Increasing willingness to pay in the food supply chain: a Blockchain-oriented trust approach

Xavier Brusset[a,*], Aseem Kinra[b], Hussein Naseraldin[c], Rami Alkhudary[d]

[a]SKEMA Business School, Université Côte d'Azur, Paris, France
[b]Bremen University, Germany
[c]ORT Braude College, Israel
[d]Université Paris-Panthéon-Assas, LARGEPA, Paris, France

Abstract

Food products' quality information is advertised on labels but do customers trust them? This study investigates how the consumers' Willingness-To-Pay (WTP) for food products can be increased by deploying managerial effort and advanced technologies, such as the Blockchain Technology (BT). Our model explains how revealing verified information about product quality throughout the supply chain will generate optimal consumers' WTP and maximize profit. At each echelon of a multi-echelon supply chain, a buyer holds a Bayesian belief about the quality of the input to be procured. This belief is shaped by the accuracy and veracity of the information about this quality. Managerial effort is required both to enhance quality as well as ensure full and verified information. We show why this effort must be made across the chain and how opportunistic behaviour may be circumscribed. Using empirically grounded analytics and real prices of olive oil intermediate produce from various official bodies, we show how the application of BT may be financially justified. This research shows how trust and WTP can be further enhanced through the use of BT and additional smart technologies in a supply chain, which may be projected on other supply chains of organic and sustainable food products.

Keywords: supply chains, trust, willingness to pay, blockchain technology, Bayesian belief

1. Introduction

Consumers' purchase behaviour for food products has considerably changed over this century. Demand for local and organic food production is increasing (Research and Markets, 2022). Along the years, numerous studies highlight that consumers perceive organic products as healthier (e.g., Hoefkens et al., 2009; Bruschi et al., 2015; Prada et al., 2017; Ditlevsen et al., 2019) and that these perceived health benefits are the major driving force behind organic food purchases (e.g., Magnusson et al., 2003; Tsakiridou et al., 2008; Chen, 2009; Schleenbecker and Hamm, 2013; Rana and Paul, 2020; Britwum et al., 2021). They are willing to pay a premium price for the benefits associated with organic food products (Schleenbecker and Hamm, 2013; Kushwah et al., 2019). Of course, information plays a crucial role in influencing both the acceptance of and the WTP for the organic claim (Teuber et al., 2016; McFadden and Huffman, 2017). This means that ensuring the authentication of product quality and origin is critical for all chain partners and for all food supply chains (Laddomada et al., 2013) so that it increases consumers' buying inclination (Nuttavuthisit and Thøgersen, 2015). This is even more so in the case of food safety: consumers are increasingly sensitive about the quality of agricultural products and the implementation of safe practices (Yawar and Kauppi, 2018). The WTP increases if the information about food products comes from consumer associations, less if it comes from the European Food Authority and not at all if it comes from industrial partners (Nocella et al., 2014; Yormirzoev et al., 2020).

How can information about quality be made apparent in the food product for consumers to trust it? As we will show in the literature review, there is an abundant literature on how information can be collected along the supply chain about the quality of a food product and how this information is then relayed to the consumer. Food producers, transformers, and processed food manufacturers have invested in information systems to track quality and ensure full traceability from "farm to fork". The confidence in such traceability systems and corresponding WTP is still lacking (Zhang et al., 2020).

The fact is that there are many steps between the farm and the fork. For each step along the way, a specialized firm takes care of the required transformation or logistic task. This division of each food supply chain into many independent firms looking after their own particular interest does not breed the expected trust and information exchange. Relying on public authorities' supervisory and

*Corresponding author
Email addresses: xavier.brusset@skema.edu (Xavier Brusset), nhussein@braude.ac.il (Hussein Naseraldin), rami.alkhudary@u-paris2.fr (Rami Alkhudary)
URL: kinra@uni-bremen.de (Aseem Kinra)

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law enforcing powers is not enough (Yinghua et al., 2018).

More recently, BT has been assumed to enhance the information exchange which should breed the expected trust (Mendling et al., 2018; Kumar et al., 2019; Chang et al., 2020). However, despite the recent hype about BT and ancillary technologies to increase the veracity of information in supply chains, no research has been able to justify the deployment cost so putting its application in doubt. If the investment in BT can not be justified, the supposed advantages disappear. In what follows, we view BT as part of a new "governance mechanism to organize collaborations in supply chains" (Wang et al., 2022; Zhu et al., 2022; Koh et al., 2020).

We pose the following three questions: How can information about quality be made apparent about a food product for consumers to trust it? Which information system can be sufficiently robust that consumers trust the corresponding information and that their WTP increases? There is already a large literature addressing such questions, which is why we prefer to dedicate our attention to the question below. Given the multiple actors involved, a common information exchange mechanism to coordinate them is needed to ensure optimal quality levels and trust, we wish thus to address the following one: *What is the optimal combination of managerial and technological investment, e.g., in BT infrastructure, to build trust and increase WTP in a multi-echelon food supply chain?*

Blockchain, the Internet of Things (IoT), sensor technologies, and the development of Industry 4.0 have matured to such an extent that their combination might be expected to now lead to new breakthroughs in food safety, traceability, and sustainability thanks to increased collaboration (for example, see Iftekhar et al., 2020; Rejeb et al., 2021; Liu et al., 2022; Biswas et al., 2023). We build upon this literature to present a model which should help in answering the above question. We will show that the managerial effort described in the preceding paragraph calls for the combination of such technologies with the continuous improvement of processes and information systems, as well as the constant training of operators and managers.

In this paper, building upon already proven results in the literature, we show that BT in the supply chain must be coupled with the right managerial effort to improve the consumers' WTP and that of the multiple partners throughout the chain. In this way, the extra cost of deploying BT would be justified.

We model the increase of the WTP in food products by a stylized game theoretic model of a supply chain to show how the consumer's WTP is increased as all upstream suppliers update truthfully the necessary information about the quality of the product through its different transformation phases. To do so, we model each level of the chain as a supplier-seller-buyer triad (Mena et al., 2013). The seller engages in effort to ensure the highest WTP on the part of the downstream buyer by informing about the product quality resulting from his transformation process as well the quality of the transformation processes of the upstream supplier. We show how WTP drops when one partner cheats on the quality of the intermediate produce or if the information about such quality can be doubted. We show that a constant effort is required from all partners to ensure that no doubt arises in the minds of buyers, be they intermediate customers or consumers. We validate the mechanism by applying it in a stylized analytic example using intermediate prices for raw material for different qualities in an olive oil supply chain.

Our contribution is both positive and normative (Bertrand and Fransoo, 2002). From a positive viewpoint, our model explains how and why some partners may opportunistically engage in deceiving the next level buyer about the quality of the intermediate products being sold (as so often happens, see olive oil fraud in Al-Zoubi, 2019). We show how consumers can be made to trust a particular supply chain's products and hence be willing to pay a higher price given that they trust the quality. From a decision-making stance, two contributions are presented: (i) the Bayesian updating mechanism proposed for the different players of the game about the quality of the product being sold as well as how this mechanism can be influenced by the seller's information and the quality of such information; (ii) how governance mechanisms coupled with the right sensor and BT can help all members in the SC achieve the highest consumer WTP. From a behavioral stance, our contribution provides two theoretical arguments. The first one is justifying the partners' effort both in ensuring the highest quality intermediate product and in sharing truthfully the relevant information to the other partners. The second one, *a contrario*, explains why, in the case of absence of or misleading information, one partner can behave opportunistically by adulterating or processing sloppily the intermediate product and thus capture an undue extra profit because of lower processing and effort cost.

The paper is organised as follows: we discuss how our contribution is placed with regard to two streams of literature in 2 before developing a model in 3, and illustrating the result in 4. We draw some conclusions and inferences for future research in 5.

2. Literature review

Several streams of literature are relevant to this work and are dealt with in different subsections. We first highlight how researchers have shown how to harness BT to improve security, traceability, and information sharing in operations and supply chain management (subsection 2.1). We then bring up in subsection 2.2 how the WTP of the consumer and of intermediate partners in the supply chain is increased, specify the research gap and our contribution.

2.1. BT in operations and supply chain management

Transparency, visibility, and increased efficiency are the promises of BT when viewed from an operations or a supply chain management viewpoint (Kumar et al., 2019; Lohmer et al., 2020; Li et al., 2023; Liu et al., 2023). The database or ledger aspect of BT has advantages over traditional ways of storing data as it can scaled up efficiently, reduces human and other transaction costs (Babich and Hilary, 2020; Wu and Yu, 2023), especially more so since major platforms have now moved their consensus protocol from proof of work to proof of stake (eg, Ethereum in September 2022) which is less costly in energy (Zhang and Chan, 2020). Recent blockchain-enabled supply chain pilot projects have shown how such information systems can be harnessed to promote visibility of the information about quality (Wang et al., 2020; Bai and Sarkis, 2020; Liu et al., 2023).

The combination of BT with the corresponding and relevant technologies, be it sensors, Internet of Things (IoT) devices (Zhang et al., 2020; Iftekhar et al., 2020; Li et al., 2020), or secure communication networks, have been shown to provide a verifiable and traceable IoT network (Ben-Daya et al., 2017; Sidorov et al., 2019) enhancing the automated and trusted identification of physical objects, critical to their traceability (Balagurusamy et al., 2019; Casino et al., 2021).

Data security and integrity are guaranteed against replay attacks as well as physical attacks on sensors because they can report such attacks directly to the blockchain and because of cross-checking by sensors between themselves (for additonal reference about security, automatic transaction management, and offline-to-online data verification, see Mendling et al., 2018; Sanchez-Gomez et al., 2020; Lao et al., 2020; Wang et al., 2020; Giovanni, 2020; Krishnan, 2021; Capocasale et al., 2021). The information thus validated will then be used by smart contracts (Tapscott and Tapscott, 2017) connected through oracles (Dolgui et al., 2019; Mao et al., 2018; Kamilaris et al., 2019; Bakos and Halaburda, 2019). These are drivers that allow firms to move from the physical to the digital world (for further information please see Agrawal et al., 2018; Hawlitschek et al., 2018; Savelyev, 2018; Mendling et al., 2018; Meyer et al., 2019; Lao et al., 2020).

To summarize, the above literature, mostly at the border of supply chain and information systems research, places its emphasis on the decentralized topology, security, information sharing, and traceability necessary in a supply chain (Kumar et al., 2019). In that stream, the return on investment of investing in BT is rarely addressed (Alkhudary et al., 2020). Most only present how costs can be reduced (Chaudhuri et al., 2021; Wu et al., 2023).

On the other hand, in the supply chain game theoretic literature some interesting contributions on how BT can be harnessed must be discussed. Biswas et al. (2023) consider in a game theory model how BT will increase traceability and so overcome distrust of a product by end-consumers hence increasing sales. The model presents the conditions for an equilibrium where the cost of BT is quadratic in the level of traceability. How the end-customer is informed about the level of traceability is not explained.

Chod et al. (2020) show how transparency through BT enables inventory verifiability or Shen et al. (2020) how secondhand products can be priced higher on e-marketplaces, thus helping, for example, brand-name companies obtain a quality disclosure effect (Shen et al., 2021b). In Liu et al. (2021), customer WTP hinges on the belief about quality which is uniformly distributed between two bounds. These three papers consider that blockchain deployment immediately makes the information about quality common and truthful. In Shen et al. (2021a), conditions where quality checks prevail over a blockchain system to detect counterfeit masks are investigated but do not show how the information about quality is verified before being locked into the blockchain system (ie, opportunistic behavior can go undetected).

None are studying how a blockchain-enabled supply chain might increase the consumer's WTP which could be a way to justify the investment in BT, at least in the food supply chain.

Finally, fighting counterfeit products by adopting BT to prove product origin and so increase trust in the end-customers' mind has been modeled in Niu et al. (2021) and Pun et al. (2021). However, in Pun et al. (2021), the government must subsidize the cost of BT; while in Niu et al. (2021) multinational firms will not want to participate in chain-wide BT deployment for cost and tax reasons.

We are interested here in answering the question of how end-customers will pay more for a food product because they are confident of the *provably* true qualities of that product and so pay for the cost of implementing the corresponding solution.

2.2. *The customer's willingness to pay for quality and sustainability*

In the following we show how WTP has been shown to exist in both constructivist and positivist, normative literature.

WTP in quantitative surveys literature

Like Bresnahan (1987) and Berry (1994), we consider here that customers care about product quality, which is modelled as depending on product characteristics, some of which may be unobservable (Berry, 1994). In some cases, products may look similar but differ in customers' perceptions regarding quality, durability, status, service at the point of sale, or after-sales service. Customers maximise the utility of a product as a function of budget constraints (Hanemann, 2001) that hence directly impacts their WTP.

In particular, origin and quality are directly linked to the value of the product (Giraud and Halawany, 2006; Padilla et al., 2007; Bánáti, 2011; Santosa et al., 2013). Notably, WTP estimates are positively linked to customer trust in certified animal-friendly products (Nocella et al., 2010), or organic coffee (Dionysis et al., 2022).

They want to know if a product has been produced sustainably or through a high-quality process (Choe et al., 2009; Giampietri et al., 2018). In effect, trust in food supply chains covers a number of different concepts (Tejpal et al., 2013). The scandals concerning various foodstuffs in China in the 2010s have led to effort in real-time food tracing to enhance the safety assurance (Tian, 2018) and increase the value in the eyes of the consumers (Pang et al., 2015) through complete traceability (Chang et al., 2013), especially as compliance with food quality regulations is not enough to generate trust (Robinson and Ruth, 2020).

WTP in mechanism design literature

The game theoretic literature on supply chains considers that a Bayesian mechanism is required so that a player in an incomplete information game can update a prior belief using available information on the actions of the other players in the game (Harsanyi, 2004). The actual purchase decision is based on the perceived quality and risk associated with the product, rather than on consumers' initial intention (Khor and Hazen, 2016). Choi et al. (2020) shows how an on-demand service platform will derive the risk aversion profiles of customers and hence WTP by using BT. In some instances, consumers rely on suppliers to help them decide on whether to buy a product. The process through which a supplier provides assistance in Özer et al. (2018) includes information sharing, advice provision or delegation: the better the information, the higher the WTP. Confirmation of this result is provided by Zhao et al. (2018) when two firms compete and one has a higher quality product: the higher quality firm will prefer to disclose quality information. Both Guo (2009) and Guan and Chen (2015) discuss which of two competing manufacturers or retailers will disclose quality information to the consumer, whereas Guo and Zhao (2009) characterise which of two competitors will do so and in what order.

In a slightly different take on the same issue, an experiment has shown that when there is a large difference in service quality between firms, the social network information from feedback by other users increases the higher quality firm's market share, provides the lowest demand uncertainty and the fastest convergence to a steady-state market share between both firms (Davis et al., 2021). None of the above look into the process of building the case about the true quality of the product. The intrinsic quality of the product is supposed to preexist.

The literature is also extensive on how consumers learn from their own decisions and experience of product quality (Erev and Haruvy, 2016) and from information coming from social networks (Acemoglu et al., 2011; Besbes and Scarsini, 2018; Ifrach et al., 2019). Here we must distinguish between the B2C and B2B scenarios. In the B2C scenario, the final consumer may repeatedly choose among a set of suppliers when she is not well informed about the supplier quality level and will only converge slowly to the highest quality supplier through a Bayesian updating of her beliefs (Gans, 2002), whereas in the case of the B2B scenario the firm must also choose between suppliers (Sener et al., 2021). Here, in difference to our approach, the way the supplier will build the necessary product quality information is not in question.

The consumer is not the only echelon for considering WTP, purchasing managers are also willing to pay to assure compliance dimensions to ensure that suppliers are following sustainability standards (Goebel et al., 2018). This WTP is influenced negatively when standards are not met as evidenced in a number of annual reports in the food and textile industries (Nestlé, 2018; Inditex, 2020).

Our research extends this mechanism to all partners in the supply chain, including the consumer. Because of asymmetric information, a supply chain partner has to form a belief as to the supplier's product quality. Truthful information will help the Bayesian updating of the belief held by the buyer about the supplier's product quality, also named the Bayesian Mechanism (Cabral, 2005).

Having gone over a picture of the necessary technology to bring about the consumer's WTP, we describe in the next section how our model would apply it.

3. Model and analysis

After providing some background considerations about the motivation of the model in subsection 3.1, in subsection 3.2, we explain the way each buyer at each production step from raw material to consumer has the ability to buy the trusted quality product or an alternate one for which quality is not verified. In subsection 3.3, we evaluate the optimal effort and optimal price at each level. We explain how adopting BT must be further supported by additional effort. We then extend the model to the overall chain in subsection 3.4. We discuss the case when one or more members of the chain cheat in subsection 3.5.

3.1. *Motivation of the model*

We consider the case of a food supply chain where partners, each one in charge of a transformation step, have come to the conclusion that the consumer will be willing to pay for a quality and sustainably produced food product. In the market, there are various alternatives which fail to prove to be of quality and/or to come from a sustainable supply chain. As is common in such settings, this quality level is enshrined in a charter describing in detail the entire production process from raw material to finished consumer product including all quality requisites. The more detailed and stringent the technical specifications, the higher the expected quality. The consumers' WTP increases with such expected quality. By contrast, the nondescript product lacks such quality specification. Without loss of generality, the price for the higher quality product is higher than for the nondescript one, while the production costs are similar and standardised to 0.

In an initial phase, the partners agree to belong to one single supply chain (see Figure 1). They also agree to abide by a governance mechanism including a code of conduct and commitment to produce the quality product (Gulati and Nickerson, 2002; Robson et al., 2008; Singh and Teng, 2016). They invest in the BT required so that all partners can register immutably on a shared registry all information pertaining to the quality of the intermediate and final product.

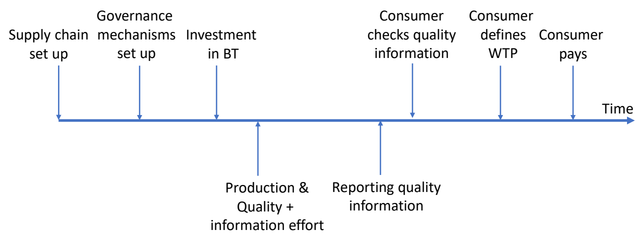


Figure 1: Sequence of events in the model: top left, all partners contribute, bottom, actions by each actor in turn. Top right: actions by the consumer.
Alt-text: Sequence of events in time in the model: top left, all partners contribute, bottom, actions by each actor in turn. Top right: actions by the consumer.

In the production phase, they ensure that the sensors duly report the correct data to prove that the quality of the products corresponds to the one expected in the charter (Tian, 2018; Fadda et al., 2018; Dolgui et al., 2019; Lao et al., 2020; Wu et al., 2021).

All such information about quality is then shared with all other partners so that each can check that the quality of products bought from upstream partners corresponds to the expected one.

It is easily understood that a partner who has too few sensors and too little control over quality will not be able to provide as trustworthy information as one who can provide verified data for all the steps of the transformation process under her responsibility. When the data is patchy, with limited verification, the trustworthiness of the quality is lower. This impairs the buyer's WTP, as well as all the downstream partners' WTP.

Hence the consumer's WTP can be treated as a Bayesian belief in the true quality of the product on offer (Harsanyi, 2004). As a Bayesian belief, it can be modelled as a random variable Z from a probability distribution $F(z) = P(Z \leq z)$ with mean μ and standard deviation σ. This Bayesian belief is built from the consumer's information available to her. The quality standard enshrined in the quality charter that the supply chain partners abide by corresponds to a specific mean μ: the topmost quality will correspond to the highest μ, whereas a nondescript product will have the lowest one since the quality is not verifiable. Now, if the quality information available about the production process also demonstrates that all such standards have been respected, then the standard deviation of the belief is low: the customer has no doubt about that the quality of the product matches that promised by the charter. When she has doubts about the veracity of the information or that the quality of the product effectively reflects the expected one, she will build a Bayesian belief with a high standard deviation. She must estimate a value $\hat{z}$ for the price to pay.

The extra rent in the supply chain is generated by the consumer who is willing to pay a higher price for a food product for which the true quality is revealed than for a product of unknown quality (Chaudhuri et al., 2021). We thus target the final price of the food product as the objective to be maximised as a proxy for the utility derived by the consumer from buying a product of known and truthful quality.

Now, consider a partner in the chain who decides to opportunistically cut corners in terms of the quality she has to supply by, for example, adding some lesser quality (and cheaper) material in her product. To do so, she must also falsify or fail to report the true quality of the product to the database in the Blockchain. Conceivably, she may also obtain the connivance or complicity of other chain members to subvert the quality of the product. The purpose might be to obtain (and share) extra rent to the detriment of the unwary customer. This situation is modelled in subsection 3.5.

For illustration purposes, let us consider the case of edible olive oil as highly representative of food supply chains. As can easily be verified, olive oil is sold with widely different prices, ranging in scale from 1 to 5 for the most commonly available brands (Devarenne, 2021). Such a supply chain can be represented in a simplified manner as composed of a farm where olives are harvested in olivars, a mill where the olives are pressed, a bottler who will bottle the bulk oil, and a retailer selling the oil bottles to the consumer (Figure 2).

3.2. *Buying process in the olive oil supply chain echelon by echelon*

We separate the chain into sub-parts each composed of a triad of three partners : a supplier who sells an unfinished product to an actor who transforms it and sells it on to the buyer (see Figure 2). In this way, the olive oil supply chain

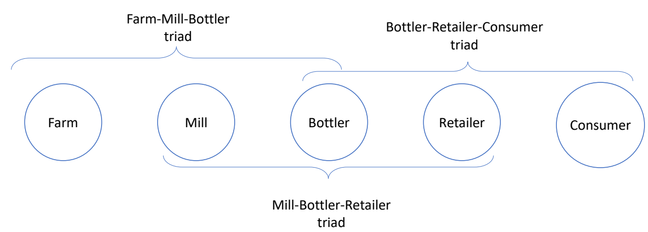


Figure 2: Supply chain triads composed of a supplier, an actor transforming the product, and a buyer buying this transformed product.
Alt-text; Supply chain triads composed of a supplier, an actor transforming the product, and a buyer buying this transformed product.

can be decomposed in several triads (Mena et al., 2013) with the same characteristics: in each case an actor (a) buys a raw material or semi-finished product from a supplier (s) and sells it on to a buyer (b). We then have the following triads: farm-mill-bottler; mill-bottler-retailer; and

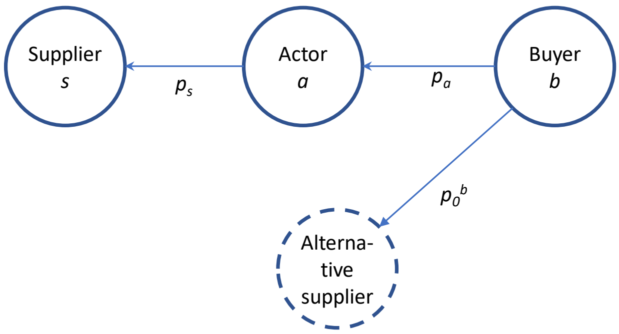


Figure 3: The buyer pays p_a to the actor who pays the supplier p_s for the intermediate product which she transforms. Alternately, the buyer can buy at price p_o^b from a non-strategic supplier.
Alt-text; The buyer pays p_a to the actor who pays the supplier p_s for the intermediate product which she transforms. Alternately, the buyer can buy at price p_o^b from a non-strategic supplier.

finally, bottler-retailer-consumer. In the following, to describe the workings of the triads, we shall subscript the supplier with an s, the actor who buys from this supplier with an a, and the buyer who buys from the actor with a b.

A buyer has a need to fulfil and will pay different prices according to the type, the origin, or some other characteristic of the olive oil (see Figure 3). Let us consider here that the buyer can buy a specific quality, as described in a particular charter (Parra-López et al., 2015; Padilla et al., 2007). Hence, she is willing to pay p_a, the going price for this quality.

Alternately, she also has the possibility of paying a price p_0^b for an available nondescript product with $p_0^b < p_a$ from another seller. Note that this p_0 is available for every triad of the chain as will be explained in Remark 3 below.

Remark 1. *The differentiating factor is the available information about quality. The buyer has a need to fulfil but has the choice of buying a product for which some information about quality is known or from an alternative source for which no information about quality is available. We do not tackle the strategic multi-supplier problem here (Laffont and Tirole, 1993; Stole, 1994; Elmaghraby, 2000).*

We will denote β_a as the effort deployed by the actor to build visibility and verifiability with $0 \leq \beta_a \leq 1$. The cost of this effort is $T_a(\beta_a)$. Without loss of generality, all other costs, such as warehousing, administration and marketing, are normalised to zero. For all triads described in the chain in Figure 2, the actor's objective function is

$$\Pi_a(\beta_a) = p_a(\beta_a) - p_s(\beta_s) - T_a(\beta_a), \tag{1}$$

with $p_s(\beta_s)$ the price of the product sold by the supplier as a function of her own effort to build trust β_s at her level of the chain. Note that the effort to build trust is a decision variable for each chain member and taken myopically at each level.

The buyer's profit then becomes

$$\Pi_b(\beta_b) = p_b(\beta_b) - p_a(\beta_a) - T_b(\beta_b) \tag{2}$$

if buying from the actor, and

$$\Pi_b(\beta_b) = p_b(\beta_b) - p_0^b - T_b(\beta_b) \tag{3}$$

if buying from the alternative supplier.

Remark 2. *The cost of developing trust as well as the effort β_a is only known by the actor. As we shall see below, if the buyer does not trust the quality of the product, she will not pay the price corresponding to that quality but only the price corresponding to the alternative no-name product available on the market. That is, the buyer's WTP will be at its lowest.*

For the consumer, the utility derived from consuming olive oil of known quality is u and, in monetary terms,

$$\Pi(u) = u(\beta_r) - p_b(\beta_r), \tag{4}$$

where β_r is the effort deployed by the retailer and, since she does not have to build trust, her utility increases with the trust in the quality of the retailer's product but must be higher than the economic utility of the price paid.

Thus to ensure that incentive and participation constraints are met,

$$\begin{cases} p_a(\beta_a) \geq p_s(\beta_s) + T_a(\beta_a), \\ p_b(\beta_b) \geq p_a(\beta_a) + T_b(\beta_b), \\ u(\beta_r) \geq p_r(\beta_r) \end{cases} \tag{5}$$

must hold.

Remark 3. *The price for unknown quality products available at each echelon corresponds to the state at which the olives have been transformed as presented in Figure 2: the miller can buy ordinary olives at price p_0^m, the bottler can buy no-name olive oil at p_0^{bo}, the retailer can buy the bottled olive oil at p_0^r, and, finally, the consumer would pay p_0^c for a no-name bottle on the retailer's shelf. In such a case, obviously, the end product is not a high quality olive oil.*

3.3. *Finding the optimal price to pay and optimal effort for each actor in the chain*

End-consumer utility increases with trust (Hanemann, 2001; Lancaster, 1979), and end-consumer WTP increases continuously with trust in the ability of the retailer to provide the expected quality (Santosa et al., 2013). In the same way, as retailers trust manufacturers, their WTP increases (Kumar, 1996).

The estimated distribution of the Bayesian belief Z follows a probability density function $f(.)$ and a cumulative density function $F(.)$ over a domain $[\underline{z}, \overline{z}]$. We consider, without loss of generality, a domain such that $0 < \underline{z} \leq p_0^b \leq p_a \leq \overline{z}$ with p_0^b as the alternative unknown quality product available to the buyer. We assume that this distribution has an Increasing Failure Rate (IFR : Barlow and Proschan, 1965), or is log-concave (Bagnoli and Bergstrom, 2005). This failure rate is given by $r(z) = f(z)/\overline{F}(z)$ and $r'(z) \geq 0$, where $\overline{F}(z) = 1 - F(z)$. Positive-valued log-concave distribution functions feature IFR characteristics and include a large variety of statistical distribution functions such as the continuous uniform, the gamma, the Weibull, the modified extreme value, the truncated normal, and the log normal as characterised in Barlow and Proschan (1965). These functions, given that we do not consider negative values, are all log-concave (An, 1998; Bagnoli and Bergstrom, 2005).

We explore how this behaviour applies to the triads as already characterised in Figure 2. For all triads in the chain, the buyer maximises the expected profit (utility) Π_b from her purchase in terms of her WTP. If she trusts the actor to provide the true quality of olive oil, she will pay a price z with a probability $\overline{F}(z)$. If, on the contrary, she does not trust the retailer and hence believes that the true quality of the olive oil is lower than advertised, she will instead buy from the alternative retailer at price p_0^b with probability $F(z)$.

Generalising for all the buyers' profit functions, from mill to retailer, the buyer's profit function changes from (2) and (3) to:

$$\underset{z}{max}\Pi_b(z) = z\overline{F}(z) + p_0^b F(z). \tag{6}$$

We now enunciate the following Theorem (the proof is in appendix Appendix A).

Theorem 1. *If the Bayesian belief distribution of f is IFR, there exists a unique maximum value z^* representing the buyer's optimal WTP given his Bayesian belief of the quality of the product solution to the above objective function such that:*

$$z^* - p_0^b = \frac{\overline{F}(z^*)}{f(z^*)}. \tag{7}$$

Corollary 1. *The optimal value corresponding to the WTP exists and is always higher than the outside price p_0^b reflecting the belief held by the buyer that there is a non-zero probability that the actor may be selling a quality product such that it would be slightly better than what can be found on the market from an untrusted seller.*

Corollary 2. *When the buyer does not trust the supplier, the Bayesian belief distribution will have a mean of p_0^b and a standard deviation of $\sigma = 0$, so that $z^* = p_0^b$.*

From the above, it appears clearly that this WTP evolves both with the mean and with the standard deviation of the probability distribution of the Bayesian belief. The buyer builds this distribution in terms of the trust inspired by the actor and the information available: trust but verify (Russian proverb used by Ronald Reagan). The more information about the quality is provided by the actor, the higher the mean of the random variable. Moreover, she will be considering that the potential distribution of such true quality cannot vary wildly: the higher the trust, the lower the standard deviation. So, the following Proposition can be enunciated.

Proposition 1. *WTP is built upon an a priori Bayesian belief which has a probability distribution $F(z)$ with μ and σ as first and second moments. Hence we can relate the effort β_a to build such WTP which stems from the shape of the Bayesian belief distribution function. This relationship is designated here by $G_a(.)$ and $H_a(.)$, as follows:*

$$\begin{aligned} \mu &= G_a(\beta_a), \\ \sigma &= H_a(\beta_a), \end{aligned} \tag{8}$$

where $G_a(.)$ is a strictly increasing function, whereas $H_a(.)$ is a strictly decreasing one over the domain of the possible values for β_a, presumed to be in a closed set.

Corollary 3. *When the buyer has an imprecise notion of the quality of the product, she will increase the variance of the Bayesian belief distribution. The higher the variance, the lower the estimate of the price the buyer is willing to pay $\hat{z}$. If the buyer expects the quality of the product to be low, she will lower the mean of the belief distribution. The actor's effort β_a in trust building is to induce the buyer into increasing the mean and lowering the variance of the Bayesian belief distribution.*

To link back to the system we are suggesting, if, for example, the buyer does not believe in the information shared on the blockchain by the actor as to the true quality, the former's WTP will be lower. The only case when the buyer is willing to pay p_a is when information available indicates the advertised quality is the right one, $\mu = p_a$, and can be trusted, $\sigma = 0$, hence $\hat{z} = p_a$. This means that $H_a(\beta_a) \geq 0$ and $p_0^b \leq G_a(\beta_a) \leq p_a$. To understand in a more visual way how this works, we refer the reader to the numerical illustration in Figure 4. Therein, note that the optimal price that the buyer is willing to pay increases with the mean of the Bayesian belief distribution and decreases with the variance of such distribution.

To the actor, the cost of building WTP is hypothesised as being increasingly costly, so that $T_a(\beta_a)$ is a strictly increasing convex function, which is plausible due to decreasing marginal considerations.

Remark 4. *Note that the case where an actor cheats or misrepresents the quality of the product is included in the model. Either μ will be lower or σ will be larger, thus reducing WTP. In the extreme, governance mechanisms to punish cheating can be triggered so that the actor is kicked out of the chain, or a penalty can be levied. We discuss the impact for the whole supply chain in subsection 3.5.*

3.4. Building WTP in the whole supply chain

We now extend the dynamics of the triplet of players developed above to the whole supply chain. We refer the reader to Figure 1: in the initial phase, the supply chain partners have decided to set up the chain, have invested in the corresponding specific assets, have trained the operators required by the BT, and set up governance mechanisms. The production phase is when all partners produce the bottled olive oil and engage in the necessary effort to ensure that the proper information about the oil is registered and shared between all chain members.

Obviously, if a consumer trusts the retailer on the quality of the product, she must trust by extension all the supply chain upstream to this retailer. Because we are in a case where the retailer represents a set of agents who can engage in a number of actions, this problem can be assimilated to the agency problem with a principal and multiple agents who can engage in multiple actions of which only a limited subset will be approximately incentive compatible for a transaction to take place because the outcomes of these actions constitute a compact space (Dütting et al., 2020). If one upstream supplier to the retailer cheats or otherwise does not sell the expected quality raw or semi-processed material, then the final product cannot be said to comply with the quality expected by the consumer, thus leading to a breach of trust. As explained earlier, this breach of trust will lead the consumer, if she still wishes to buy from the retailer, to revise her belief by increasing the standard deviation of the distribution of that belief. In the worst case, as mentioned in Corollary 2, the alternative for the consumer is to buy a no-name product but at the price for a product of unknown quality. In this case, her WTP is null, as is her utility.

In the general case, for the different actors in the chain, the profit functions can be established in terms of the effort deployed by each as

$$\begin{aligned}
\Pi_f(\beta_f) &= p_f^*(\beta_f) - T_f(\beta_f),\\
\Pi_m(\beta_m) &= p_m^*(\beta_m) - p_f^*(\beta_f) - T_m(\beta_m),\\
\Pi_{bo}(\beta_{bo}) &= p_{bo}^*(\beta_{bo}) - p_m^*(\beta_m) - T_{bo}(\beta_{bo}),\\
\Pi_r(\beta_r) &= p_r^*(\beta_r) - p_{bo}^*(\beta_{bo}) - T_r(\beta_r),\\
\Pi_c &= u(\beta_r) - p_r^*(\beta_r),
\end{aligned} \tag{9}$$

where Π_c is the utility obtained by the consumer from consuming the olive oil and the star in superscript denotes the optimal price achieved because the WTP of each buyer in turn is at its highest. Each of those prices is evaluated using (7) in Equation 1.

BT can provide the backbone along the supply chain for information to be shared but can not guarantee that the only true information is registered due to the *"trust-frontier"* (Glaser, 2017; Hawlitschek et al., 2018; Altmann et al., 2019; Hawlitschek et al., 2020). The necessary condition for trust to emerge can only come from constant effort, captured in our model by β, by all members of the chain $(\beta_f, \beta_m, \beta_{bo}, \beta_r)$ in ensuring that the information is truthful and verifiable (Shermin, 2017; Dolgui et al., 2019; Giovanni, 2020; Chaudhuri et al., 2021). The retailer has all the arguments to inform the consumer about that true and exact quality. The retailer can enhance this visibility effort by providing through a QR code label on the final product's container the full quality report (Bumblauskas et al., 2020).

In the case where the BT has been deployed throughout the supply chain and the required investment costs have been incurred (meaning that they are now sunk), the overall chain's total profit function in terms of the effort decisions $(\beta_f, \beta_m, \beta_{bo}, \beta_r)$ of ongoing continuous effort developed by each chain member (farm, mill, bottler, retailer), using Equation 9, can be evaluated as

$$\Pi(\beta_f, \beta_m, \beta_{bo}, \beta_r) = p_r^*(\beta_r) - \sum_i T_i(\beta_i), \quad i \in \{f, m, bo, r\}. \tag{10}$$

Each member of the chain has a distinct cost function of the effort to build trust so that, at the retail level, the retailer can charge the optimal price in relation to WTP $p_r^*(\beta_r)$ to the consumer, a higher price than in the case of a chain where BT has been deployed but information about the true quality of the product is not verified because the chain partners have not deployed effort to do so.

Given both Equations 9 and Equation 10, it is clear that the price of the olive oil must be maximised under the constraint of positive utility of the consumer and from the overall cost of the effort in building trust from below for extra rent to be captured by the chain partners. In this way, each partner in the chain can sell at a higher price if his downstream partner trusts the quality of the product being sold. For instance, if the farmer chooses to deploy an effort to increase the trust that the mill has in his product, she will be able to sell at a higher price than if she would not. Hence, each actor can choose to enhance this trust through the proper effort in monitoring and reporting quality so that the consumer may trust that the quality of the product is due to the overall care along the chain in ensuring the highest quality.

It is obvious that all the constraints of the chain members in Equation 5 must also be met. The chain members have an overall incentive to lower the total cost of this effort. There is no misalignment of incentives here as each member must also maximise her own profit function in terms of her effort to build WTP, but she must also reduce or minimise her own cost of effort.

This guaranteed quality is a factor for increased market share, increased profit for all, and maximised utility for the consumer.

The result achieved above is due to the visibility and corresponding WTP that the deployment of BT and of the ongoing trust enhancing effort provides to the different actors.

3.5. Opportunistic behaviour and effect in the chain

Building from Remark 4, in one period *after* having invested in trust-building effort, one actor may cheat or multiple actors in the chain may enter into a coalition to defraud the remaining members on the quality of the product sold. For this to be possible, data on the blockchain database must be inconsistent with the reality of the product's quality. Now, as part of their constant effort to control and ensure that digital information in the Blockchain is truthful and verifiable, the cheated partners should be able to observe the inconsistency between digital records and the true quality of the product (for how this is to be done, we refer the reader to subsection 2.1).

In the following period, the buyer is now saddled with a tainted product which can no longer be sold as a quality product. If the buyer does nothing and sells on the tainted product, that loss ripples down to the other actors downstream from the cheater as the batch of tainted oil progresses in the chain since the WTP is now lower. When this tainted product comes to market, given the corresponding batch information available to the consumer, her WTP decreases. Further, as reported in subsection 2.2 of the literature review, consumers will share information about the true quality further eroding WTP and market participation.

It is easily understood that no downstream partner from the opportunistic one should invest in trust-building effort $T_a(\beta_a)$ for this batch (and possibly ulterior ones) since this effort cannot be recouped through the selling price and violates the participation constraints in Equation 5. The best strategy is not to sell the intermediate or final product through the regular channel but dump it on a buyer willing to pay the unknown quality price p_0^b and forfeit the corresponding profit but at least keep the reputation and hence, the WTP intact.

To prevent opportunistic behaviour, the supply chain partners should adopt the governance mechanism which matches the characteristics of the relationships at different levels (Ghosh and Fedorowicz, 2008; Kittilaksanawong, 2016). We argue that in the context of a supply chain which intends to set up an information system linking all partners to share information about quality, such governance mechanisms must be set up at the same time to deal with all the possible issues related to quality at the different levels. For example, if a batch lacks the proper quality, the actions necessary for its withdrawal from the chain must be scripted and the corresponding cost attributed.

In case of opportunistic behaviour occurring in the production phase, the governance mechanism that the partners set up in the initial phase for just such a case is triggered. Depending on the severity of the case and the balance between value creation and appropriation (Kittilaksanawong, 2016), punishment by exclusion from the chain of the cheating actor is possible (the game is a repeated one, Axelrod, 1981). In a multi-period setting, even if the same partner is still in the chain, trust will have been reduced and so will the WTP of the downstream partner buying from the opportunistic one for a number of periods. This entails that, once trust building has started, the best strategy for all actors is to maintain the effort and receive $p_a^*(\beta_a)$ in every period (it is reasonable to take into account the discounted future profits as described in Fudenberg and Maskin, 1986).

To show this, we model the corresponding behaviour as a Nash equilibrium multi-period game with five players (the four of the chain plus the consumer), where a cheating strategy is observable. In any triad, suppose that actor a can cheat, then in the period where he may cheat

$$\Pi_a(\beta) = \delta[p_a - p_s(\beta_s)] + (1-\delta)[p_a(\beta_a) - p_s(\beta_s) - T_a(\beta_a)] \quad (11)$$

where $\delta \in \{0, 1\}$, the decision to cheat or not. Clearly, in this period, the actor's profit is higher if $\delta = 1$ and he obtains a "short-run gain" in the sense of Shapiro (1983). However, in the next period, this cheating action is now observed by the other actors, including the consumer, because the lower quality has been recorded on the immutable ledger. This means that all the downstream actors of the chain will refuse to buy from the cheater from that next period on. Hence, over n periods, if he decides to cheat in period $1 < k < n$, we can write the cheater's profit function as

$$\begin{aligned} \Pi_a(\beta_a, \delta_k) &= (k-1)[p_a(\beta_a) - p_s(\beta_s) - T_a(\beta_a)] + \\ &\quad [p_a(\beta_a) - p_s(\beta_s)] + (n-k)p_0^b. \end{aligned} \quad (12)$$

Since $p_0^b < p_a(\beta_a) - T_a(\beta_a)$, it is clear that the decision to cheat is detrimental to the actor's multi-period profit and that his Pareto improving strategy is to stick with a trust-building strategy (Lahno, 2004). It is easy to demonstrate also that each of the supply chain partners' profit is reduced because of the consumer's decision to stop buying from this supply chain.

4. Numerical illustration

This illustration is divided in three parts: in the first we show how a buyer (in this first part, the retailer) will build her optimal price she is willing to pay. In the second, we illustrate this Bayesian belief held by each buyer can be modified by managerial effort. In the third part, using actual price data for the intermediate products in the extra virgin olive oil supply chain, we illustrate the model for each player in the chain and the overall supply chain extra rent.

4.1. Evaluation of the optimal price

Let us identify in this illustration the actor of our model as a bottler and the buyer as a retailer. Suppose that the bottler wants to sell to the retailer. As a bottler, he has access to several sources of olive oil. Suppose he behaves opportunistically, he can choose to mix the premium product with a given quantity of a product of lesser value, which will then enable her to increase his margin to the detriment of the quality of the product sold on to the retailer. Let us consider the following parameters for a litre of olive oil.

$$p_0^r = 10, \quad z = 50, \quad (13)$$

where z is the quality product value and p_0^r is the standard quality alternative available widely on the market.

In a supply chain without deployment of BT, under the assumption of asymmetric information, two belief situations may be distinguished. In the first, the retailer may take at face value the statement of the bottler about the premium quality of the product and yet not trust him entirely. In the second, she may consider that the information about the quality is at best dubious. We deal with both situations as follows.

In the first case, the retailer will build her belief of the true value of $\hat{z} = 50$ a distribution function with the corresponding mean and standard deviation. Let us consider here an IFR distribution such as a truncated normal distribution function and $Z \sim \mathcal{N}(\mu = 50, \sigma = 10)$. In this case, according to (7), we have $z^* = 40.93$. In the case of dubious quality, let us suppose that she estimates $\hat{z} = \mu = 30$, and has a lower belief of the true quality, so that she will assume that the estimate has a broader distribution $Z \sim \mathcal{N}(\mu = 30, \sigma = 15)$. This leads to $z^* = 29.41$. These values are the prices that the retailer is willing to pay the bottler (her WTP) based upon her belief of the true quality of the olive oil in the two situations of belief. In Figure 4 we plot, in two different hypotheses of standard deviations, the retailer's WTP when her estimate of the true quality of the olive oil varies from the one with minimum value p_0^r to the maximum quality. We see that the willingness increases with her estimate of the quality but never reaches the price she would pay if she were certain of the quality (dashed line). Note also that, by construction, the lower bound of this WTP is the price for the alternative product with no guarantee of quality (here set at $p_0^r = 10$). The upper bound for μ is when an optimal value can no longer be found solving (7), in our case $\mu = 57$ when $\sigma = 15$ and $\mu = 64$ when $\sigma = 5$ does not admit an optimal z^*.

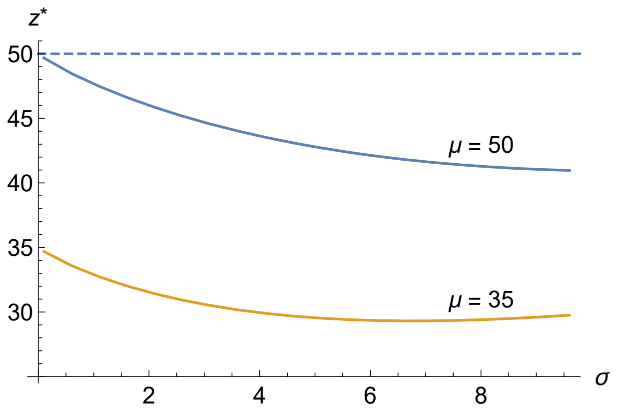


Figure 4: Representation of the price the retailer is willing to pay in terms of the standard deviation of the Bayesian belief: the optimal price z^* increases as the precision and confidence in the validity of the expected decreases (except when the variance is so large that the buyer is misled so leading to a higher optimal price as can be observed when $\sigma > 7$).
Alt-text: Representation of the price the retailer is willing to pay in terms of the standard deviation of the Bayesian belief: the optimal price z^* increases as the precision and confidence in the validity of the expected decreases (except when the variance is so large that the buyer is misled so leading to a higher optimal price as can be observed when $\sigma > 7$).

4.2. *Evaluation of the optimal effort by each chain player*

Let us now suppose that the partners in the chain have proceeded with the initial phase as illustrated in Figure 1. The production phase starts and trust-building effort can take place. We now present an illustration of Proposition 1: how the trust-building effort of the bottler improves the retailer's WTP. To do so, we must characterise the functions H_a and G_a which represent the connection between the effort and the first and second moment of the Bayesian belief distribution function f of the retailer.

We present two cases, in the first, the functions are linear, and in the second polynomial.

linear	polynomial
$G(\beta_{bo}) = 53\beta_{bo} - 3$	$G(\beta_{bo}) = 50\beta_{bo}^3 - 3\beta + 12,$
$H(\beta_{bo}) = -15\beta_{bo} + 16$	$H(\beta_{bo}) = -10\beta_{bo}^2 + 11.$

Using a truncated Normal distribution for the Bayesian belief with $\mu(\beta) = G(\beta)$ and $\sigma(\beta) = H(\beta)$, we see in Figure 5a how optimal z^* is obtained from the trust-building effort. The evolution of the bottler's effort thus illustrates Corollary 3.

In the second case, the relationships are polynomial and represented in Figure 5b:

We note that (i) the structure of the behaviour is decreasing and then increasing; (ii) it reaches the upper bound when $\beta_{bo} \to 1$, unlike the linear case.

Next, we explore the impact of the cost of effort $T_{bo}(\beta_{bo})$ on the bottler's profit function. We use a suitably strictly increasing concave function for the cost of building trust such as

$$T_{bo}(\beta_{bo}) = 25\beta_{bo}^2 + 5\beta_{bo}. \tag{14}$$

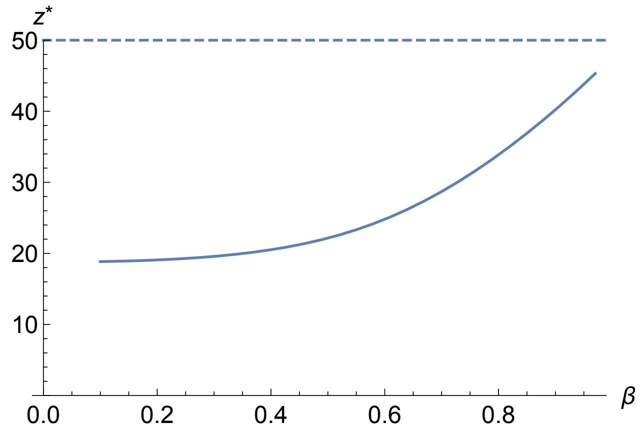
Assume that $p_m(\beta_m) = 12$ so that the profit function in (1) becomes

$$\Pi_{bo}(\beta_{bo}) = p_{bo}(\beta_{bo}) - 12 - 12\beta_{bo}^2 - 5\beta_{bo}, \tag{15}$$

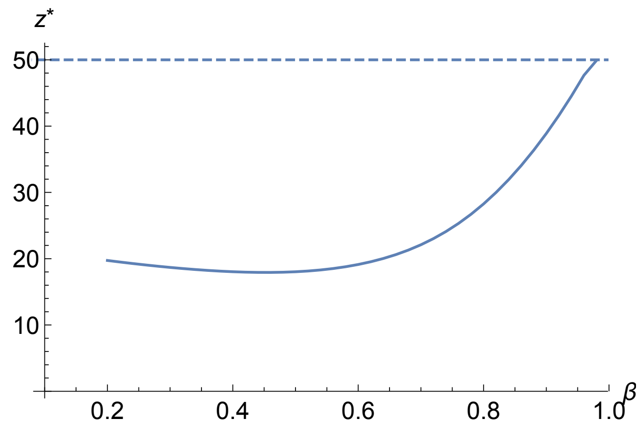
with $p_{bo}(\beta_{bo})$ solving the retailer's optimal WTP from Theorem 1. The corresponding profit function is presented in Figure 6. In this illustration, the bottler should either provide no effort at all or maximise it. Witness how profit increases even with a strongly convex cost $T_{bo}(\beta_{bo})$. Note that even in this specific instance where it would appear that the bottler is better off by shirking, such behaviour would backfire as the bottler would be punished and obtain a loss in the following period.

4.3. *Stylized numerical study of an extra virgin olive oil supply chain*

To support the above calculations, we have collected information about actual costs for producing the different intermediate products or the cost of retailing a bottle of extra virgin olive oil (see Table 1). The price of a kilogramme of olives cost 2.75 €/kg (average weighted price in 2012 in Spain). The average cost of crushing olives is 0.03 €/kg (Spain). The average volume of a kg of olive oil is 1.12 L.



(a) when the relationships between the effort and the Bayesian belief distribution parameters are linear.
Alt-text: Curves slopes upwards as effort β increases.



(b) when the relationships between the effort and the Bayesian belief distribution parameters are polynomial.
Alt-text: Curve slopes upwards and reaches z^* as β tends to 1.

Figure 5: Representation of the WTP price z^* in terms of the effort β.

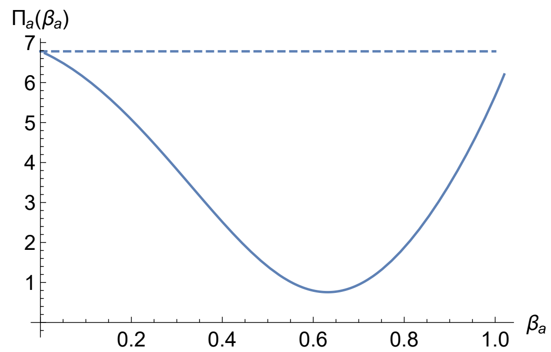


Figure 6: Representation of the actor's profit function in terms of the trust-building effort β_a.
Alt-text: Actor's profit slopes downwards through a minimum before curving upwards as β_a increases from 0 to 1.

The bulk olive oil can be bought for 3.88 €/litre (average cost of imported bulk olive oil in France in 2019 Autentika Global, 2020). As for the crushing, the bottling cost including bottle, label and carton cases is approximately 0.35 €/litre. The wholesale price of a bottle to the retailer is approximately 4.5€/l which then retails for 7.5€/l. Those are presented in Table 1. We evaluate the overall profit of the chain using results from subsection 3.4. We consider that all chain members do act in a way to maximise WTP (that is, β is maximal).

To represent the cost of managerial effort in a plausible manner, we propose to evaluate it as a cost to be divided into litres of final product (that is, litres of olive oil) for each echelon. Traditionally, such cost of effort function should be convex to represent the fact that improving quality has an increasing marginal cost. We adapt the cost of building trust from Equation 14 so that $T_i(\beta_i) = (p_0^{i2}/2)\beta_i^2$, $i \in \{f, m, bo, r\}$. The Bayesian belief distribution is evaluated as a truncated normal distribution with the mean and variance being functions of effort as in (8) and using the corresponding prices for the alternative price

Table 1: Approximate selling price, transformation costs of Extra Virgin Olive Oil, optimal price and profit (€/litre) in the European market in 2020, (Autentika Global, 2020; Barjol et al., 2015; Devarenne, 2021)

Chain partner	Selling price range €/litre p_0^i	Selling price range €/litre z^*	Effort cost	Transfor- -mation cost	Profit per level
Farm	2.45	4.66	0.61	2.4	1.65
Mill	3.88	7.39	0.97	0.03	1.72
Bottler	4.6	8.76	1.15	0.05	0.17
Retailer	7.5	14.29	1.87	1.5	2.34

for non-descript product in each echelon using the p_0^i, $i \in \{f, m, bo, r\}$, from Table 1 so that $G(\beta_i) = p_0^i\beta_i^3 - (p_0^i/5)\beta_i + p_0^i$ and $T(\beta_i) = -(p_0^i/5)\beta_i^2 + p_0^i$. We obtain the optimal selling prices in the second column of Table 1. In the same way, when we consider that the effort at each level is $\beta_i = 1$, $i \in \{f, m, bo, r\}$ and that the effort cost function at each level is $T_i(\beta) = (p_0^i/2)^2\beta^2$, the profit by each partner before transformation cost can be evaluated from Equation 9. We present in the last column of Table 1 the profit made by each level *net of transformation cost*.

This numerical example comforts the results obtained in Dionysis et al. (2022) where participants in the study were willing to pay between 5 and 30% more for an organic coffee with blockchain guaranteed traceability as opposed to a traditionally certified organic coffee.

5. Discussion and implications

This paper complements prior literature on the applications of BT infrastructure can realize interorganizational processes, increase trust among partners, and achieve traceability in food supply chains (Kumar et al., 2019). Our contribution spans two levels. On the first, our contribution is in showing how such technology has to be complemented by managerial effort and can be paid for because consumers are willing to pay more for products from such supply chains. Dionysis et al. (2022) showed that properly informed consumers are willing to pay more. As presented in the literature review, many authors have shown that traceability can be ensured using blockchain but not that opportunistic behavior can be detected.

It follows from the discussion presented in subsection 2.1 that even though technology connecting sensors to IoT networks, the Physical Internet, and BT exists, it is only a necessary condition. As said in Wang et al. (2022), "managers should consider blockchains as an important strategic tool to organize collaborations, (...) [they] should consider the joint use of different approaches to mitigate collaborative hazards and enhance efficiency." Even though sensors connected to IoT networks and validated by smart contracts may result in logged traceability records on the blockchain, that is not enough to certify that they reflect reality or are to be trusted. In particular, some unscrupulous actors may engage in cutting corners or even sell inferior quality products as high quality ones. So far, besides our own, we have not found any research showing how this should be done.

Following upon the research opportunities outlined in Wang et al. (2022), other mechanisms have to be deployed and carefully designed *ex ante*. In particular, effort has to be deployed throughout the chain to complement BT, sensors and other redundant devices to constantly check and report on the validity of the information being recorded both in each and across levels of the chain. Some of the necessary effort that will have to be deployed includes the training of technical operators to monitor the calibration and operation of field sensors (Wang et al., 2022). The outlays in information systems and sensors require more than ongoing maintenance. Managers will have to be trained in ensuring that the reports and monitoring software are indeed operational and correctly understood and manipulated by the relevant operational staff (as has been implemented in Wang et al., 2020). Smart contracts will also warrant careful consideration (Kumar et al., 2019). When stepping back, we venture to say that such routines, processes and skill sets are akin to those necessary in total quality management and would provide a specific competitive advantage as in the dynamic capabilities approach of the resource-based view of the firm.

Given the heterogeneity in managerial sophistication of partners in any food supply chain, whether in the case of BT (Mathivathanan et al., 2021), or, even earlier, in the case of information technology in SMEs (Harland et al., 2007), progress has stalled. This is why we believe that our approach provides a possible way forward.

On the second level, our model establishes in a normative and prescriptive manner how managerial effort at each level (a) ensures that the information about quality of a product is trustworthy, (b) presents the evidence to the intermediate buyers of the semi-finished product and to the consumer, (c) leads to a higher WTP for all the members of the chain, and (d) generates a higher rent for all of them. We show how each actor is responsible for the effort required to provide evidence of the quality of the product at her level. Her profit also increases insofar as her effort includes verifying that her partners upstream and downstream do their part so that the final product benefits from the consumer's highest WTP as shown in the numerical illustration with true prices of the intermediate products.

We model how effort and WTP are positively related. This relationship is based on the modification of the *a priori* Bayesian belief of each buyer in the chain (including the consumer) about the quality of the intermediate (final) product sold. Two outcomes are presented, one when information is true and WTP is high, the other when opportunistic behaviour by one or several actors entails loss of WTP and rent.

In other words, the overall chain-wide rent is linked to the consumer's WTP. Such a result and such a model have never yet been described. In the present model, the information about the quality of a product is linked to the consumer's WTP and to the corresponding managerial effort by the actors. In general, in literature, two unproven statements are assumed: (i) WTP increases only with user experience, and (ii) information about the quality of a product is always trustworthy. As ample evidence both in scientific literature and the general press can attest, consumers are sensitive to the information about the quality of the food products they buy, and do not take for granted that such information is trustworthy.

Food scandals will always happen, whatever the sophistication of the technology used. Managers must still arrive at *ex ante* governance mechanisms, and *ex post* continuously oversee and control the whole supply chain so that consumers are informed about and are willing to pay for the quality they are expecting. The present research opens up new avenues in operations-management modelling to help managers in this endeavour.

Appendix A. Proof of existence of a unique z^* in Theorem 1

This proof has first been established in Brusset and Cattan-Jallet (2009) and also used in Brusset (2014) and Brusset and Agrell (2017). The first differential of the *expected* buyer's profit function in terms of the threshold level z is written

$$\frac{\partial \Pi_b(z)}{\partial z} = f(z)(p_0^b - z) - F(z) + 1. \tag{A.1}$$

For threshold z to be a maximizing one in terms of profit to the buyer, we must have as $\frac{\partial \Pi_b(z)}{\partial z} = 0$, $z \in \left[\underline{Z}, \overline{Z}\right]$, $\frac{\partial^2 \Pi_b(z)}{\partial z^2} < 0$, $z \in \left[\underline{Z}, \overline{Z}\right]$. The first order condition (FOC) is

$$p_0^b - z = -\frac{\overline{F}(z)}{f(z)}, \tag{A.2}$$

and as second differential, under the restriction that $f(z) \neq 0$,

$$\frac{\partial^2 \Pi_b(z)}{\partial Z^2} = (p_0^b - Z) f'(Z) - 2f(Z) < 0. \quad (A.3)$$

If both conditions have to be realized, then, replacing $\pi_0 - Z$ by its value in (A.2) in (A.3), we must verify that

$$f'(Z)\frac{F(Z)-1}{f(Z)} - 2f(Z) < 0. \quad (A.4)$$

Since $f(Z)$ is positive for all Z in the range $[\underline{Z}, \overline{Z}]$, we can restate this inequality as

$$f'(Z)(F(Z)-1) - 2f^2(Z) < 0. \quad (A.5)$$

However, we have assumed that the distribution of Z is IFR which means that the failure rate $r(Z) = f(Z)/\overline{F}(Z)$ is weakly increasing for those values of Z for which $F(Z) < 1$. Then the first differential of the function r, which is written

$$\frac{\partial r(Z)}{\partial Z} = \frac{f'(Z)(1-F(Z)) + f(Z)^2}{(1-F(Z))^2} \quad (A.6)$$

must be positive or null, so

$$\frac{\partial r(Z)}{\partial Z} \geq 0 \Rightarrow f'(Z)(F(Z)-1) - f(Z)^2 \leq 0. \quad (A.7)$$

This last condition is stronger than the one spelt in (A.5) because $(Z)^2 > 0$. □

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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