smart contracts can be based on existing digital inputs without the need for additional sensors, and each of the technologies has a different implementation cost. In this paper we examine under what conditions it is most beneficial to pursue smart contracts, set up new sensors, or apply both technologies together. We use a simple model to characterize the implications of automated execution (which is at the core of smart contracts) and the more granular states of the world that can be identified by connected sensors ("IoT"), and how they each affect the scope and efficiency of contracting.

We model the implications of IoT sensors and smart contracts in a supply chain setting where a perishable good ("fruit") is transported requiring a costly action by the transportation company ("refrigeration"). We analyze how the abilities of IoT sensors and smart contracts to respectively refine the observable states of the world and allow automated execution of certain actions can change the contracting space and the efficiency of the resulting trades. We show that both smart contracts and IoT sensors are likely to improve contracting efficiency, but in different ways, and under different conditions.

[3]Certifying the information provided by IoT sensors to make the identified states "verifiable" will likely present a tradeoff between cost and degree of verifiability, which will need to be addressed to the satisfaction of the contracting parties.

One contribution of our analysis is that it highlights the different capabilities of the two technologies and confirms that advances in sensors and smart contracts will have different although potentially complementary implications. What can be delegated to smart contracts directly depends on what information can be obtained in machine-readable form, which in turn depends on the capabilities of available sensors. Smart contracts by themselves cannot increase the strategy space. They may change the attractiveness of certain actions by of limiting strategic options down the road.

Our model allows us to characterize situations where it would be socially optimal to implement only smart contracts (based on limited existing digital data), only connected sensors (providing additional verifiable information), or both sensors and smart contracts (i.e., where the synergies exist). We also show that the incentives to adopt these two technologies may differ for different economic agents, and may not be aligned with social optimality.

The distinction between smart contracts and connected sensors has important implications for theory and practice. This distinction should be explicit in future research on the economics and efficiency implications of these technologies, when welfare gains justify the cost of their development and deployment, and when private incentives result in suboptimal technology adoption, i.e., either not adopting when one should, or adopting when one should not. Furthermore, awareness of this distinction and the cost of each technology will also help implement appropriate applications in practice.

2 Related Literature

While blockchain and smart contracts are relatively recent phenomena, they have sparked a number of increasingly important streams of research (see Halaburda et al, 2020 for an overview). Tinn (2018) investigates how the new functionality afforded by smart contracts could improve the efficiency of financing contracts. Cong and He (2019) study the impact of smart contracts on the competitive environment and find that the effect of the technology on welfare is ambiguous. Depending on the environment and use of smart contracts, they may facilitate firm entry and enhance competition and welfare; but they may also help incumbent firms to prevent new entrants, thus perpetuating oligopolies to the detriment of social welfare. Gans (2019) looks at more general implications of smart contracts. He shows that by improving observability and reducing the costs of verification of the performance of contractual obligations, the space of feasible contracts can be enlarged. However he concludes that smart contracts can do neither because it is impossible to provide them with verifiable inputs originating outside the blockchain network on which they are implemented.

The potential impact of smart contracts has also been analyzed in the law literature. Werbach and Cornell (2017) investigate the popular claim that smart contracts could replace contract law and the need for courts to adjudicate contractual disputes. As they investigate both the potential and the limitations of smart contracts, they conclude that while smart contracts will require new legal responses, they will not displace contract law. Casey and Niblett (2018) envision more advanced forms of smart contracts than what is currently available, with smart contracts that utilize Artificial Intelligence to dynamically fill in the gaps that may have been overlooked in the initial agreement, without direct involvement of the contracting parties. This would substitute for courts filling these gaps ex-post and raise the question of what changes in the doctrine and theory of contract law would be needed to account for this possibility. Holden and Malani (2018) discuss how the automatic execution of terms in smart contracts on blockchain networks can help to overcome the hold-up problem by either preventing renegotiation of agreements or providing a structure within which such renegotiation can take place. They argue that smart contracts may thus provide a tool to implement theoretical mechanisms that increase the efficiency of contracting, but which have been difficult to execute in practice. They postulate that for this to work, all relevant data and assets must be available on the same blockchain platform that supports the smart contract, and that the core function of blockchain networks is "witnessing," i.e., the provision of authoritative and publicly observable information based on its use of appropriate cryptographic algorithms.

Gans (2019) also recognizes the importance of verifiable digital inputs for applications of smart contracts and agrees that blockchain systems can provide verifiable information in certain cases, but he argues that typically what the blockchain can provide is not enough. Thus he finds limited appeal in smart contracts and instead searches for mechanisms to optimize trading given the impossibility of verifiable digital information. As an example, he sets up a clever multi-step mechanism that achieves efficient trade without verifiable digital information, based on the information voluntarily revealed by the parties.

In contrast, we focus on the more optimistic case where IoT sensors can provide reliable and verifiable digital inputs that can be observed and trusted by all parties, and where these inputs can be made available to smart contracts.[4] We also recognize that introducing these

[4]We believe that in reality this is a question of degree; there is a tradeoff between the strictness of

connected sensors offers benefits (and imposes costs) by itself, before smart contracts are added. In this paper we distinguish the impact of the information provided by the connected IoT sensors from the impact of automated execution afforded by the smart contracts, and we formalize how each technology affects the contracting game, the strategy space, and the resulting equilibria.

Finally, given the question we study, established tools of principal-agent theory and contracting theory are directly relevant. Digital sensors affect the observability of the states of the world, and offer the possibility to account for more such states in the contract, which has implications that go back to Spence and Zeckhauser (1971), and Holmström (1979). The core of smart contracts is automated execution, which relates to credible commitment, e.g., as in Schelling (1960), and the hold-up problem, e.g., as in Grossman and Hart (1986) and Hart and Moore (1988).[5] In order to make our point, however, a simpler setting than most of this literature suffices: we assume no uncertainty and thus we do not need to consider risk preferences, and no asymmetric information; however we do assume moral hazard.

3 Model Setup

We model contracting to trade in a setting similar to Holden and Malani (2018) and Gans (2019). Specifically, we model a setting with a principal F that desires to transport a perishable good to which we refer as "fruit." Transportation is provided by an agent T that has a costly but unobservable action to which we refer as "refrigeration" that affects the quality of the good upon delivery and thus the economic value generated. If the fruit is shipped under proper refrigeration, it is of high quality when delivered, will last longer on the shelf, and provide higher utility to the end consumers. If not properly refrigerated, the fruit will deteriorate in condition and taste faster and may even spoil before it can be sold.

More formally, the value of the delivered fruit to F is v, and T's cost to provide transportation is c, with $v > c$. If the fruit is not transported, both parties obtain a baseline payoff of 0. Thus it is socially optimal to transport the fruit (we assume there are no other externalities) and transportation for any price between c and v is profitable for both F and

requirements placed on the verifiability of "off-chain" inputs, and the feasibility and cost of obtaining them and connecting them to smart contracts.

[5] Maskin and Tirole (1999) argue that complex contracts can solve the hold-up problem when there are ex-ante indescribable contingencies, while Hart and Moore (1999) counter-argue that this solution does not work when renegotiation cannot be ruled out.

T. If the fruit was properly refrigerated, F obtains high value v_H and T incurs high cost c_H. If the fruit is shipped without refrigeration, F obtains low value $v_L < v_H$ and T incurs lower cost $c_L < c_H$. We assume that $v_H - c_H > v_L - c_L > 0$, i.e., refrigeration results in higher total surplus and thus is socially efficient.

Whether the fruit was refrigerated during transportation is neither observable to F upon delivery, nor can be verified by a third party such as a court. The fruit delivery and the payment from F to T are both verifiable by third parties. Let $S = \{s_i\}$ be a set of mutually exclusive verifiable states of the world and $A_F = \{a_{F_i}\}$ and $A_T = \{a_{T_i}\}$ be sets of verifiable actions by F and T respectively. Then F and T can enter into a contract, which is a set of mappings $\{s_i \to a_{F_i}, a_{T_i}\}$. We assume that if contractual performance is verifiable by a third party, disputes between F and T can be settled by an arbitrator or a court that can determine whether a particular state s_i has occurred.[6] In case of a dispute, each party $i = \{F, T\}$ bears the cost λ_i of legal action, which does not depend on who initiated the action and who prevails. We also assume that the courts are always fair, and they are able to enforce performance of the contract terms in full.

The game is sequential. After the parties agree on a price p, T transports the fruit, and F pays (or not) p upon delivery. The base game is shown in Figure 1.

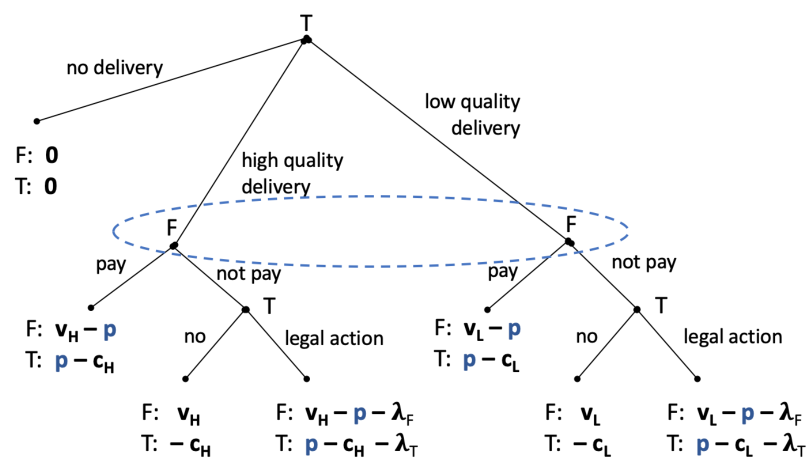


Figure 1: Benchmark fruit delivery contracting game (without smart contract or additional sensors) in extensive form.

In this setting, providing high quality transportation (i.e., properly refrigerating the fruit during transportation) is always dominated for T as F cannot determine at the time of

[6]We assume that if the states and the corresponding actions are observable by F and T but not verifiable by a third party, a court cannot enforce the contract.

delivery whether refrigeration was provided nor is the absence of refrigeration verifiable in court, and thus the contract between F and T must specify the same price p for high- and low-quality transportation. The price promised to T upon delivery needs to be at least λ_T, i.e., sufficiently large that it would be worthwhile for T to go to the court to enforce the payment if F were to renege. If the agreed price is less than λ_T in our single shot game, T will not go to court if he is not paid, and thus F will not pay. If the legal cost is larger than the value of the delivered good to F, there is no price F is willing to pay at which T would want to deliver. Thus low-quality transportation (without refrigeration) will be contracted for and take place if $\lambda_T \leq p$, which is possible only if $\lambda_T \leq v_L$.[7] The resulting equilibrium in the one-shot game is never efficient, as transportation either is low-quality or doesn't take place. This result is stated in the following Lemma:

Lemma 1 *In the benchmark contracting game (without smart contract or additional sensors), the equilibrium is never efficient.*

- *For* $\lambda_T \leq v_L$, *low quality transportation is contracted and executed, at price* $\max\{\lambda_T, c_L\} < p < v_L$, *yielding profits* $\Pi_F = v_L - p$ *and* $\Pi_T = p - c_L$. *The social welfare created by the trade is* $v_L - c_L > 0$.

- *For* $\lambda_T > v_L$, *there is no contracting. Profits and social welfare are 0.*

Even though in equilibrium legal action is never taken, T's cost of legal action λ_T crucially affects the equilibrium outcome as it determines whether the threat of legal action is credible or not. When the cost of legal action is high enough for T, specifically when $c_L < v_L < \lambda_T$, there will be no trade (i.e, agreement to transport the fruit) even though transporting would be efficient. Even when trade occurs in equilibrium, it is inefficient, as low quality transportation is contracted, even though high quality transportation would be more efficient. Note, however, that when $c_L < \lambda_T < v_L$, then T is guaranteed positive profits.

4 Impact of smart contracts

Even though refrigeration during transportation cannot be verified, both the fruit delivery and F's payment to T are verifiable and are also likely to be captured by the existing

[7] Gans (2019) obtains a similar result. In his model, the cost of providing verifiable evidence plays the same role as our cost of legal action in leading to failure of trade.

technology infrastructure, e.g., as digital confirmation of delivering a shipping container or processing a bank transfer. Thus we assume that delivery by F and payment by T can be used as digital inputs to a smart contract. With a smart contract, payment can be executed automatically after delivery is established. This means that F cannot renege on payment, which truncates the strategy space, as is represented in Figure 2. A smart contract protects T against being held up by F by automating payment upon delivery and this protection adds value when the legal cost T would incur in enforcing the contract is so high that it would prevent contracting. This leads to the following Lemma:

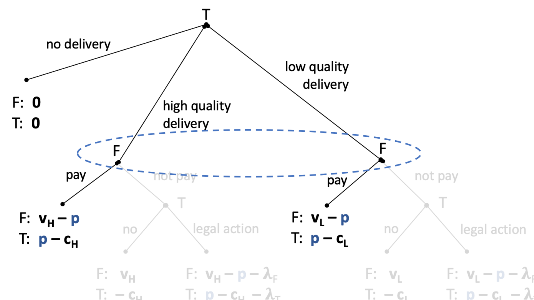


Figure 2: Fruit delivery contracting game with a smart contract conditioned on delivery (and no additional sensors). Strategies which are no longer available to F due automated execution are greyed.

Lemma 2 *In the contracting game with only smart contracts, low quality transportation is contracted and executed whenever $c_L < v_L$, at price $c_L < p < v_L$, yielding profits $\Pi_F = v_L - p$ and $\Pi_T = p - c_L$. The social welfare created by the trade is $v_L - c_L > 0$.*

Thus, in this setting, smart contract technology improves efficiency by extending the contracting region over which trade takes place, but does not improve the resulting trade outcomes, and thus still falls short of the social optimum.

5 Impact of connected digital sensors (IoT)

Progress in sensor and connectivity technologies, frequently referred as the "Internet of Things" or IoT, enable reliable digital sensors that can measure the temperature inside the shipping container and are securely connected to the outside world, so that their readings can be viewed, recorded and trusted by the appropriate parties, including a court. Such connected digital sensors allow to verify whether the fruit was properly refrigerated during transportation. This allows F (and the court) to distinguish between the two different states—refrigerated and not refrigerated—and to set a different contract price for high quality transportation (with proper refrigeration) and low quality transportation (without refrigeration), which we denote as p_H and p_L. Figure 3 shows how this affects the contracting game.

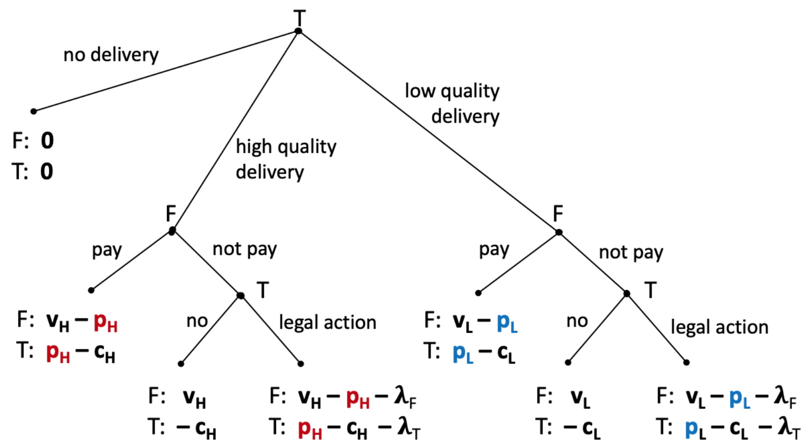


Figure 3: Fruit delivery contracting game with IoT sensors verifying the quality of transportation (and no smart contracts).

Since $v_H - c_H > v_L - c_L$, the optimal contract will have p_L and p_H such that $v_H - p_H > v_L - p_L$ and $p_H - c_H > p_L - c_L$. Thus, contracting takes place only for high quality transportation; to ensure that F will not renege on its payment to T it is necessary that $\lambda_T < p_H$, which is possible only if $\lambda_T < v_H$. This leads to the following Lemma:

Lemma 3 *In the contracting game with IoT sensors verifying the quality of transportation (but no smart contracts) trade is efficient when it takes place but there is no trade when T faces high enough cost of legal action.*

- *For $\lambda_T \leq v_H$, high quality transportation is contracted and performed, at price p where $\max\{\lambda_T, c_H\} < p < v_H$, yielding profits $\Pi_F = v_H - p$ and $\Pi_T = p - c_H$. The social surplus created by the trade is $v_H - c_H > 0$.*

- *For $\lambda_T > v_H$, there is no contracting. Payoffs and social surplus are 0.*

Compared to the base case, employing IoT sensors improves both the region of contracting, and the efficiency of the contracted outcome when contracting takes place. IoT sensors do not achieve full efficiency, however, in the sense that certain efficient trades will not take place when T faces a high cost of legal action.

Compared to the employing smart contracts only, there is less expansion of the contracting region, but the efficiency of contracting is improved when contracting does take place. IoT sensors expand the contracting region to the interval (c_H, λ_T), which is smaller than the (c_L, λ_T) interval by which the contracting region is extended when implementing smart contracts only. Whenever contracting takes place, however, IoT sensors increase the gains from trade to $v_H - c_H$, while smart contracts offer only $v_L - c_L$.

6 Combining smart contracts and IoT sensors

Utilizing both a smart contract and IoT sensors increases the state space over which we can contract, by allowing F and the courts to determine whether T provided refrigeration during transport, and limits strategy space by not allowing F to renege on payment. The game with both a smart contract and sensors is represented in Figure 4. As a result, contracting and trade take place when socially efficient, i.e., when $c_H < v_H$, at a price between these values, as described in the following Lemma.

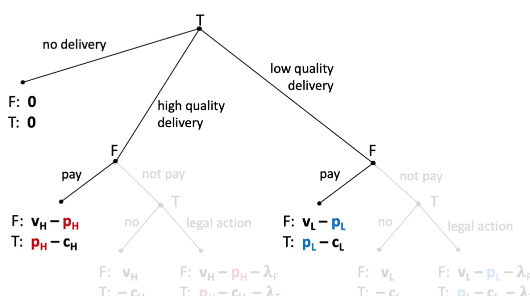


Figure 4: Fruit delivery contracting game with both IoT sensors verifying the quality of transportation and a smart contract based on the quality of transportation.

Lemma 4 *In the contracting game with both IoT sensors and smart contracts, contracting is fully efficient. High quality transportation is contracted for and executed when* $c_H < v_H$ *at price* p *where* $c_H \leq p \leq v_H$.

Based on the Lemmas 1–4 above, we obtain the following Proposition:

Proposition 1 *In the game represented in Figure 4, smart contracts extend the contracting region, and IoT sensors improve the efficiency of contracting when such contracting takes place.*

It can be seen from the above analysis that while smart contracts and IoT sensors both can improve efficiency, they do so in different ways, as is represented in Table 1. Smart contracts automate certain actions, and thus create commitment by limiting the strategy space. This results in increased efficiency by preventing hold-up and extending the contracting region. Without IoT sensors the contracting region is extended to $\lambda_T > v_L$, and with IoT sensors it is extended to $\lambda_T > v_H$. IoT sensors establish verifiable proof of the quality of transportation provided, and thus extend the space over which contracts can be agreed to. This improves efficiency by ensuring that when trade occurs, it is for high quality transportation. Without smart contracts, however, IoT sensors do not extend the contracting region when λ_T is high. Similarly, without IoT sensors, smart contracts do not enable contracting for high quality transportation.

SMART CONTRACT \ SENSORS	NO	YES
NO	(Lemma 1) low-quality when $\lambda_T < v_L$	(Lemma 3) high-quality when $\lambda_T < v_H$
YES	(Lemma 2) low-quality when $c_L < v_L$	(Lemma 4) high-quality when $c_H < v_H$ (efficient)

Table 1: Quality of fruit transportation in equilibrium under different technologies.

That means that each of these technologies may improve efficiency or provide no benefit, depending on the situation. There is also some range of parameters where a positive benefit can be obtained only when the two technologies are implemented together. This is what we explore in the next section.

7 Value created by IoT sensors and smart contracts

IoT sensors can create value with or without smart contracts, by enabling trades with high quality transportation and thus increasing total surplus. They may also enable certain trades (by extending the contracting region) even in the absence of smart contracts. Smart contracts create value by enabling trades that were prevented by fear of contractual reneging. In our setting, when smart contracts are implemented for existing trades, they do not improve the efficiency of these trades and thus they decrease total welfare if we take account of their implementation cost.[8]

The following Lemma states these results formally:

Lemma 5 *The value added by sensors and smart contracts depends on λ_T as follows:*

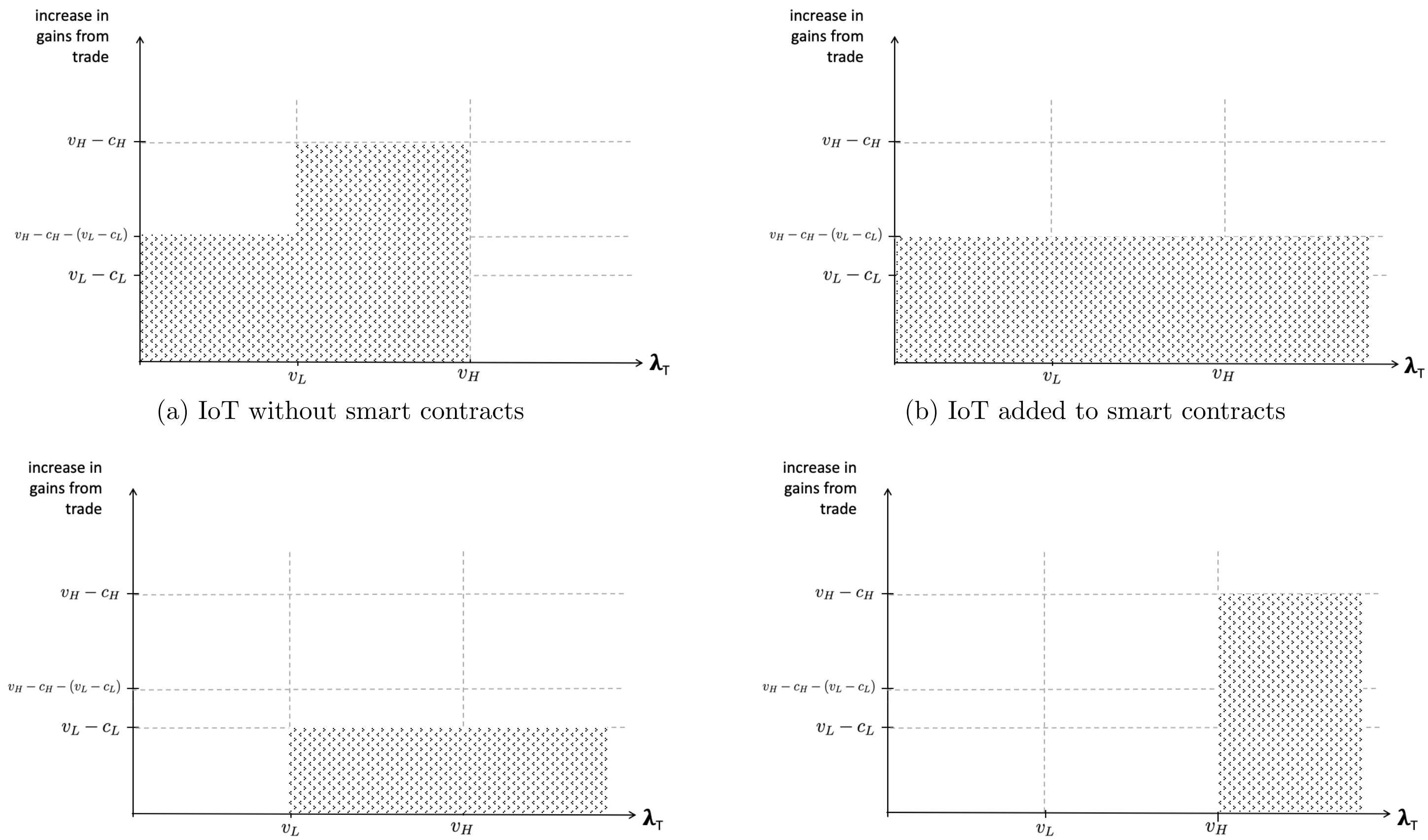
- *Without smart contracts, sensors increase the gains from trade by $v_H - c_H - (v_L - c_L) > 0$ for $\lambda_T < v_L$, and they increase the gains from trade by $v_H - c_H$ for $\lambda_T \in (v_L, v_H)$.*
- *When added to smart contracts, sensors always increase the gains from trade by $v_H - c_H - (v_L - c_L)$.*
- *Without sensors, smart contracts increase the gains from trade by $v_L - c_L$ for $\lambda_T > v_L$.*
- *When added to sensors, smart contracts increase the gains from trade by $v_H - c_H$ for $\lambda_T > v_H$.*

The results of Lemma 5, which are illustrated in Figure 5, suggest that smart contracts may indeed help to facilitate small-value trades where the gains from trade would be less than legal costs, or enable transactions with small agents that would not be able to afford legal action, as frequently claimed in the popular literature.

To assess which, if any, technology is socially beneficial to implement, we need to weigh the benefits of each technology against its cost of implementation. In the case of smart contracts, the primary cost of implementation would include the cost of linking the necessary digital inputs, programming the algorithmic part, and ensuring execution of the contract itself as well as the actions prescribed by its execution.[9] In the case of IoT sensors, there

[8] Automation provided by smart contracts can result in operational efficiency improvements, which we do not model in our setting, and which can offset their implementation cost and thus result in increased total surplus.

[9] Contract execution itself may require resources, such as gas on the Ethereum platform.



(a) IoT without smart contracts

(b) IoT added to smart contracts

(c) Smart contracts without IoT

(d) Smart contracts added to IoT

Figure 5: Value added of IoT sensors and smart contracts.

may be significant development costs, in addition to the cost of deploying and operating the sensors.

We use $\kappa_{SC} > 0$ and $\kappa_{IoT} > 0$ to denote the cost of implementing smart contracts and IoT, respectively. If both technologies are implemented, both costs are incurred. As shown in Figure 5, with the exception of IoT sensors added on top of smart contracts, there are regions of parameters where the technology is adding no value. This suggests that it is not always socially optimal to incur cost of implementing one or both technologies.

Proposition 2 *Which technologies are socially beneficial to implement depends on the cost of their implementation, κ_{SC} and κ_{IoT}, as well as T's cost of legal action, λ_T, as follows:*

(1) for $\lambda_T < v_L$, it is socially optimal to implement sensors if $\kappa_{IoT} < v_H - c_H - (v_L - c_L)$, and it is not beneficial to implement smart contracts, for any cost.

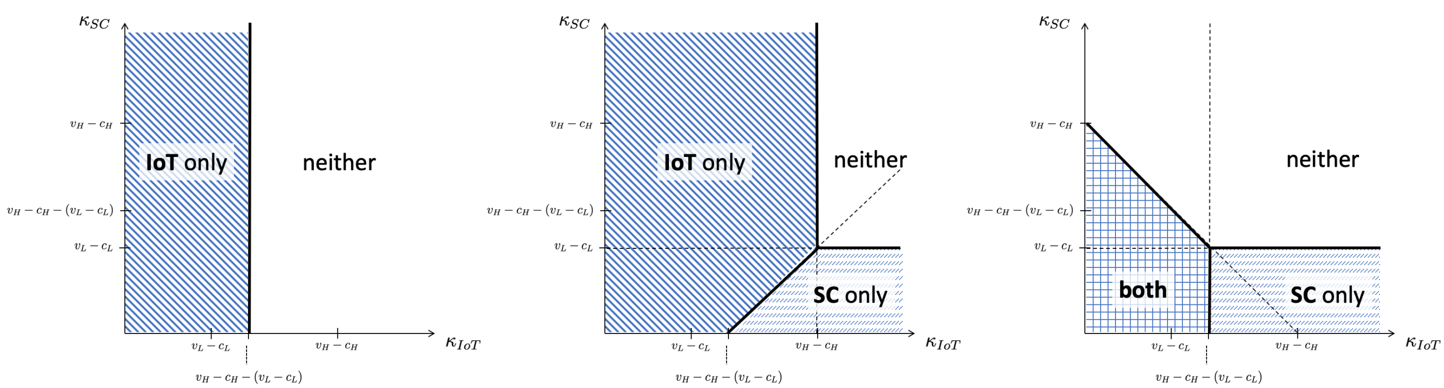
(2) for $\lambda_T \in (v_L, v_H)$, it is socially optimal to implement

- *sensors, but not smart contracts when* $\kappa_{IoT} < v_H - c_H$ *and* $\kappa_{IoT} < v_H - c_H + \kappa_{SC} - (v_L - c_L)$*,*
- *smart contracts, but no sensors when* $\kappa_{SC} < v_L - c_L$ *and* $\kappa_{SC} < v_L - c_L + \kappa_{IoT} - (v_H - c_H)$*,*
- *if it is socially beneficial to implement sensors, there is no added benefit from implementing smart contract on top of the sensors.*

(3) for $\lambda_T > v_H$*, it is socially optimal to implement*

- *sensors and smart contracts when* $v_H - c_H > \kappa_{SC} + \kappa_{IoT}$ *and* $\kappa_{IoT} < v_H - c_H - (v_L - c_L)$
- *smart contracts, but not sensors when* $v_L - c_L > \kappa_{SC}$ *and* $\kappa_{IoT} > v_H - c_H - (v_L - c_L)$
- *it is never optimal to just implement sensors without smart contracts.*

The results of Proposition 2 are illustrated in Figure 6.



(a) $\lambda_T < v_L$ (b) $\lambda_T \in (v_L, v_H)$ (c) $\lambda_T > v_H$

Figure 6: Socially optimal implementation of smart contracts and IoT sensors, depending on κ_{SC}, κ_{IoT} and λ_T.

It should be noted that if the cost to implement IoT sensors is less than $v_H - c_H - (v_L - c_L)$, then for $\lambda_T < v_H$ implementing smart contracts reduces total surplus. The reason is that IoT sensors enable a large enough price for high quality transportation to protect T from being held up. In that case, smart contract technology will not change the gains from trade, and thus will not offset its cost of implementation. It may increase the surplus captured by F, however, and thus F may favor its adoption, as discussed in the next section.

Also, as can be seen from Figure 6, when $\lambda_T > v_H$, IoT sensors improve the equilibrium only if they can be implemented together with smart contracts. For $\lambda_T > v_H$, when $v_H - c_H > \kappa_{SC} + \kappa_{IoT}$ but $v_L - c_L < \kappa_{SC}$, it is socially beneficial to implement both technologies together while it is suboptimal to implement either one alone; in that sense, smart contracts and IoT sensors can be complementary.

The above results depend on λ_T, T's cost of enforcing a contract. If this cost is ignored, any benefit from smart contracts would come from their ability to automate processes, like other types of IT, rather than their characteristic ability to change the contracting game. Sensors will still be optimal to implement as long as $\kappa_{IoT} < v_H - c_H - (v_L - c_L)$.

8 Incentives for adoption

The above results show that both smart contracts and IoT sensors will increase gains from trade for certain parameter values, and thus it is socially optimal to implement them if the implementation cost is sufficiently low. T and F, however, may differ in their private incentives to adopt, as this may improve payoff for one party, but decrease payoff for the other.

Specifically, assume that T has bargaining power $\gamma \in (0, 1)$ against F, meaning that T can capture γ fraction of any trading surplus, that γ is determined by factors not captured in our setting, such as the parties' available alternatives, and that γ is not affected by the adoption of smart contracts or IoT sensors. Without smart contracts, trade can take place only if $p \geq \lambda_T$, which may allow T to capture a larger share of the surplus than is warranted by its bargaining power; essentially T must be protected against F reneging on their agreement.

8.1 Incentives to adopt smart contracts

When T's bargaining power is low, F may have incentive to introduce smart contracts which would decrease social welfare. For $\lambda_T < v_L$, contracting without smart contracts takes place if the price $p > \lambda_T$, creating the trading surplus $v_L - c_L$. When γ is so low that $\gamma (v_L - c_L) + c_L < \lambda_T$, T must be offered a higher price than what it could obtain based on its bargaining power in order to trade, as a price below λ_T leaves T exposed to being held up by F. Introducing smart contracts allows contracting at price $p = \gamma (v_L - c_L) + c_L$, which yields $\Pi_T^{SC} = \gamma (v_L - c_L)$ and $\Pi_F^{SC} = (1 - \gamma) (v_L - c_L)$.

In this case introduction of smart contracts would make T worse off and F better off. In fact, F would be willing to spend up to $\lambda_T - (\gamma(v_L - c_L) + c_L)$ to introduce smart contracts and thus capture more surplus, even though it would be socially inefficient as the cost of implementation would be incurred without increasing trade surplus.

Other than the above case, the incentives to adopt smart contracts are aligned with social efficiency. For $\lambda_T > v_L$, both sides benefit from introduction of a smart contract. And for $\gamma(v_L - c_L) + c_L > \lambda_T$, smart contracts are socially suboptimal, and neither T or F find it beneficial to adopt.

8.2 Incentives to adopt IoT sensors

When T's bargaining power is low enough, it may also be made worse off by the introduction of IoT sensors. This is the case when $\gamma(v_H - c_L) + c_H < \lambda_T < v_L$, which is possible for low enough γ when $v_L < c_H$. In such a case, the contract offers T the same price $p = \lambda_T$ with or without the sensors, but T earns $\Pi_T^{IoT} = \lambda_T - c_H$ with sensors, while the profit without sensors, $\Pi_T = \lambda_T - c_L$, is strictly greater. Thus, T would oppose implementation of sensors, even when such implementation would be socially beneficial. When $\gamma(v_H - c_L) + c_H < \lambda_T < v_L$, T's surplus is further reduced if both sensors and smart contract are adopted, as $\Pi^{IoT,SC} = \gamma(v_H - c_H) < \Pi_T^{IoT} < \Pi^{SC}$.

The incentives for F and T to adopt IoT sensors are aligned when $\lambda_T > v_H$ or when T has sufficiently large bargaining power.

9 Discussion and Concluding Remarks

In this paper we discussed how predictions of the increasing prevalence of smart contracts often ignore the need to provide the necessary digital inputs, which can lead to incorrectly attributing the benefit from these inputs, such as IoT sensors that provide information about the occurring states of the world, to the smart contracts that use them.[10] This can bias theoretical analysis of the role of smart contracts, and promote inefficient implementation of technology in practice. Our main contribution is to distinguish the technologies of smart

[10] The Internet of Things also provides connected "actuators" that allow the triggering of *actions*, such as remotely disabling the car in Szabo's smart lien example. Like sensors, the end result of such actuators is to enable or facilitate new actions, and therefore extend the strategy space of the contracting parties; thus they have similar implications in terms of their economic analysis, and our analysis of IoT sensors can be thought as also encompassing IoT actuators.

contracts and connected sensors in terms of their implications for contracting and economic efficiency:

- *IoT sensors increase available information and thus expand the strategy space* of the parties to the contract, by allowing payoffs to depend on actions and outcomes not previously observable.

- By contrast, *smart contracts automate execution and thus restrict the strategy space* of the parties to the contract, typically by eliminating actions like reneging or hold-up, and thus allow commitments that previously would be expensive to enforce.

Availability of connected sensors helps promote smart contracts, but they can be implemented separately. The two technologies are often confounded, both in theoretical analysis and in applied practice, assuming that the verifiable machine-readable information necessary to execute a smart contract somehow just appears as an input to the platform that executes the smart contract. Sometimes this is the case, as properly coded information is in fact available to the smart contract platform. For instance, in Tinn (2018) the benefit from smart contracts on the blockchain network comes from reliable real-time information about transactions, which is a normal feature of the blockchain and is used to adjust the terms of the smart contract based on this information.

On the other hand smart contracts in shipping industry platforms such as TradeLens (provided by IBM Blockchain Solutions in cooperation with Maersk) are largely enabled because of developments in sensor technology that allow information to be collected and provided as an input to these contracts without the need for a human to observe and report. Progress in IoT technology allows to incorporate connected sensors in traded goods, such as the shipping container in our fruit transportation example. These sensors provide additional information such as the location, condition and use of the good and therefore enable contracting based on more contingencies. Consistent with this, we have been told that a large number if not a majority of developers at IBM Blockchain are working on creating and patenting sensors.

Our analysis also shows why on-chain ecosystems make smart contracts more effective by enabling everything to happen within the blockchain, allowing digital inputs within the system to be utilized by smart contracts, typically at zero or very low cost, and removing potential steps that can be intercepted by a human agent who may then renege. This highlights the challenge of linking blockchain smart contracts to off-chain activities in the real world in a verifiable way that prevents any of the parties from reneging by blocking contract execution. Addressing this challenge by providing appropriate technology and acting as a trusted party can be a major component of the value-added by the providers of commercial blockchain platforms.

The driving force of our results is the parameter λ_T, the agent's cost of *ex-post* enforcing the contract. This cost typically is not considered in the contracting literature, which typically is concerned with uncertainty, and the conditions needed for the parties to be willing to enter into the contract, assuming its terms will be fulfilled (or later renegotiated). Transaction cost theory and incomplete contracts theory do consider enforcement costs as an important reason why certain relationships are subject to hold-ups and certain actions are non-contractible. They use vertical integration and the ownership of assets as mechanisms to address these situations (e.g., Williamson 1975, Grossman and Hart 1986, Hart and Moore 1988).

One mechanism to avoid the costly enforcement of traditional contracts is repeated relationships (i.e., relational contracts). Another mechanism to mitigate the cost of ex-post enforcement is reputation. However relying on relational contracts or reputation creates barriers to entry for new market participants. A big premise of smart contracts (and more generally blockchain technology) has been that they would democratize the marketplace, countering the advantage that established large players enjoy even if they do not offer a better product. In our analysis, we investigate to what extend smart contracts indeed allow for this premise to be realized; we find that while smart contracts can in deed provide a mechanism to address enforcement costs, in many cases the ability to deliver on this premise (and promise) depends on the simultaneous deployment of appropriate IoT sensors.

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