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STRICT LIABILITY, SCARCE GENERIC INPUT AND DUOPOLY COMPETITION

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Strict Liability, Scarce Generic Input and Duopoly Competition

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Summary: This paper analyzes the impact of strict liability on imperfect competition and shows first that it is not an obstacle to achieving a socially optimal level of care. Second, this result is compromised when firms face a scarce generic asset. Under this asset limitation, this paper shows that competition (here a Cournot-Nash duopoly) leads to a lower level of prevention even if more product at lower price is supplied at the equilibrium. Introducing standards linked to operating permits improves the economy's safety level but may lead firms to exit.

Key Words: Tort Law, Strict Liability, Negligence Rule, Imperfect Competition, Oligopoly, Cournot Competition

JEL Classification: D43; L13; L52; K13

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"The greater the risk of an accident... The stronger is the case for strict liability".
Indiana Harbor Belt R.R. Co. v. Am. Cyanamid Co., 916 F.2d 1174, 1177 (7th Cir. 1990). 227.

1. Introduction

Object of the paper

At the dawning of the 20th century, the industrialized countries suffered an increasing number of workplace accidents due to failures related to safety conditions in fledgling, unhealthy and hazardous factories. At the time, the burden of fault and the accompanying high costs of gathering evidence fell on the victims of these accidents who had no certainty that their claims would be successful. Consequently, the courts introduced generalized strict liability which allows faster reparations.

Under strict liability, an individual who harms another individual even in the absence of fault or negligence, must make good the damage caused. This contrasts with the negligence rule whereby the court exonerates wrongdoers able to show that they acted with due diligence. Thus, strict liability obliges the possible perpetrators of the damage to ensure the highest accident prevention levels. In most countries, strict liability applies to any extraordinary activity which is likely to hazardous. A person who performs an abnormal dangerous activity and causes damage can fall within the legal scope of strict liability. Under converging case law and legal texts, strict liability applies to agents who have engaged in the exploitation, use or handling of abnormally hazardous activities (Cantú (2001), Verges (2014)). Strict liability is increasing due to the effects of new technologies and new scientific knowledge about damage they may cause. For example, environmental prejudice can be subject to strict liability according to the European Parliament and European Council Directive 2004/35/EC on environmental liability dated 21 April 2004.

The economic literature discusses tort law in two distinct areas (Shavell, 1987, Ch. 3). The first and best-documented area deals with 'product liability'. The second applies to all types of 'non-contractual' litigation - mainly 'firm and strangers' lawsuits such as if a company damages the health and property of its neighbors, the environment, etc. (Mihailidou, Antoniadis and Assael (2012)).

This paper focuses on the second area and analyzes legal disputes between strangers and firms under monopolistic and duopolistic competition when, under strict liability, the firms see one of their fundamental assets restricted. This restriction can take different forms: budgets and

financial rationing, limited land (industrial real estate), human resources (tight labor market), national and international regulations, or the time needed to implement a new process to remain competitive. As we know, competition insures an optimal access to goods and services in terms of price and quantity. However, this is not always the case for the firms' safety level. Obviously, when firms face no other constraints than technological ones in producing the desired quantities, as in standard schemes, then firms can choose sequentially the optimal level of security, which corresponds to the socially optimal level under strict liability, and the equilibrium quantities that maximize their profit given their technological constraints. However, as soon as firms encounter problems of access to a fundamental resource for safety, competition leads to a limitation of the care level. Limitations on assets and inputs are not conducive to the optimal level of social care achievable by a comparable, unconstrained firm within a standard unilateral accident model. Under strict liability, competition reinforces equilibrium sub-optimality by revealing the difference between a monopoly and a duopoly. In duopolistic competition, we would expect equilibrium quantities to be higher and prices lower compared to a monopoly; nevertheless, competition contributes to significantly lowering the equilibrium care level. The question then arises as to the impact of a regulation that would set minimum prevention levels on market equilibrium and industrial organization.

To illustrate the effects of competition and asset scarcity on safety we present two examples. Both highlight that scarce assets associated to competition influence the firms' choices about care and safety. The first example concerns the Boeing case. Indeed, in 2018 and 2019, this company experienced two devastating plane crashes involving its 737-MAX 8s. These accidents were not casual but were the result of terrific industrial failure. The second example is the LUBRIZOL chemical fire accident in Rouen (France) which broke out on September 26, 2019. .

Stylized fact 1: The BOEING 737-MAX 8 tragedies

In October 2018 and March 2019, two Boeing 737-MAX 8 aircrafts crashed resulting in the deaths of 346 people. As a precaution, most countries banned these airplane types and this embargo led to Boeing registering a loss of 8 billion dollars in 2019. Between 2010 and 2017 it was under competitive pressure from Airbus which in 2010, had conceived a more fuel-efficient aircraft, the A320Neo. Boeing's first response was to design a revolutionary concept, the Y1 model which would have taken ten years before its full launch. In addition, a long-standing Boeing customer, American Airlines, ordered 100 aircraft from Airbus. As a result: *"To win over American, Boeing ditched the idea of developing a new passenger plane,*

which would take a decade. Instead, it decided to update its workhorse 737, promising the plane would be done in six years”¹. In a bid to stay in the game, Boeing rushed its decisions and chose to restructure both the architecture and the design of three types of its MAX 737 (8, 9 and 10); however, the safety levels it opted for were too low. For example, Boeing's management outsourced the guidance and safety systems to underpaid software developers² who likely made code errors which caused the failures. The haste of the project configuration and a tight budget explain these choices: « *Engineers were pushed to submit technical drawings and designs at roughly double the normal pace, former employees said. Facing tight deadlines and strict budgets, managers quickly pulled workers from other departments when someone left the Max project*”³. All these aspects made the "time factor" a constraint which led to poor safety.

Stylized fact 2: The Rouen Lubrizol catastrophe

On September 26, 2019, in Rouen, France, the Lubrizol plant owned by Berkshire Hathaway suffered a major fire. The plant synthesizes and stores chemical products (phosphorus and organosulfur compounds) intended for use as lubricant additives and employs 300 people. It falls under the European Seveso 3 July 4, 2012 directive (high threshold authorization). The quantity of burnt products amounted to 9,505 tons, including 5,253 tons of chemicals in the Lubrizol site and 4,252 tons of products stored at the Normandy Logistics (NLC) site (including 1,691 tons of Lubrizol products). The toxic smoke plume formed a heavy, black cloud which remained relatively concentrated at low altitude and extended over some 20 km by 6 km. The cause of the accident remains unclear. In early 2019, the Seine-Maritime prefecture authorized Lubrizol to increase its storage volume for unspecified "highly flammable" products by 1,598 tons which would have required a more specific permit and higher administrative control. Faced with a legal limit on its storage capability, Lubrizol stored its products on the NLC site illegally and increased the pollution level to 4,252 tons of unspecified hazardous hydrocarbons. It would seem that the accident was the result of a chain of events and severity of the accident was due to too much hazardous product stored in too small a space

Both examples show how scarcity of a given input induces firms to make arbitrage between production and safety. In the Boeing example, the losses go beyond the amount that could decide a Court. because they also include the commercial and reputation losses. However, this example emphasizes the relationship the flaw in safety due to the competition pressure.

¹ New York Times, 23/03/2019

² Indian software developer HCL Technologies Ltd, Bloomberg (2019).

³ New York Times (23/03/2019)

The paper is organized as follows. Section 2 reviews and compares the ‘product liability’ and firms and strangers’ literatures. Section 3 investigates a perfectly competitive system under a liability regime as a benchmark and introduces duopolistic competition without asset constraint. Section 4 compares a monopoly and a duopoly both with a scarce generic asset and shows that competition alters the market equilibrium conditions and reduces the equilibrium care level. Section 5 analyses the setting of government norms and permits to overcome the consequences of competition allied to a scarce generic asset. Section 6 concludes.

2. A literature review: “product liability” and “firms and strangers”

While product liability implies a contract between a company and its customers; ‘firms and strangers’ relationships do not. Economists apply a cost-benefit approach to deal with accidents⁴ which consists of minimizing the accidents costs (i.e. the prevention costs and the expected cost of the damage). Since both relationships require a trade-off between compensation and maintenance of economic efficiency, they can lead to similar results. In a context of perfect information, agents are risk neutral and both approaches lead to similar results: strict liability and negligence are equivalent, and both approaches achieve the socially optimal level of care.

2.1. « Product liability »: The fundamental role of consumers and information

Obviously, the “product liability” question lies out of the scope of the ‘firms and strangers’ concern. However, the literature on the latter point is scarce compared to the former one. This difference is mainly due to the fact that product defaults can have a greater impact on a larger share of the population and the damage could amount to billions of dollars (Geistfeld, 2009). Literature developed in several directions and more and more strict liability rather than negligence rule is at stake. We refer to this literature in order to better specify how competition is apprehended in this corpus by comparison with the sparse contributions concerning the relations between ‘firms and foreigners’. Concerning the products liability point, information and industrial organization play an essential role whereas for ‘firms and strangers’, the notion of information is reduced to its simplest expression.

⁴ Inspired by Coase (1960).

Strictly speaking, product liability mainly concerns injury caused by defective products. US⁵ and European Union legislation impose quite similar strict liability regimes (EC Directive 85/374) which have been copied by many occidental countries.

Eplee and Raviv (1978) consider that in a context of perfect insurance and perfect information for consumers, the market structure and liability rules have no effect on product safety. Consequently, strict liability and negligence are equivalent and ensure the highest safety level. Conversely, in a context of imperfect competition and imperfect information, questioning the effectiveness of liability rules becomes relevant. Priest (1985) suggested that producers use their market power to lower the level of care; they either increase their price or decrease the level of care. Consequently, the market structure has an influence on product safety. Under imperfect competition, safety investments depend on production. Spulber (1989, pp. 407-10) suggests that a monopoly's security investment will depend on the cross effects of the safety cost and its production costs. Similarly, Priest (1985) shows that imperfect competitive markets may provide insufficiently safe products.

The consumer's information is another product liability concern. McKean (1970) and Oi (1973) assume that it is perfect, but Goldberg (1974) suggests this is generally not the case. Imperfectly informed consumers must be able to assess their losses and many authors emphasize consumer access to information and especially its impact on risk assessment. Goldberg's paper spawned a vast literature on consumer information and attitude to risk. However, this literature is beyond the scope of the present paper. Therefore, to sum up, what constitutes a defective product depends on the consumer's attitude to both information and risk.

Spence (1977) and Polinsky and Rogerson (1983) were among the first to study the interaction between market power and standard liability rules. Polinsky and Rogerson (1983) analyze consumers that under-estimate their potential losses under imperfect competition. Strict liability leads to the socially first-best care level but with a restriction on output. Under negligence, a firm may escape liability if it can prove careful management of the process. Consequently, the consumer bears the default risk. However, since the consumer may underestimate this risk, it will buy more of the product than under strict liability. The study by Baniak and Grajzl (2017) shows that among heterogeneous consumers purchasing durable goods, consumers cognitive errors and biases lead to inaccurate predictions about the goods' future benefits and use. The social welfare is linked to both the agents' beliefs and the current liability

⁵The U.S. Restatement Third of Torts (1998) considers three product defect categories: i) manufacturing defects, ii) design defects, iii) defects due to inadequate instructions or warnings.

regime as in Polinsky and Rogerson (1983). Hence, welfare is highest if the agents overestimate future profits/benefits under strict liability.

Several contributions consider the link between firms and the attitude to risk of consumers linked to their level of information e.g., information on the risks associated to the product. Firms sometimes may prefer voluntary disclosure in order to retain control over their information (Polinsky and Shavell, 2012; Daughety and Reinganum, 2008). Daughety and Reinganum (2006) study differentiated goods produced in an oligopolistic competition ruled by liability regimes. The firm costs include safety investments, production activities, and liability-related costs. Compensation is incomplete due to both inefficiencies in the bargaining process and (possibly) statutorily established limits on awards. The authors examine which regulations lead to better safety by comparing two types of arrangements: setting a safety standard or controlling safety efforts and output. Boyds (1994) analyzes a monopoly facing huge potential repair costs which could result in its insolvency. Here, consumer behavior is fundamental to assess the relative performance of the strict liability and negligence rule. It rests on the consumer's ability to fully discount the risks related to the product. If the consumer has this ability the strict liability dominates negligence, and vice versa. Product liability depends heavily on the consumer's attitude to risk and information. However, in the "firms and strangers" case the consumer aspect is missing, and the firm is solely responsible for prevention and information.

2.2. 'Firms and strangers' literature

Polinsky (1980) and Shavell (1987) compare the efficiency of strict liability and negligence under free competition. Polinsky contrasts short-term competition where the number of firms is known to long-run competition where the number of firms varies. All the firms involved are small, identical, and unlimited. In the short term, strict liability, and negligence lead to the same level of care and equilibrium price; in the long run, only strict liability is efficient. Indeed, if the negligence standard corresponds to the efficient level of care, the equilibrium price is too low because firms have not internalized the accident costs: too many firms are likely to enter the market.

Basically, the unilateral standard accident model describes how a risk-neutral representative firm manages its profit function facing costly hazard. When the gain is given, the program consists of minimizing the expected accident costs which comprise the level of care x ($x \geq 0$) and the random cost of damage $l(x)$ where $C(x)$ represents the expected accident cost: $C(x) = x + l(x)$.

In this framework, by assumption, the economy works under conditions of free competition: “Firms will be presumed to maximize profits and to do business in a perfectly competitive environment. This means that the price of a product will equal the unit costs associated with production, including expected liability costs” (Shavell, 2003, p.1). See also Shavell, 1987, p. 47, and Polinsky, 1980). The firm determines both its optimal production level q and its optimal care level x by minimizing the expected cost of a primary accident (i.e. the value of prevention x plus the expected repairs or damage value $l(x)$) (Calabresi, 1970). $G(q)$ is the utility that the consumer derives from the activity or product q if c is the unitary production cost, then without the liability rule, the social welfare is:

$$G(q) - q(c + x)$$

Consequently, the consumer chooses \bar{q} which maximizes $G(q) - qc$ where $G'(\bar{q}) = c$ and there are no care measures in place. The marginal utility equals the marginal production cost. Under strict liability, the social welfare $ESW(q, x)$ becomes:

$$G(q) - q(c + x + l(x)) \equiv ESW(q, x)$$

The model to solve consists of identifying the respective first-best production and care levels $\{q^* \geq 0, x^* \geq 0\}$ which solves the following program:

$$\{q^*, x^*\} = \underset{q, x > 0}{\operatorname{argmax}} ESW(q, x)$$

The optimal care level must satisfy the following first order conditions in x :

$$q(1 + l'(x^*)) = 0, \text{ or, equivalently, } -1 = l'(x^*).$$

Regarding the optimal production level q^* , it can be written as:

$$G'(q^*) = c + x^* + l(x^*)$$

It follows that the marginal utility from an increase of 1 unit of product equals the marginal direct cost of product c plus the marginal cost of an accident. Then, under free competition, the equilibrium price Π is equal to the total marginal cost:

$$\Pi = c + x^* + l(x^*)$$

Strict liability involves determining a higher equilibrium price than in the no-liability configuration: $P > c$.

Under negligence, the injurer escapes all liability if it knows x^* and complies with it. Consequently, the equilibrium price Π_{NR} under negligence does not support the expected accident cost:

$$\Pi_{NR} = c + x^*$$

And obviously, the equilibrium prices are: $\Pi > \Pi_{NR} > c$. Strict liability involves the full weight of the internalization process while in the case of negligence, the firm that complies with x^* may escape liability at a lower price.

Charreire and Langlais (2017) use oligopoly models to analyze the joint actions of competing firms which cause environmental damage and/or harm to several (third party) victims. They assume different strict liability regimes all based on different compensation and repair schemes. The question they address is how to compensate victims when individual liability is intertwined with other liabilities. Is a “per capita” or an “in solidum” payoff more likely to induce the firm to adopt better prevention? They also study how different industrial organization types (competition, oligopoly, monopoly) interact with different strict liability regimes. Our purpose is different; we are interested in assessing the impact of strict liability on given market organization types.

3. The model’s basic feature and the standard duopoly model

The model belongs to the Cournot-Nash class. Here, two firms take their production and prevention decisions. Each knows its opponent’s cost structure and payoff functions. So, the game is one of complete but imperfect information, and competition is static (Tirole, 1988). The duopolistic industry is ruled by strict liability. Both firms (indexed as i , $i = 1,2$) produce a homogeneous good (quantity q_i). The production process may induce hazard to its neighborhood. A potential major accident may cause damage proportional to the firms’ production q_i (See e.g. Dari-Mattiacci and De Geest, 2005). Facing random events, we assume that firms are neutral to risk. Then, if the damage per unit of output is D , the firm i ’s total damage is:

$$d_i = Dq_i. \quad (1)$$

By assumption, the firms’ wealth, W_i , $i = 1,2$, covers the maximum possible damage-cost: $d_{i \text{ Max}}$ (i.e. $d_{i \text{ Max}} < W_i$). It is worth noting that the firms’ wealth differs from the assets involved in production. This assumption means that firms are never judgment-proof (see Shavell, 1986).

The accident probability can be written as $p(x_i)$, (with $(1 - p(x_i))$, then the probability of no-accident), $p(x_i)$ depends on the level of care $x_i \geq 0$ which firm i puts in place with $p(0) = 1$. The expected cost of an accident $EC(x_i)$ where (given (1)) is:

$$EC(x_i) = p(x_i)Dq_i \quad (2)$$

For simplicity, we suppose that the market price can be expressed as the following affine inverse demand function:

$$\pi(q_1, q_2) = K - (q_1 + q_2) \quad (3)$$

(where $K > 0$ is a sufficiently high coefficient to prevent prices from becoming negative). Furthermore, the firms differ with respect their unitary production costs: $c_i \neq c_j, i, j = 1, 2, i \neq j$. Since firms compete on a Cournot-Nash basis, we can define a Nash equilibrium given the firms' profit functions $B_i(q_i, x_i)$ ($i, j = 1, 2, i \neq j$) where:

$$B_i(q_i, x_i) = q_i(K - q_i - q_j) - q_i c_i - q_i x_i - q_i p(x_i) D \quad (4)$$

(where $i, j = 1, 2, i \neq j$).

Then, the firms choose the production and prevention levels (x_i^*, q_i^*) to maximize $B_i(q_i, x_i)$.

Definition 1: A set of actions $\{(x_1^*, q_1^*), (x_2^*, q_2^*)\}$ constitutes a Nash equilibrium if:

$$B_1((x_1^*, q_1^*), (x_2^*, q_2^*)) \geq B_1((q_1, x_1), (x_2^*, q_2^*)) \quad (5)$$

$$B_2((x_2^*, q_2^*), (x_1^*, q_1^*)) \geq B_2((q_2, x_2), (x_1^*, q_1^*)) \quad (5')$$

Then (x_i^*, q_i^*) is a Nash equilibrium if each firm cannot improve its position by playing its Nash equilibrium action given the other firms play their Nash equilibrium strategy.

Definition 1 is generic and applies to both the standard and asset limited duopolies. Considering the standard duopoly, the market equilibrium is analogous to the Polinsky's (1980) competitive industry equilibrium. In the Polinsky context, as resources are unlimited, solving the program comes to consider two resolution stages. The first one consists of fixing the socially necessary level of prevention, and the second consists of the equilibrium quantities as in all competitive markets. In this competitive conjecture, the marginal utility from an increase of 1 unit of product equals the marginal direct cost of product c plus the marginal cost of an accident. Within this framework, the economy works under conditions of free competition: *"Firms will be presumed to maximize profits and to do business in a perfectly competitive environment. This means that the price of a product will equal the unit costs associated with the production, including expected liability costs"* (Shavell, 2003, p. 1; see also Shavell, 1987, p. 47 and Polinsky, 1980).

In Appendix A, of this contribution, we develop the case of an unlimited asset duopoly model. As in the case of the perfectly competitive equilibrium, the resources required by firm i is known ex-post.

$$R_i^* = q_i^*(c_i + x_i^0)$$

R_i^* is known afterwards; it is given by the sum of the cost of prevention plus the cost of the input. Then, to produce q_i^* , the firm needs $q_i^* c_i$, and to produce this level at the lowest possible risk, the prevention costs amount to $x_i^* q_i^*$. Consequently, when duopolistic firms dispose of assets without restriction in terms of production and prevention, the results are similar to those derived from the standard unilateral model under strict liability.

4. Strict liability and firms facing a generic scarce asset

We next study the case of a duopoly with a scarce generic asset which is used for both production and care.

4.1. The meaning of scarce generic asset

Modern industrial activities often face partial availability of crucial inputs including skilled labor (Inderst and Wambach, 2002), access to upstream resources (raw materials), specialized machinery, (Esó, Nocke and White, 2010, Pu-yan Nie and You-hua Chen, 2012) or energy (Veit et al., 2011). The set of limited capacities can include land and warehouse space (as referred to in the Lubrizol case) or transportation such as airport areas (Evans and Schaefer, 2011). Firms also may face financial limitations as discussed in the credit rationing literature. Following Jaffee and Modigliani (1969, pp. 850–51), “*credit rationing [is] a situation in which the demand for commercial loans exceeds the supply of these loans at the commercial loan rate quoted by the banks*”. We let aside the information asymmetry question as Stiglitz, and Weiss (1981) initiated it by linking information asymmetry adverse selection and moral hazard. This goes beyond our scope.

Subsidiaries of large corporations may face limited budget and several studies discuss their consequence. Campello, Graham and Harvey (2010) analyze a large sample of US, Asian, and European firms and show that firms were credit rationed following the 2008 crisis with detrimental effects on investment. More recently, Aghion et al. (2019) developed an econometric study on the impact of this finance constraint on innovative and incumbent French manufacturing firms. They provide evidence of an inverted-U relationship between access to credit and productivity growth where better access to credit makes it easier for the entrepreneur to innovate. However, better access to credit also allows less efficient incumbent firms to remain in the market for longer, thereby discouraging the entry of new and potentially more efficient innovators. All these elements show that in an imperfect world, firms including the subsidiaries of large international corporates suffer from this limited access to financing (see e.g. Shi, Townsend, and Wu, 2019, and Almeida and Kim, 2015).

To sum up, binding capacities play an effective role in our economies and few competing firms have unlimited means.

4.2. The duopoly equilibrium with a limited generic asset

Here, two firms produce a homogeneous good under a strict liability regime. For simplicity, we consider that neither firm establishes a guarantee fund nor employs insurance as might be expected in this context. We assume also that the firms engage in a Cournot-Nash type game i.e., they choose what quantities they will offer on the market. This choice requires them to determine their equilibrium supply and the required quantities of inputs. Since inputs are restricted, the firms must arbitrate between inputs for production and inputs for care. Choosing the equilibrium production level therefore defines the optimal prevention level. Thus, each firm maximizes its profit within the limits of its assets, (i.e. $q_i(c_i + x_i) \leq Y_i, i = 1,2$) and based also on its competitor's supposed behavior.

Decisions are made with complete but imperfect information i.e. each firm knows the other's strategies and payoffs but does not know its effective choice. Compared to a standard oligopolistic competition model, we need to consider the accident cost dimension. We assume that the firms use the same prevention technologies so that a given care level corresponds to the same cost. It follows that the firms' choices are complex because each firm's care level depends indirectly on the other firm's production and care choices.

Under imperfect information, the firm must estimate not only the equilibrium quantities provided by its opponent but also its chosen prevention level. In the model outlined in appendix B, we reduce this uncertainty to its simplest expression. We assume that the level of damage per unit of product is identical for both firms and that the distribution of accident probabilities is common knowledge. It follows that each firm knows the damage level and thus the hazard that the other firm presents. We can then define the game's tree :

Stage-1: The regulator enforces strict liability.

Stage-2: Each firm maximizes its profits by choosing its optimal care and production levels given the other firm's supply.

Stage-3: Nature intervenes:

Stage-3(a): No accident occurs, the firms receive their payoffs and the game stops; or

Stage-3(b): An accident occurs and causes damage.

Stage-4: The court checks the existence of a causal link between the firm's activity and the harm, and if necessary, determines the value of the reparations to be borne by the injurer.

Note that the firms must choose simultaneously safety means and production considering that their own generic asset is limited. This is different from the unlimited resource

case of the standard representation where solving the program comes to choose first the accurate care level and then, only after, the scale level. We can now present, the duopoly's program when the latter sees its generic asset limited. Then, for $i, j = 1, 2$ $i \neq j$, each firm maximizes the following payoff function:

$$\max_{q_i, x_i} B_i(q_i, x_i) = q_i (K - q_i - \bar{q}_j) - q_i c_i - q_i x_i - q_i p(x_i) D \quad (6)$$

Under the constraints:

$$q_i(c_i + x_i) \leq Y_i \quad (6a)$$

$$0 \leq p(x_i) - 1 \leq 0 \quad (6b)$$

$$q_i, x_i \geq 0 \quad (6c)$$

It follows the following equilibria, that are resumed in the following proposition 1:

Proposition 1: *Under the assumption that the coefficients K, D, c_i combine to make the payoff function quasi-concave and since it is twice derivable then the program (6) to (6'.c) admits at least one Nash equilibrium (q_i^0, x_i^0) which maximizes the firm 's (respectively firm j 's) payoff-functions $B_i(q_i, x_i), i = 1, 2$.*

Proof: See appendix B.

This proposition establishes the existence of at least one Nash equilibrium subject to the quasi-concavity of payoff functions for a duopoly equilibrium when a fundamental firm's asset is scarce. As such, defining an equilibrium situation does not bring much information. Consequently, it may be interesting comparing this situation with a monopoly situation that encounter the same kind of limitation on one of its assets.

4.3. Monopoly equilibrium with a generic limited asset

Determining the monopoly equilibrium corresponds to the standard accident model where the optimal level of prevention is solved independently of the equilibrium quantities. The literature shows that in this situation, under strict liability, the firm's optimal prevention level corresponds to the socially optimal level. When the monopoly knows a limited asset ($q_m(c + x_m) \leq Y_m$) (where m represents the monopoly index), the determination of equilibrium quantities is no longer independent from the prevention level. Indeed, the monopolist must arbitrate between the quantities of inputs for production and for prevention. The generic program for such a situation is written as follows:

$$\max_{q_m, x_m} B_m(q_m, x_m) = q_m(K - q_m) - q_m c - q_m x_m - q_m p(x_m) D \quad (7)$$

Under the constraints

$$q_m(c + x_m) \leq Y_m, \quad (7a)$$

$$0 \leq p(x_m) \leq 1 \quad (7b)$$

To give a heuristic tractable representation, we simplify the above program by using a specific accident probability function $p(x_M) = (1 - x_M)$ as (Hiriart and Martimort (2006)). Then the program rewrites as

$$\text{Max}_{q_m, x_m} (B(q_m, x_m) = q_m(K - q_m) - q_m c - q_m x_m - q_m(1 - x_m)D) \quad (7')$$

Under the constraints:

$$q_m(c + x_m) \leq Y_m \quad (7'a)$$

$$0 \leq x_m \leq 1 \quad (7''b)$$

$$q_m \geq 0 \quad (7'''c)$$

Using the same resolution methods as before, the equilibrium solutions (q_m^0, x_m^0) are:

$$- \quad q_m^0 = \frac{1}{2}(K - D - Dc) \quad \text{with } K > D(1 + c) \quad (8)$$

$$- \quad x_m^0 = \frac{Y_m}{\frac{1}{2}(K - D(1 + c))} - c < 1, \quad \text{for } K > 0, \quad \text{with } K > \frac{2Y_m}{1 + c} + D(1 + c), \quad (9)$$

- And the equilibrium price is:

$$\pi_m^0 = \frac{1}{2}(K + D(1 + c)) \quad (10)$$

Concerning the equilibrium care level, it is easy to see that, considering our assumption $p(x_M) = (1 - x_M)$, this level is below that reached under a standard monopoly where this value is equal to 1. Indeed, as the quantity determination and care level are determined independently, it is easy to check that without binding capacities, the monopoly must choose the optimal care level $x_m^0 = 1$. It follows that the equilibrium care level of the monopoly facing a limited asset is less than 1.

4.4. Comparing monopoly and duopoly when both face a scarce asset

We compare a monopoly facing a scarce resource to a duopoly where each firm sees the same kind of limitation. As mentioned in the text, to make things comparable, we assume that both firms have the same accident probability distribution $p(x_i) = (1 - x_i)$, $i = 1, 2$, the same technology (identical marginal costs $c_1 = c_2 = c$), and that the variable K is such that it does not induce negative values for the strategic variables. Furthermore, we assume that the damage D level for product unit is the same for both firms. Also, the capacities of each firm mean the following relationship must be respected: $Y_1 + Y_2 = Y_m$ with $0 < a, b < 1$: $aY_m = Y_1$ et $bY_m = Y_2$. Then, the firm 1's program (similar to firm 2) becomes:

$$\max_{q_1, x_1} B_1(q_1, x_1, \bar{q}_2) = q_1(K - q_1 - \bar{q}_2) - q_1 c_1 - q_1 x_1 - q_1(1 - x_1)D \quad (11)$$

Under the constraints:

$$q_1(c_1 + x_1) \leq Y_1 \quad (11a)$$

$$0 \leq x_1 \leq 1 \quad (11b)$$

$$q_1 \geq 0 \quad (11c)$$

By similar reasoning we can deduce the firms' reaction functions:

$$q_1(\bar{q}_2) = \frac{1}{2}(K - D(1 - c_1) - \bar{q}_2)$$

$$q_2(\bar{q}_1) = \frac{1}{2}(K - D(1 - c_2) - \bar{q}_1)$$

The Nash-equilibrium quantities are:

$$q_1^0 = \frac{1}{3}(K - D(1 - 2c_1 + c_2)) \quad (12)$$

$$q_2^0 = \frac{1}{3}(K - D(1 - 2c_2 + c_1)) \quad (12')$$

And the optimal care level can be written as:

$$x_1^0 = \frac{3Y_1}{K - D(1 - 2c_1 + c_2)} - c_1 \quad (13)$$

$$x_2^0 = \frac{3Y_2}{K - D(1 - 2c_2 + c_1)} - c_2 \quad (13')$$

The equilibrium price π_D^0 becomes:

$$\pi_D^0 = \frac{1}{3}(K + 2D + D(c_1 + c_2)) \quad (14)$$

Having established the equilibrium prices, quantities and care level for the monopoly and oligopoly situations, constrained on a generic asset, we are able to compare these two imperfect competition situations. Proposition 2 summarizes these results.

Proposition 2: *With comparable parameters (unit cost, unit cost of damage) and a maximum asset level (constraint):*

- a) *The equilibrium quantities of a duopoly are higher than with monopoly.*
- b) *The equilibrium prices are lower for the duopoly than for the monopoly.*
- c) *However, the optimal level of prevention is higher for the monopoly than for the duopoly situation.*

Proof provided in appendix C

As expected, the comparison of the competitive equilibria of a monopoly and an oligopoly (points a) and b)) are standard. Competition is beneficial for society because the equilibrium prices are lower, and the quantities offered are greater under an oligopolistic competition. However, concerning prevention with a binging input, oligopolistic competition leads to a lower safety level compared to monopoly (point c). Proposition 2 suggests that competition amplifies the impact of the asset limitation. Compared to a monopoly, a duopoly

induces the firms to supply more goods and services. Thus, the duopoly uses more production factors, and as the generic asset is limited this results in lower levels of safety. Here, the firms are mutually dependent which means that their best-response functions are mutually linked as are their care levels. The literature distinguishes between strategic substitutes and complements. We prove this in the following lemma:

Lemma 1: *Under strict liability, the firm i 's best response (q_i^0, x_i^0) depends also on its opponent's choice, (y_j^0, x_j^0) ($j \neq i, i = 1, 2$). Then, q_i^0 and q_j^0 are strategic substitutes whereas x_i^0 and x_j^0 are strategic complements.*

Proof: See appendix C

Lemma 1 takes its origins in Bulow, Geanakoplos, and Klemperer (1985) who deal with multimarket oligopolies involving two firms and two markets. A given firm exerts monopoly power in the first market but is challenged by the other firm in the second market. Both compete on quantities and both face economies or diseconomies of scope. Strategic effects appear in the competitive market where the firms challenge one another due to the existence of a second market. They are defined as strategic substitutes (if they mutually offset one another) and strategic complements (if they mutually reinforce one another).

Here, being a strategic substitute means that every time one firm reduces its market supply, the other firm is liable to offer a corresponding amount and increases its production. Strategic complement means that the increased safety efforts by one firm due to its reduced supply (and thus its reduced production) are compensated by a decrease in the safety efforts of the other firm. Implicitly, in this model, the second market is virtual and concerns safety. This makes aggregate safety dependent on the individual production and care strategies.

5. Introducing ex-ante regulation

Proposition 2 and Lemma 1 show that oligopolistic competition leads firms to choose a lower strategic care equilibrium than expected by society. Comparison with the monopoly suggests that it tends to reduce further the socially optimum care level. Consequently, this higher risk may make the regulator more inclined to make hazardous facilities safer. This is usually achieved by mixing ex-post liability with ex-ante prevention by enforcing a minimum care level as in Kolstad, Ulen, and Johnson (1990) for example. However, their results apply to a representative firm which is subject to the charge of negligence if the court is uncertain about the firm's liability. The present approach is radically different because it assumes competition under strict liability, and now an ex-ante standard.

Indeed, we assume that the regulator sets a mandatory standard with which in order to be allowed to produce, the firms must comply. To avoid moral hazard, we assume also that the regulator systematically monitors the firms at no cost. Previous work shows that ex-ante norms involve inefficiencies because of information asymmetries between injurer and regulator (see Shavell, 1984a,b) and reducing them is crucial; however, for reasons of space, we do not investigate this further but rather assume that monitoring is cost-free.

Proposition 3 summarizes the consequences of a standard set-up under the above conditions.

Proposition 3: *The combined use of an ex-ante prevention rule (here a given accident probability) and strict liability leads to the following results:*

- i) *If both firms decide to remain in the market, they must increase their level of prevention and reduce the level of their production because they are making a "forced" arbitration on the scarce asset,*
- ii) *The equilibrium price is higher due to a negative shift in the aggregate supply,*
- iii) *If the firms differ in their resources, the weaker firm may be forced to leave the market leaving the other firm in a monopoly situation.*

Proof: See appendix D

As a simplification, the regulator's standard takes the form of a minimum accident probability which must be respected. To achieve this, the firms must subtract a part of the generic asset from their production of safety which causes a decrease in their scale of production and increase their prevention level. This result is expected. However, proposition 3 also refers to the minimum conditions for companies to remain in the market. Overly restrictive conditions may induce them to exit. Nevertheless, even if the firms remain in the market, introducing standards leads to a reduction in the equilibrium quantities and an increase in the equilibrium price. Consequently, the consumers' well-being suffers a loss even though the neighborhood is better protected.

If the conditions are too restrictive, firms may forego production (point (iii) in proposition 4). Since they are supposed not to be identical and differ in their levels of asset constraint, one of them might exit the market. It follows that the other firm (for instance firm 1) will occupy a monopoly position. In this case, assuming a given care level (because it is strictly controlled by the regulator) the monopoly behaves in a classical way and its payment function is $q_1(K - q_1) - q_1c - q_1\bar{x} - q_1\bar{p}D$ under the constraint: $q_1(c + \bar{x}) \leq Y_1$. As a result, the maximum production becomes $q_{1max} = Y_1/(c + \bar{x})$ and the associated price (minimum) is $p_{1min} = K - Y_1/(c + \bar{x})$. It can be reasonably assumed that if the situation of the standard-

compliant monopoly increases the safety level, it will worsen the exchange terms related to lower equilibrium quantities and a higher equilibrium price.

Proposition 3 is in line with Shavell's (1984) results where a combination of the instruments allows achievement of the socially optimal care level. However, here, the standard may be lower than this level. This can happen if too high a standard leads firms to exit the market despite the social utility of their production.

6. Conclusion

The model we analyzed is a simplified version of reality. We included the most restrictive conditions in order to enable comparison. These simplifications relate to the technology which is assumed to be identical for all competitors, common knowledge of the risk assessment, and the assumption of a homogeneous product. We have highlighted that compared to a monopoly facing a rationed asset, if the contest leads to improved access to resources at lower cost, this tends to increase the risk rate through a higher probability of accident. We show that when the quantities of some production factors are limited, rivalry leads the firms to reduce their prevention levels regardless of the existence of an objective liability rule which does not exonerate the entity responsible for the accident. This competition leads firms to allocate more resources to production than to safety. This choice is "automatic» and is linked to the game conditions.

In the present case, it is obvious that the prevention level achieved by firms under the impetus of competition is no longer linked to the socially optimal care level since this would result also from competition with unlimited generic assets. Therefore, standards are necessary. We assume the regulator is omniscient and can observe compliance with the standard at any time, and that authorization of production is conditional on compliance. In reality, the high cost of monitoring does not allow continuous verification of compliance with standards, so firms are able to compare the benefits from non-compliance to the cost of the sanction (the latter can take the form of a fine with banning of production the highest level of punishment). This does not change the substance of the argument. In other words, our results are not sensitive to the existence of informational asymmetries between regulator and firms.

7. References

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APPENDIX A

Strict liability equilibrium for firms without restricted inputs

In this economy, both firms use the generic asset without restriction. This assumption means that the firms disconnect their market activities (production and selling) from accident prevention. Under duopolistic competition this leads to the following program:

$$\max_{q_1, x_1} B_1((q_1, x_1); q_2) = q_1(K - q_1 - q_2) - q_1 c_1 - q_1 x_1 - q_1 p(x_1)D \quad (1a)$$

$$\max_{q_2, x_2} B_2((q_2, x_2); q_1) = q_2(K - q_1 - q_2) - q_2 c_2 - q_2 x_2 - q_2 p(x_2)D \quad (1'a)$$

From the first-order conditions, we get:

$$\frac{\partial B_1(-)}{\partial q_1} = 0 \implies \frac{\partial B_1(-)}{\partial q_1} = K - 2q_1 - q_2 - c_1 - x_1 - p(x_1)D = 0 \quad (2a)$$

$$\frac{\partial B_2(-)}{\partial q_2} = 0 \implies \frac{\partial B_2(-)}{\partial q_2} = K - 2q_2 - q_1 - c_2 - x_2 - p(x_2)D = 0 \quad (2'a)$$

Calculating the best response functions requires determining the care level because otherwise, they would interfere with the expression of quantity q_i in relation to quantity q_j , $i \neq j$, $i, j = 1, 2$. Similar to free competition, this determination is independent of the knowledge of q_i for firm i . Then it is preferable to fix the firms' optimum care level (here $x_i^0 > 0$), such that⁶:

$$p'(x_i^0) = -\frac{1}{D}$$

Solving the above equations for q_1 and q_2 we can define the game Nash equilibrium (q_1^*, q_2^*) :

$$q_1^* = \frac{1}{3}(K - 2c_1 + c_2 - 2(x_1^0 + Dp(x_1^0)) + x_2^0 + Dp(x_2^0)) \quad (3a)$$

And,

$$q_2^* = \frac{1}{3}(K - 2c_2 + c_1 - 2(x_2^0 + Dp(x_2^0)) + x_1^0 + Dp(x_1^0)) \quad (3'a)$$

⁶ Because: $\frac{\partial B_i(-)}{\partial x_i} = -q_i(1 + p'(x_i)D) = 0$

APPENDIX B

Strict liability equilibrium for firms with restricted inputs

Each firm disposes of a limited but generic asset (a “generic input” or a “generic asset”) ($Y_i \neq Y_j, i, j = 1, 2, i \neq j$) and makes a strategic tradeoff between production and care according to the other firms’ choices. The program corresponds to the equations (6) to (6c) in the main-text argument. Solving this program proves the following proposition:

Proposition 1: *Under the assumption that the coefficients K, D, c_i combine to make the payoff function quasi-concave and since it is twice derivable, then the program (6) to (6’c) admits at least one Nash equilibrium (q_i^0, x_i^0) which maximizes the firm ’s (respectively firm j ’s) payoff-functions $B_i(q_i, x_i), i = 1, 2$.*

Proof of Proposition 1:

To simplify we solve the program for firm 1; the proof is the same for firm 2. The object is to set up the best-response functions, and then to determine the game’s Nash equilibrium. The results are derived for firm 2 given the supply i.e., \bar{q}_2 . We consider that the coefficients $D, K, c_1 \leq 1$ are such that the function $B_1(q_1, x_1)$ is quasi-concave. This is analyzed in part a) of the proof. Part b) defines the best response functions of each firm while part c) describes the Nash equilibrium of the game. However, first we must write the Karush-Kuhn-Tucker conditions which are:

$$\mathcal{L}(x_1, q_1, \lambda_1, \lambda_2) = q_1(K - q_1 - \bar{q}_2) - q_1 c_1 - q_1 x_1 - q_1 p(x_1)D + \lambda_1(-q_1(c_1 + x_1) + Y_1) + \lambda_2(-p(x_1) + 1) + \lambda_3 p(x_1). \quad (6.d)$$

$$\frac{\partial \mathcal{L}}{\partial x_1} \leq 0 \Rightarrow -q_1 - q_1 p'(x_1)D - \lambda_1 q_1 - \lambda_2 p'(x_1) \leq 0 \quad (6.e)$$

$$x_1 \geq 0 \quad (6.f)$$

$$x_1 \frac{\partial \mathcal{L}}{\partial x_1} = 0 \Rightarrow x_1(-q_1 - q_1 p'(x_1)D - \lambda_1 q_1 - \lambda_2 p'(x_1)) = 0 \quad (6.g)$$

$$\frac{\partial \mathcal{L}}{\partial q_1} \leq 0 \Rightarrow K - 2q_1 - \bar{q}_2 - x_1 - c_1 - p(x_1)D - \lambda_1(c_1 + x_1) \leq 0 \quad (6.h)$$

$$q_1 \geq 0$$

$$q_1 \frac{\partial \mathcal{L}}{\partial q_1} = 0 \Rightarrow q_1 \left(K - 2q_1 - \bar{q}_2 - x_1 - c_1 - p(x_1)D - \lambda_1(c_1 + x_1) \right) = 0 \quad (6.i)$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_1} \geq 0 \Rightarrow -q_1(c_1 + x_1) + Y_1 \geq 0 \quad (6.j)$$

$$\lambda_1 \frac{\partial \mathcal{L}}{\partial \lambda_1} = 0 \Rightarrow \lambda_1(-q_1(c_1 + x_1) + Y_1) = 0 \quad (6.k)$$

$$\lambda_1 \geq 0$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_2} \geq 0 \Rightarrow -p(x_1) + 1 \geq 0 \quad (6.l)$$

$$\lambda_2 \geq 0. \quad (6.m)$$

$$\lambda_2 \frac{\partial \mathcal{L}}{\partial \lambda_2} = 0 \Rightarrow \lambda_2(-p(x_1) + 1) = 0 \quad (6.n)$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_3} \geq 0 \Rightarrow p(x_1) \geq 0 \quad (6.o)$$

$$\lambda_3 \geq 0 \quad (6.p)$$

$$\lambda_3 \frac{\partial \mathcal{L}}{\partial \lambda_2} = 0 \Rightarrow \lambda_3(p(x_1)) = 0 \quad (6.q)$$

a) Quasi-concavity of the program

To simplify the process of obtaining a solution we consider strictly positive x_1 and q_1 , discarding $x_1 = 0$ (no prevention) and $q_1 = 0$ (no production), and negative values (i.e., we study the “normal” state of affairs). We also consider the particular case where the constraint is binding (i. e. $\lambda_1 > 0$). Thus, the firm is limited by its asset. We reject $\lambda_2 > 0$ and $\lambda_3 > 0$ because if they are not equal to zero this means that $x_1 = 0$ and/or $p(x_1) = 0$ which would violate our assumptions that x_1 is strictly positive. It is easy to verify this when $\lambda_1 = \lambda_2 = \lambda_3 = 0$, then, the system becomes similar to the situation without rationed asset.

We can study the concavity or the quasi-concavity of $B_1(q_1, x_1)$.

Since the constraint is binding, we replace x_1 by $x_1 = \frac{Y_1}{q_1} - c_1$ in the payoff function:

$$B_1(q_1) = q_1(K - q_1 - \bar{q}_2) - Y_1 - q_1 p\left(\frac{Y_1}{q_1} - c_1\right) D$$

It is easy to see that $q_1 p\left(\frac{Y_1}{q_1} - c_1\right) D$ increases and $q_1(K - q_1 - \bar{q}_2)$ decreases as q_1 increases in the interval $[0, Y_1]$. Then on this interval, both functions $q_1 p\left(\frac{Y_1}{q_1} - c_1\right) D$ and $q_1(K - q_1 - \bar{q}_2)$ cross once. Thus, there exists $\tilde{q}_1 \in [0, Y_1]$ such that:

$$\tilde{q}_1(K - \tilde{q}_1 - \bar{q}_2) - \tilde{q}_1 p\left(\frac{Y_1}{\tilde{q}_1} - c_1\right) D = 0$$

It follows that: $B_1(\tilde{q}_1) = B_1(0) = -Y_1$ and for \tilde{q}_1 and 0, $B_1(-)$ is negative. To be sustainable, there must be an interval $[q_a, q_b] \subset [0, Y_1]$ such that for all $q_1^a \in [q_a, q_b]$, $B_1(q_1^a) > 0$, with $B_1(q_a) = B_1(q_b) = 0$. If q_1^a does not exist that fulfills this condition, and the program is not viable because, $B_1(q_a) < 0$.

Then the condition for having a viable program (i.e., a positive payoff) is that:

$$\text{Condition A: } K > \frac{Y_1}{q_1^a} + q_1^a + \bar{q}_2 + p(q_1^a) D, \quad q_1^a \in [q_a, q_b]$$

With this assumption, from $B_1(\tilde{q}_1) = B_1(0) = -Y_1$, and with $q_1^a \in [q_a, q_b] \subset [0, Y_1]$, there exists q_1^a , such that $B_1(q_1^a) > 0$, and from Rolle's lemma there exists at least one q_1^* , $q_1^* \in [q_a, q_b]$ such that $B_1'(q_1^*) = 0$. It follows that for $[0, Y_1]$, the program admits an interval $[q_a, q_b] \subset [0, Y_1]$, where for all $q_1^a \in [q_a, q_b]$, $B_1(q_1^a) > 0$ and $B_1(q) \leq 0$, for all $q \notin [q_a, q_b]$. Then the program is quasi-concave on $[q_a, q_b]$.

b) Formation of the best-response function.

$x_1 > 0$ in (6.g) implies:

$$-q_1 - q_1 p'(x_1) D + \lambda_1 q_1 = 0 \quad \text{and consequently, } x_1^0 > 0 \text{ such that:}$$

$$p'(x_1^0) = -\left(\frac{1 + \lambda_1}{D}\right)$$

Concerning $q_1 > 0$, by (6.i):

$$K - 2q_1 - \bar{q}_2 - x_1 - c_1 - p(x_1) D - \lambda_1(c_1 + x_1) = 0 \quad (b)$$

But $\lambda_1 > 0$, implies $q_1(c_1 + x_1) - Y_1 = 0$.

It follows that we determine a system with three unknowns q_1, x_1, λ_1 and, three equations:

$$q_1(c_1 + x_1) - Y_1 = 0 \quad (\text{a.1})$$

$$p'(x_1) = -\left(\frac{1+\lambda_1}{D}\right) \quad (\text{a.2})$$

$$K - 2q_1 - \bar{q}_2 - x_1 - c_1 - p(x_1)D - \lambda_1(c_1 + x_1) = 0 \quad (\text{a.3})$$

To define the best response function for firm 1, it is sufficient to extract λ_1 from (a.2), $\lambda_1 = -1 - Dp'(x_1)$, and report this value in (a.3) where, previously, q_1 , from (a.1) has been expressed in terms of x_1 . Then considering these changes, from (a.3) we get an equation in terms only of x_1 :

$$K - Dp(x_1) - \frac{2Y_1}{c_1+x_1} - \bar{q}_2 + D(c_1 + x_1)p'(x_1) = 0$$

Obviously, solving this equation depends on the probability density $p(x_1)$. The solution obtained depends on \bar{q}_2 , then $x_1^0 = x_1(\bar{q}_2), x_2^0 = x_2(\bar{q}_1)$. We replace all expressions in x_1 in (a.3) to determine the best response functions or reaction functions. Then by the implicit function theorem the first order condition for firm 1 alone defines what is its best strategy given \bar{q}_2 . A similar argument holds for firm 2:

$$q_1(\bar{q}_2) = \frac{1}{3} [K - 2Dp(x_1^0) + p(x_2^0) + 2c_1Dp'(x_1^0) + 2Dx_1^0p'(x_1^0) - c_2Dp'(x_2^0) - Dx_2^0p'(x_2^0)]$$

$$q_2(\bar{q}_1) = \frac{1}{3} [K - 2Dp(x_2^0) + p(x_1^0) + 2c_2Dp'(x_2^0) + 2Dx_2^0p'(x_2^0) - c_1Dp'(x_1^0) - Dx_1^0p'(x_1^0)]$$

c) *Nash Equilibrium determination*

From the reaction functions we can define the Nash equilibrium of the game (see definition 1 above) which consists of determining the quantities (q_1^0, q_2^0) which the firms will supply at equilibrium. The Nash equilibrium can be seen as occurring when each firm 1 strategy is the best response to the other firm's strategical choice (similarly for firm 2). Substituting firm 2's best response function into firm 1 gives:

$$q_1^0 = q_1(q_2(\bar{q}_1))$$

And for firm 2.

$$q_2^0 = q_2(q_1(\bar{q}_2))$$

Having determined q_1^0 and q_2^0 , we deduce the game's equilibrium level of care for both firms $(x_1^0$ and $x_2^0)$ and then $B_1((x_1^0, q_1^0), (x_2^0, q_2^0)), B_2((x_2^0, q_2^0), (x_1^0, q_1^0))$ is the Nash game equilibrium.

APPENDIX C

Proof of proposition 2

To demonstrate a) it is sufficient to show that q_m^0 must be such that $q_m^0 < q_1^0 + q_2^0$.

Then assume that $q_m^0 \geq q_1^0 + q_2^0$. As $q_1^0 + q_2^0 = \frac{2}{3}(K - D(1 - c))$ and $q_m^0 = \frac{1}{2}(K - D(1 + c))$ (by assumption $c_1 = c_2 = c$), with respectively $K > D(1 - c)$ and $K > D(1 + c)$ to guarantee positive quantities, and develop:

$$\frac{1}{2}(K - D(1 + c)) > \frac{2}{3}(K - D(1 - c))$$

This inequality is true if $D(1 - 7c) > K$ but this contradicts the condition that

$$K > D(1 + c) \text{ and } K > D(1 - c)$$

Then it follows that:

$$q_m^0 < q_1^0 + q_2^0$$

From this result, b) it follows that the duopoly equilibrium price π_D^0 is lower than the monopoly price π_m^0 then:

$$\pi_m^0 > \pi_D^0$$

It remains to prove c). For this, as previously, we compare the respective care levels namely: x_i^0 et x_m^0 . Let us assume that $x_m^0 > x_i^0$, and by taking their respective value:

$$\frac{Y_m}{\frac{1}{2}(K - D(1 + c))} - c > \frac{3Y_i}{K - D(1 - c)} - c$$

After our simplifications and as $aY_m = Y_i$

$$\frac{1}{\frac{1}{2}(K - D(1 + c))} > \frac{3a}{K - D(1 - c)}$$

Then:

$$K > D \left(1 - c \left(\frac{2 + 3a}{2 - 3a} \right) \right)$$

For $a \neq \frac{2}{3}$, this expression is true because by hypothesis $K > D(1 + c)$ and,

$$D(1 + c) > D \left(1 - c \left(\frac{2 + 3a}{2 - 3a} \right) \right) \Rightarrow 1 > - \left(\frac{2 + 3a}{2 - 3a} \right) \text{ i.e. } 2 > -2$$

Consequently, $x_m^0 > x_i^0$ i.e., the care level of the monopoly is higher than the level chosen by the duopoly firms.

Proof of Lemma 1

The proof is made for firm i but can be readily extended to firm j . Let us consider the expression of q_i^0 and x_i^0 i.e., respectively,

$$q_i^0(q_j) = \frac{1}{2}(K - D(1 - c_i) - q_j)$$

And,

$$x_i^0(q_j) = \frac{-c_i \left(\frac{1}{2} (K - D(1 - c_i) - q_j) \right) + Y_i}{\frac{1}{2} (K - D(1 - c_i) - q_j)}$$

We can take their derivative with respect to q , q_i^0 and x_i^0 depend on q_j then, where:

$$\frac{\partial q_i^0(q_j)}{\partial q_j} = -\frac{1}{2} < 0$$

This means that as firm j increases its production, firm i decreases its production, which implies that firm i devotes more input to safety. Consequently, as

$$p(x_i^0(q_j)) = 1 - x_i^0(q_j) = 1 - \left(\frac{-c_i \left(\frac{1}{2} (K - D(1 - c_i) - q_j) \right) + Y_i}{\frac{1}{2} (K - D(1 - c_i) - q_j)} \right)$$

$$\frac{\partial p(x_i^0(q_j))}{\partial q_j} = -\frac{2Y_i}{(-K + D + Dc_i + q_j)^2} < 0$$

Then as firm j increases its market share, firm i decreases its production, but also increases its care level and decreases the probability of suffering an accident.

Appendix D

Proof of proposition 3

a) General feature and proof of i)

The regulator introduces a standard corresponding to a minimum probability threshold \bar{p} which needs $\bar{x}_i, i = 1,2$ as the care effort needed to achieve it. It follows that the firm uses $q_i \bar{x}_i$ as the input for prevention, then $\bar{x}_i = \bar{x}, i = 1,2$ (by assumption the firms use the same technology). Firm i 's program depends on q_i , given \bar{q}_j , we look for an interior solution $q_i > 0$:

$$\max_{q_i} B_i(q_i, \bar{q}_j) = q_i(K - q_i - \bar{q}_j) - q_i(c_i + \bar{x}) - q_i \bar{p}D.$$

With $q_i \in \left[0, \frac{Y_i}{(c_i + \bar{x})}\right]$. given the asset constraint $q_i(c_i + \bar{x}) \leq Y_i$. Then, $q_i^0(\bar{q}_j)$ the interior solution is such that:

$$\frac{\partial B_i(q_i, \bar{q}_j)}{\partial q_i} = K - \bar{p}D - \bar{x} - c_i - 2q_i^0(\bar{q}_j) - \bar{q}_j = 0$$

With :

$$\frac{\partial^2 B_i(q_i, \bar{q}_j)}{\partial^2 q_i} = -2 < 0$$

Then the above program is concave and admits a solution. Does this solution lie within $\left[0, \frac{Y_i}{(c_i + \bar{x})}\right]$? To address this, we build the best response functions and determine the Nash equilibrium of the system:

$$q_i^0 = \frac{1}{3}(K - \bar{p}D - \bar{x} - 2c_i + c_j)$$

And for j :

$$q_j^0 = \frac{1}{3}(K - \bar{p}D - \bar{x} - 2c_j + c_i)$$

Function $B_i(q_i^0, q_j^0)$ reaches a maximum at $q_i^0 \leq \frac{Y_i}{(c_i + \bar{x})}$. As q_i^0 is determined independently of $\frac{Y_i}{(c_i + \bar{x})}$, which results in q_i^0 being higher or lower than this value. If it is lower (unsaturated constraint) the firm i (respectively j) maximizes its profit for this value. Then, it will not be able to produce beyond $\frac{Y_i}{(c_i + \bar{x})}$ (respectively $\frac{Y_j}{(c_j + \bar{x})}$). Thus, the production level is reduced.

b) Proof of ii) The equilibrium price is higher due to a lower supply,

To simplify we assume that $(c_i = c_j \equiv c)$ and that $Y_j < Y_i$. The following relationships result from these assumptions:

$$q_i^0 = q_j^0 = \frac{1}{3}(K - \bar{p}D - \bar{x} - c) \text{ or also:}$$

$$q_i^0 = \frac{1}{3}(K - \bar{p}D - \bar{x} - c) = \frac{Y_i}{(c + \bar{x})}$$

$$q_j^0 = \frac{1}{3}(K - \bar{p}D - \bar{x} - c) > \frac{Y_j}{(c + \bar{x})}$$

Hence, firm j does not own enough resource to provide q_j^0 when firm i supplies $q_i^0 > \frac{Y_i}{(c+\bar{x})}$. The firm must then forgo this value. The question then is whether $q_j^1 = \frac{Y_j}{(c+\bar{x})}$, a Nash-equilibrium may exist. As the constraint is binding for firm j , then:

$$\frac{\partial B_i(q_i, q_j^1)}{\partial q_i} = K - \bar{p}D - \bar{x} - c - 2q_i - \frac{Y_j}{(c+\bar{x})} = 0$$

We deduce:

$$q_i^1 = \frac{1}{2} \left(K - \bar{p}D - \bar{x} - c - \frac{Y_j}{(c+\bar{x})} \right)$$

Then (q_i^1, q_j^1) is a Nash equilibrium for a higher price compared to if firms were not facing the limited asset. This corresponding price is $\pi^1(q_i^1, q_j^1) = K - q_i^1 - q_j^1 = \frac{1}{2}(K - \bar{p}D - \bar{x} - c)$ and may be compared to the price that would result from a firm j without restricted assets, i.e.

$$\pi^0(q_i^0, q_j^0) = K - \frac{2}{3}(K - \bar{p}D - \bar{x} - c)$$

It turns out that $\pi^1(q_i^1, q_j^1) > \pi^0(q_i^0, q_j^0)$, indeed, as firm j restricts its offer to $\frac{Y_j}{(c+\bar{x})}$. Consequently, as expected, the equilibrium price is higher.

c) Proof of iii): The potential exit of the weakest firm.

How does firm j achieve a positive profit? This involves knowing the conditions for which $B_j^1(q_i^1, q_j^1) > 0$. This is true for $\frac{K}{3} > (\bar{p}D + \bar{x} + c)$ ⁷. It should be emphasized that this condition is general and applies to both firms because of their symmetric costs. If, instead, we consider differentiated costs, (including unit accident costs) then the following relationship makes sense:

$$B_j^1(q_i^1, q_j^1) > 0 \implies \frac{1}{2}(K - \bar{p}D - \bar{x} - c) > (\bar{p}D_j + \bar{x}_j + c_j) > 0$$

Then, the equilibrium price per unit must be twice the value of the total marginal costs for the profit of firm j to be positive. For firm i , if the costs are lower than those of j , the price level at which it will make positive profits will be lower. For example, if $(\bar{p}D_j + \bar{x}_j + c_j) = 2(\bar{p}D - \bar{x} - c)$ (where the second member of equality designates the costs of i), then:

$$\frac{1}{2}(K - \bar{p}D - \bar{x} - c) > (\bar{p}D_j + \bar{x}_j + c_j) = 2(\bar{p}D - \bar{x} - c)$$

Firm i , for the same price level, makes a profit if:

$$\frac{1}{4}(K - \bar{p}D - \bar{x} - c) > (\bar{p}D + \bar{x} + c), \text{ i.e. for a lower price.}$$

Here, if $\pi^1(q_i^1, q_j^1) \in \left] \frac{1}{4}(K - \bar{p}D - \bar{x} - c), \frac{1}{2}(K - \bar{p}D - \bar{x} - c) \right[$ then, firm i achieves a positive profit while firm j makes a loss and firm i remains alone as a monopoly.

⁷ Indeed, $\pi^1(q_i^1, q_j^1)q_j^1 - cq_j^1 - \bar{x}q_j^1 - \bar{p}Dq_j^1 > 0 \implies \pi^1(q_i^1, q_j^1) - c - \bar{x} - \bar{p}D > 0$ or, $\frac{1}{2}(K - \bar{p}D - \bar{x} - c) - c - \bar{x} - \bar{p}D > 0$ i.e. $\frac{1}{2}K - \frac{3}{2}(\bar{p}D + \bar{x} + c) > 0$.

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