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**Civil Liability, Safety and
Nuclear Parks:
Is Concentrated
Management Better?**

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Ultra-hazardous risky activities as the nuclear industry cannot be considered as “normal industries” i.e. without abnormal environmental and health risks. This theoretical paper studies the industrial organization of electro nuclear sectors from the view point of the general cost of impact prevention policy and civil liability. It assesses on a theoretical basis, how civil liability rules may induce or discourage the extension of nuclear parks to new emergent operators. It compares the consequences of extending to several independent owners the management of nuclear stations. This question can apply to the unification process of the European electricity market in which several public and private nuclear power operators are running. The paper shows that the choice between either a monopolistic scheme (one operator for several plants) or a decentralized one (one operator by station) depends on the condition of application of the legal civil liability regime and on the strength of the safety control exerted by the Nuclear Regulatory Authorities. It is shown that when the control is high, then the safety costs generated by the monopolistic organization are less than the same costs of a decentralized one. However, conditions on the insurance policy can mitigate this result.

Keywords: Strict Liability, Electric Energy, Nuclear Plants

JEL Classification: Q5, Q58, Q53, K23, L13, L52, L94

I'd like to thank Evens Salies for the long discussions we had about this contribution. All errors are of my sole responsibility.

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Is concentrated management better?

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Ultra-hazardous risky activities as the nuclear industry cannot be considered as “normal industries” ie without abnormal environmental and health risks. This theoretical paper studies the industrial organization of electro nuclear sectors from the view point of the general cost of impact prevention policy and civil liability. It assesses on a theoretical basis, how civil liability rules may induce or discourage the extension of nuclear parks to new emergent operators. It compares the consequences of extending to several independent owners the management of nuclear stations. This question can apply to the unification process of the European electricity market in which are running several public and private nuclear power operators. The paper shows that the choice between either a monopolistic scheme (one operator for several plants) or a decentralized one (one operator by station) depends on the condition of application of the legal civil liability regime and on the strength of the safety control exerted by the Nuclear Regulatory Authorities. It is shown that when the control is high, then the safety costs generated by the monopolistic organization are lesser than the same costs of a decentralized one. However, conditions on the insurance policy can mitigate this result.

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0. Introduction

The fast development of nuclear power has benefited of the successive economic and environmental oil and gas crisis that occurred at the end of the 20th Century and the beginning of the 21th one. Indeed, the mandatory GHG emissions reduction² or, still, the willingness of nations to gain access to their energy independence face to the rising price of fossil energies explained the general revival of nuclear programs³. This state of matter was still true until March eleventh 2011 after that the 9.0-magnitude Tohoku earthquake and tsunami devastated Japanese northeast coast. The catastrophic consequence has been the knocking out of the reactor cooling systems of the Fukushima Daiichi and Daini electro-nuclear plant. This induced leakage of irradiated contaminant that threatens populations located in the plant's vicinity, the supply of fresh water, the sea resources and the agriculture products on a large scale in Japan.

As for the 1979 Three Miles Island⁴ accident and the 1986 Tchernobyl catastrophe, by its severity, the Fukushima accident undermines the position of the defenders of the nuclear option. Already, in Europe, some countries put into question their recent nuclear power programs as Germany and Italy for instance. Anyway, the industrial and economic consequences of this catastrophic event are still unknown because at the present time (March 2011) and Japanese authorities are far from controlling the situation. The Fukushima catastrophe is still going on and developing. Consequently, it can be taken for granted that these events will spark a close control of the viability and the safety of the whole nuclear plants in the entire World. Hence, without doubt, some stations will be closed or submitted to strong unexpected costs for refurbishment. However, the present situation could be different from the past. Indeed, the Three Miles Island and Tchernobyl events entailed either the break down or some serious slow down of the electro-nuclear projects in most Countries. By now, emergent countries are deeply involved in the development of their energy project and going back to fossil energy could be difficult for them. Hence, in spite of the Fukushima accident, nuclear program will spread, even if at a slower rate.

This structural trend and this tragic accident put spotlights on the very sensitive question of the safety of the electro-nuclear plants. Even if nuclear catastrophes are deemed to

²See e.g. the Intergovernmental Panel on Climate Change, Fourth Assessment Report, (2007).

³ So for example the Ampere(2000) report.

⁴Rogovin and Frampton, (1980).

occur with very low probability⁵, they have far-reaching consequences for health and the Environment. Furthermore, the very recent history has shown that unexpected scenarios can develop as seen in Fukushima where the four reactors had been simultaneously damaged by the tsunami that followed the earthquake.

As a consequence, giving up the nuclear sector is a long run project and more probably, nuclear programs will last several more decades; it is then natural and legitimate to consider that the industrial organization of this ultra-hazardous risky industry is becoming a major stake⁶. Initially, Governments boosted the development of electro-nuclear industry in the wake of the development of military activities. Nowadays, however, private interests are growingly involved and interested in the development of nuclear programs. They take the shape of public-private participation. For instance, in the United States from July 1999 to September 2008, eighteen US nuclear plants changed ownerships⁷. Private firms are all the more encouraged to invest in this sector by the international institutional improvement of the coverage conditions of third party damages. The temptations to break State monopolies in this sector are great for favoring decentralized organization. Furthermore, the unification of the electricity market (as it is the case in Europe) induces several nuclear operators to live together. Taking into account these factors leads to wonder whether a greater safety is guaranteed by a monopolistic organization of the nuclear sector, or whether the arrival of new comers can contribute to increase the level of care and protection. Since the end of the nineties this point is controversial, (see for instance Varley and Paffenbarger (1998), or still AEN-OCDE (2000)). These last contributors insist on the dangers of an uncontrolled subcontracting process for the maintenance of security.

This paper assesses on a theoretical basis how civil liability rules influence the entrance of new operators on the electronuclear production. This is done by appraising the consequences on care levels of the splitting-up of an electro-nuclear park to independent

⁵ “It is sometimes argued that for, so-called” *Damocles risks*”, i.e. risks with a very high damage and a low probability, the risk assessment of the public is not proportional to the risk. The occurrence of a very high damage should be avoided, even if the costs for the avoidance are much higher than the expectation value of the damage. However past attempts to quantify this effect have not been successful or accepted, so there is currently no accepted method on how to include risk aversion in such an analysis. Consequently it is currently not taken into account within the *ExternE* methodology. Research on how to assess this, for example with participatory approaches, is clearly needed.”, Bickel and Rainer (2005), p. 226

⁶ See for instance protests against the building of a new nuclear power station in Armenia at Metzamor who sits in a seismic zone that has suffered one of the worst earthquakes in modern history.
http://www.nuclearpowerdaily.com/reports/Environmentalists_decry_risks_of_new_Armenia_nuclear_reactor_99.html.

⁷Source Nuclear Energy Institute.

<http://www.nei.org/resourcesandstats/documentlibrary/reliableandaffordableenergy/graphicsandcharts/usnuclearplantsales/>

operators. Performance is evaluated by the level of safety and the global cost of liability and prevention. Choosing between centralizing and decentralizing the organization of a park of nuclear plants depends on several factors as the nature of the legal civil liability regime, the strength of the control exerted by the Nuclear Regulatory Authorities and the nature of the insurance policy. When the control is low, we show that both structures are equivalent because of the similarity of their safety costs. However, under a high control, a centralized organization generates lesser safety costs than a decentralized structure. However, this opinion has to be moderated. Indeed, the model shows that a high insurance cover may favor the decentralized organization. This may be done, for instance, by pooling the financial resources of different operators as in the US Price-Anderson Act of 1957, or the German insurance system. This question has policy implications. For instance, it may be applied to the unification process of the European electricity market characterized by several public and private nuclear operators⁸.

For this reason, compared to the wide field of the electro-nuclear economics, this paper will deal neither with the economic benefits of nuclear energy compared to other energies (MIT (2003), (2009), Bickel and Rainer (2005)), nor with the operating conditions of the nuclear deal with price uncertainty (Gollier, Prout, Thais and Walgenwitz (2004), Linares and Conchado, (2009)), nor with the question of decommissioning plants, and, still, nor with the reprocessing of nuclear waste. Its argument borrows some features of the debate about civil liability in the electro-nuclear industry. Most of these controversial contributions (Dubin and Rothwell (1990), Heyes and Heyes, (1998), (2000a), 2000b), Faure and Borre, (2008), Faure and Fiore (2009), Rothwell (2001)) show that putting ceiling on the level of repairs is subsidizing implicitly this industry⁹ and tend to let the externality costs unpaid. This is not the road that this paper takes. Starting from the civil liability question, it rather focuses on understanding the best economic organization scheme that insures the best safety level.

A first paragraph explains the nature of civil liability in the electro-nuclear sector. It underlines the importance of the ceiling of the level of repairs for inducing private operators to enter the market. A second paragraph describes the model based on the comparison of the expected costs of the organization of a park of two stations managed either by a unique operator or by two operators. A third one compares each kind of organization considering the

⁸ In October 1, 2010, in Europe, Russia and Ukraine included, there is a total of 195 nuclear power plant units with an installed electric net capacity of 170 GWe in operation in Europe 19 units with 16,9 GWe were under construction in six countries. (source European Nuclear Society).

<http://www.euronuclear.org/info/encyclopedia/n/nuclear-power-plant-europe.htm>

⁹ See also the synthesis achieved by Carroll and Froggatt (2007).

level of effort dedicated to safety. A fourth one concludes and gives some policy recommendation.

1. Civil liability and the development of the nuclear industry

Before 1988, Soviet Union acceded neither to any nuclear conventions nor to national nuclear liability law and, after the Tchernobyl 1986 disaster, this Country escaped to the duty to compensate damages to health, crops of national and international economies. To avoid future detrimental situation, the international community amended the existing nuclear conventions¹⁰. The 1988 Joint Protocol linked together the IAEA's Vienna Convention on Civil Liability for Nuclear Damage of 1963 and the OECD's Paris Convention on Third Party Liability 1960. Protocols amending the Paris Convention and the Brussels Convention were signed on February 12, 2004.

The joint protocol promotes a strict liability regime but maintains the principle of limiting liability in amounts settled by the previous international conventions¹¹. These last one set a global framework that national legislation can make more, but not less, stringent. Under the Joint Protocol, the operators of civil nuclear facilities are made strictly liable for damage resulting from nuclear incidents. Furthermore, there is an obligation of insurance or financial guarantee by the operator up to the fixed liability amounts in order to guarantee the availability of funds. This disposition is submitted to the approval of the Members States. What makes things complicated is that the States may have signed one convention, but not another one. This contributes to differentiate the liability ceilings of the Members States. To put in a nutshell we can quote the 2005 report Eurotom on the harmonization of nuclear civil liability rules in Europe.

“In sum, the protection of victims of nuclear accidents, the obligations of nuclear operators, transporters, (re-)insurers and public authorities in the EU Member States are governed by a patchwork of diverse legal regimes: (i) the liability of some operators is unlimited, whereas others have a capped liability; (ii) the operators’ insurances differ both as regards their coverage and payable fees; and (iii) the obligation to compensate victims of a nuclear accident differs both as regards the damages covered and the payable amounts.”

¹⁰ See for instance, Faure and Fiore (2009),

¹¹ Under the Joint protocol of 1988, the operator’s liability is absolute, i.e. the operator is held liable irrespective of fault, except for "acts of armed conflict, hostilities, civil war or insurrection", terrorism acts do not enter in the exclusion category.

Why ceiling the amount of redress rather than applying some “standard” strict civil liability regime? In fact, the hugeness of repairs after the occurrence of a nuclear hazard and the application civil strict liability prevents private firms to exert an activity in the nuclear field. Schwartz, (2006, p.39) summarizes the point very well: “*With no protection against a liability that was potentially unlimited both in time and amount, nuclear plant owners/operators, builders and suppliers were understandably hesitant to commit to the development of the industry.*”

Therefore, developing nuclear industry involves relieving nuclear operators of the burden of potentially ruinous liability claims¹². The governments ceiled the amount of compensation payable to victims by liable operators in the aim at avoiding them to become judgment proof. Under the evolution of international agreements, the caps to liability may be subject to institutional changes and, generally, the tendency is to increase the level of the ceiling. For instance, under the Brussels Convention, in France, the operator’s liability is limited to €1.5 million per nuclear accident in a facility and to €2.9 million per nuclear accident during transportation. The State in which the accident occurred will be liable for the compensation of victims up to a maximum of €28.6 million. Above this amount, the signatory’s members of the Brussels Convention contribute collectively to compensation up to a ceiling of €81.1 million. However, under the 2004 protocol, the availability of compensation amounts is much greater and covers a greater number of victims and collateral damages. Accordingly, the operator’s liability is around €700 million per nuclear accident in a facility and €80 million per nuclear accident during transportation. The State where the nuclear facility responsible for the damage is located will be liable for amounts above the €700 million for which the operator is liable, up to a maximum amount of €1,200 million. Above this amount, the States that are a party to the Brussels Convention will be liable up to a maximum amount of €1,500 million.

In the USA, the Price-Anderson Act of 1957 rules the civil liability for damages caused by a nuclear accident. Since the 1988 amendments, nuclear power plant licensees must purchase the maximum amount of commercial liability insurance available in the private market at a reasonable price. This is currently \$200 million per plant. In addition, all nuclear power plant licensees must participate in a joint-insurance pool. In the case of a nuclear accident whose costs exceed the first layer of private insurance coverage, each nuclear plant is

¹² More explicit still is The “*Exposé des Motifs*” for the 1960 Paris Convention that considers that “unlimited liability could easily lead to the ruin of the operator without affording any substantial contribution to compensation for the damage caused” (*Exposé des Motifs*, Motif 45).

obligated to make payments of up to \$88 million to cover any additional costs up to about \$9.3 billion at the present time. The compensation provision of both the first and the second layers of insurance are “no fault” and are not subject to civil liability litigation. The financial cap is fixed to \$9.5 billion and beyond this limit there are no further financial obligations.

2. The Model

We compare the cost structure dedicated to safety and civil liability of two electro-nuclear power structures. The first one is monopolistically organized. A unique operator (public or private) manages two perfectly similar nuclear plants. The monopolist structure may be split up by the introduction of a new plant managed by a new entrant. The situation will be understood as the separation of the existent park into two independent plants. Each of them is owned and managed by a single operator. “Similar” plants mean that each one belongs to the same technological generation, is built on the same engineering structure and has the same capacity¹³.

2.1 Notations and assumptions

2.1.1 The operators

The considered economy comprises two similar electro-nuclear plants indexed by $i, j = 1, 2$. The plants can be managed either by a unique operator (indexed by M or by no letter when ambiguity is impossible) or by two independent operators $i, l = 1, 2$ (each one manages one plant).

Assumption 1: *The operators (monopoly or competitive agents) are risk neutral.*

Assumption 2: *Both plants are identical.*

We consider now then the financial capacity of each operator. This is the total amount used for redress after the occurrence of a major accident. Let d be the total financial capacity of the natural monopoly, and d_i the capacity of the owner $i, l = 1, 2$. For the monopoly this value is $d = y + Q$, where y is the share of the wealth of the monopoly dedicated to the redress and Q is the amount that insurance companies accept to cover. Symmetrically, let

¹³ For engineers our economic assumptions could appear quite unrealistic. For instance Lochbaum (2000) notes the over-simplifications usually made to deal with this question: i) The plants are operating within technical specifications and other regulatory requirements, ii) Plant design and construction are completely adequate, iii) Plant aging does not occur; that is, equipment fails at a constant rate, iv) The reactor pressure vessels never fail, iv) Plant workers make few serious mistakes, v) Risk is limited to reactor core damage. If this set of assumptions cannot be insured for one plant, obviously it can hardly be done for a park even if plants belong to the same generation.

$d_l = y_l + Q$ be the financial capacity of the individual operator, $l = 1, 2$, (where y_l is the share of their wealth due to repairs).

Assumption 3: *The civil liability for nuclear accident is ruled by a capped strict liability regime where c is the amount of the legal compensation (liability cap).*

If D is the total damage due to a severe harm, the institutional level of the cap c is such that $0 \leq c \leq D$ (with the polar cases of no-liability regime when $c = 0$, (Ex-USSR situation), or standard strict liability regime when $c = D$ (India case until 2010). For most nuclear countries, $0 < c < D$. Assumption 3 means that insurance companies will not cover fully the cap. Hence, $Q < c$, the share Q is identical whatever the exploitation structure. This involves that the financial capacities of the monopolist or individual operators must be such that financial capacity to repair must be higher or equal to the institutional cap: $d, d_l \geq c$. If $d < c$ or $d_l < c$ then, the operator goes insolvent and it runs the risk to go judgment-proof (Shavell, 1986). This situation is excluded from the field of the analysis simply because if the relationship is verified, then, the insurance companies will not insure the facility.

2.1.2 The states of nature

The elementary states of nature are denoted as follows. Let, the events A and B be respectively A: “a major accident occurs in a nuclear plant” and B: “business as usual” or still “no accident”. A major accident induces the major damage D . Because the electro-nuclear park is constituted of two plants, the set of potential events (accident A , or no-accident B) may be described by the following sets:

- $H_1 = (A, A)$: Major accidents occurred on both plants 1 and 2,
- $H_2 = (A, B)$: A major accident occurred on plant 1 but not on plant 2,
- $H_3 = (B, A)$: No accident occurred on plant 1, but a major one on plant 2,
- $H_4 = (B, B)$: No accident occurred on both plants 1 and 2.

Then Ω is the set of sample: $\Omega = \{H_1, H_2, H_3, H_4\}$

The electro-nuclear park is controlled by a regulatory authority. This control can be strict (noted S), or sloppy (\bar{S}). A strict control is this set of necessary mitigation measures that the regulatory authority imposes to the operator to limit the occurrence of another catastrophic event after that a major accident has occurred. The regulator has to induce the operator to take relevant safety means to avoid the duplication of an accident in the safe facility. In fact, after a major nuclear hazard, measures have to be taken to check the safety of

the stations of same generation. This can be checked after the Fukushima accident. Everywhere, national nuclear authorities are launching checking programs. Morgan Stanley (2006, p. 46) asserts that a severe accident in one reactor can “lead to the shutdown of the facility in question and, potentially, similar facilities that may be considered to present the same risks”. This matter of fact leads to slow down or interrupt the production. Consequently, the risk of other similar failure is significantly reduced to zero. This is true for both the monopolistic operator and the individual ones. The effective control applies for plants of the same generation in which identical defects may be suspected. Then, we can formulate the following assumption.

Assumption 4: *After the occurrence of an ultra-hazardous accident, when strong control is exerted, the remaining safe plant is either slowed down or stopped temporarily.*

We can add that a failure of a plant of a given generation means that the similar stations “do not meet the highest safety requirements and therefore pose safety risk must be identified and their safety performance must be raised to the necessary level. This task is primarily a national responsibility, but it should be facilitated through assistance measures by the international community”, Milenin, Skokov and Supeno (1997).

The costs of controls, the slowing down or the temporarily brake of the activity of the plant involves a cost. This is expressed by the following assumption.

Assumption 5: *After the occurrence of a major event, under assumption 4, the cost of stopping or slowing down the remaining plant is equal to c , ($c > e > 0$).*

The cost e should not be interpreted as a cost for care but rather as an opportunity cost such as the cost of increasing the load factor in the safe plant and checking the management of safety.

2.1.3 The probability distribution of a major accident

Here, identical plants allow us to consider that they share the same probability distribution of major failure. Each state of nature occurs with a given probability¹⁴. Hence, a major accident in a plant is reputed to occur with a probability $P(A) \in (0, 1)$ or still P . Let

¹⁴ It is difficult to assign a probability to what is considered as a rare event. As pointed by Schneider (2007) external and internal event may influence the probability distribution (external events are external flooding (Central of Blayes, France, 1999), Tsunami (Indian Ocean, 2004), external fires (Los Alamos 1996, 2000), tornado and Hurricanes (David Besse USA, 1998, Hurricane Andrex). Considering internal events, have to be understood the losses of coolant (Kozloduy, Bulgaria 2003), numerous turbine fires, and secondary cooling circuits. These events combine with human errors and violation of procedures. Hence, as such, the probability of the melting down of the core takes sense when considering the whole set of potential failure of the security system.

the probability of the event B (“business as usual or no accident”), be $p(B) = 1 - p(A) = 1 - p$. In this industry the nature of the control, weak or sloppy, is common knowledge. Hence, there is no uncertainty from the operators’ side about the type of control¹⁵. Both situations are clearly identified.

2.2 The costs structures: infra-comparison between strong and weak control

The nature of control as defined in 2.1.2 impacts on the expected costs of the industry:

- After a major accident, the level of the cap has to be paid deducing the amount of the insurance coverage $Q : c - Q$. Let μ the insurance premium μ this one is equal to $pQ = \mu$, (Shavell (1985)).
- When a strong control is exerted then, in the case of accident, the safe plant has to stop or slow down its activity for checking and this incurs some costs in compliance with assumption 5:

Now, we dispose of all elements to define the cost structure of an individual operator. To make easier the exposition we begin by describing the cost structure of the facility owned by a unique operator.

2.2.1 The cost structure of an individual operator

We will examine successively both cases: the weak and the strong control.

i) *Weak control*

Under a weak control, the regulatory authority does not induce the operator to reduce or to stop the activity level for some deep check after an accident and assumption 5 does not

¹⁵ The question of the probability of a major accident will be considered on a larger scale than the usual question of the melting of the core of a reactor. Indeed, it is the accumulated fission products in a reactor that forms the potential of radiation hazard. The melt down of the core of the reactor induces a severe accident. Safety is to prevent the release of these radioactive products and fuel isotopes. Accidents that issue on massive rejection of such material and threat populations and natural resources are particularly rare events. Indeed, in Western plants, an airtight containment reinforced concrete building (1.2 to 2.4 meters) tends to limit the effect of a melting of the nuclear core. Probabilistic methods (Probabilistic Risk Assessment) are used since the mid-seventies (Murray, 2000). The object is to determine the probability of occurrence of an undesired event such “as core damage, breach of containment, or release of radioactivity, and to determine potential causes” Murray, (2000 p.277). Considering internal relationships, a catastrophic event does not occur suddenly. It supposes a succession of failure and events trees show the probabilistic path from a current incident to the disastrous event. That justifies the use of Bayesian approaches (Chen and Chu (1995)). Studies in the mid-nineties show that the probability of the melting of the core in Europe of the nuclear plant is quite variable and depends on the generation of the power plant.

The ExternE study of 1995 considered a core meltdown probability of 10^{-5} . However, the probability of such an event depends on the nature of reactors that have evolved throughout time following technical progress. Lembrechts, Slaper, Pearce and Howarth (2000) show that the range of probability of core meltdown is comprised between 10^{-3} and 10^{-6} according to the reactor generation. For instance, they report the studies concerning a study on two French reactors, a 900 MW Pressurized Water Reactor (PWR) and a 1300 MW PWR, indicated the following risk probability of a major core meltdown (World Bank, 1991) respectively $4.95 \cdot 10^{-5}$ and $1.05 \cdot 10^{-5}$.

apply. As a consequence, the operator $l, l = 1, 2$ is not affected by the accident suffered by the other plant. He has only to pay the insurance premium μ whatever the state of nature. The entire situation may be described by the following table:

Cost structure of a strictly controlled operator		
States of nature	Cost	Explicit probabilities
$H_1 = (A, A)$	$c + \mu - Q$	p^2
$H_2 = (A, B)$	$c + \mu - Q$	$p(1 - p)$
$H_3 = (B, A)$	μ	$p(1 - p)$
$H_4 = (B, B)$	μ	$(1 - p)^2$
Sum		1

Table 1

Hence, this situation is equivalent to be faced to only two states of nature because the plants are independent one from the other one and the sample set reduces to:

$$\Omega_1 = (A, B), l, l = 1, 2$$

Thus, for the event B, the costs incurred includes only the cost of the insurance premium, μ plus the one of the disastrous event, A, $(\mu + (c - Q))$. The expected costs $EC_l(\bar{S}), l = 1, 2$, for the operator are then:

$$\begin{aligned} [EC]_{l, l}(\bar{S}) &= [p]^2 + p(1 - p)(c + \mu - Q) + \mu[(1 - p)^2 + p(1 - p)] \\ &= p(\mu + (c - Q)) + (1 - p)\mu, \end{aligned} \quad [1]$$

And, after the simplification (where $pQ = \mu$):

$$E_l C(\bar{S}) = pc \quad [2]$$

Consequently, under a weak control (\bar{S}), the expected cost of strict capped liability is equal to the expected cost of the accident mitigated by the cap c .

ii) *Strong control*

As mentioned above, after an accident on one plant, the remaining safe plant will be submitted to some strong costly control and/or breaks. These operations will incur a cost e (following assumptions 4 and 5). Under a strong control, the state $H_1 = (A, A)$ becomes unrealistic and a null probability is associated to it. This explains by the fact that the probability of a major accident is very weak, then, after the checking of the other plant, the probability of a new catastrophic event on it is still weaker. The states $H_2 = (A, B)$ and $H_3 = (B, A)$ which are not symmetric at the individual level deserves some attention. Consequently, if the operator undergoes the accident (event $H_{1,2}$), he will have to pay $(c - Q)$

for repairs, while if his plant is safe, he will incur the opportunity cost e . The entire situation may be described by the following table 2:

Cost structure of a strictly controlled operator		
States of nature	Cost	Explicit probabilities
$H_1 = (A, A)$	$c + \mu - Q$	0
$H_2 = (A, B)$	$c + \mu - Q$	p
$H_3 = (B, A)$	$\mu + e$	$p(1 - p)$
$H_4 = (B, B)$	μ	$(1 - p)^2$
Sum		1

Table 2

The expected costs for the operator $i, i = 1, 2$, $EC_i(S)$ are then:

$$EC_i(S) = 0(c + \mu) + p(c + \mu) + p(1 - p)(\mu + e) + \mu(1 - p)^2 \quad [3]$$

and, as previously by simplifying with $pQ = \mu$, we get:

$$EC_i(S) = p(c + e) - ep^2 \quad [4]$$

We can check that the expected costs of a strictly controlled structure are higher or equal to a weak one, indeed:

$$EC_i(S) \geq EC_i(\bar{S}) \Rightarrow p(c + e) - ep^2 \geq pc \quad [5]$$

This is always true because after developing:

$$e(1 - p) \geq 0 \quad [6]$$

We deduce then the following proposition:

Proposition 1: *Under the assumptions 1 to 5, a unique plant managed by a single operator incurs higher costs when it is strongly controlled rather than when the control is weak.*

(Proof: discussion above).

We can define now the cost structure for the monopolistic situation and compare then both industrial structures.

2.2.2 The monopolistic operator

The distribution of probability corresponding to each kind of control may be summarized in the following tables considering that the insurance premium is $\bar{\mu}$. As before, we will examine both cases: the weak and the strong control.

i) *Weak control*

Under a weak control the monopolist can go on producing energy after a major accident by using his safe plant. Hence, as previously, the plants are fully independent one relative to the other one. We can draw then the following table:

Cost structure of a weakly controlled monopolistic operator		
States of nature	Cost	Explicit probabilities
$H_1 = (A, A)$	$2c + \bar{\mu} - 2Q$	p^2
$H_2 = (A, B)$	$c + \bar{\mu} - Q$	$p(1 - p)$
$H_3 = (B, A)$	$c + \bar{\mu} - Q$	$p(1 - p)$
$H_4 = (B, B)$	$\bar{\mu}$	$(1 - p)^2$
Sum		1

Table 3

The expected costs for the monopolistic operator under a weak control are then:

$$EC(\bar{S}) = (2c + \bar{\mu} - 2Q)p^2 + 2p(1 - p)(c + \bar{\mu} - Q) + \bar{\mu}(1 - p)^2$$

$$EC(\bar{S}) = 2p(c - Q) + \bar{\mu} \quad [7]$$

The expected cost of liability is equal to the expected amount that the operator has to supply for repairs. This corresponds to the level of the cap minus the amount reimbursed by the insurance company plus the premium.

ii) *Strong control*

Under the strong control, assumption 5 applies and the monopolistic operator has to slow down or stop the production of the safe plant. He will incur the opportunity cost ϵ but equally the cost of due repairs. Hence, the table of cost is reproduced in the following:

Cost structure of a strongly controlled monopolistic operator		
States of nature	Cost	Explicit probabilities
$H_1 = (A, A)$	$2c + \bar{\mu} - 2Q$	0
$H_2 = (A, B)$	$c + \epsilon + \bar{\mu} - Q$	p
$H_3 = (B, A)$	$c + \epsilon + \bar{\mu} - Q$	$p(1 - p)$
$H_4 = (B, B)$	$\bar{\mu}$	$(1 - p)^2$
Sum		1

Table 4

The event H_2 means that once an accident has occurred on one plant, the operator has to stop or slow down immediately the activity of the other facility. Then, the payoff is $c + \epsilon + \bar{\mu} - Q$, which occurs with a probability p . However, considering that a specific

plant $i, j = 1, 2$ works “well” with a probability $(1 - p)$ does not prevent, that the other one can fail with a probability p . This explains the state of nature H_3 . This may be seen in the following decision tree.

[insert decision tree 1]

A priori we do not know what plant among plant 1 and 2, which of them will fail. Hence, because they are similar, we consider that Nature (N in the decision tree) chooses with an equal probability $\pi = \frac{1}{2}$ the plant that will incur an accident. Rigorously, the expectation cost should write:

$$EC(S) = \pi[(2c + \mu - 2Q)Q + p(c + s + \mu - Q) + p(1 - p)(c + s + \mu - Q) + \mu(1 - p)^2] + (1 - \pi)[(2c + \bar{\mu} - 2Q)Q + p(c + s + \bar{\mu} - Q) + p(1 - p)(c + s + \bar{\mu} - Q) + \bar{\mu}(1 - p)^2] \quad [8]$$

This writing is justified for plants presenting different risk level. This could be useful for the analysis of different generations for instance where the older generations may be considered as riskier than the younger ones. Here, this is not the case under assumption 1 ($\pi = 1/2$). Then, the expectation costs function writes:

$$EC(S) = (2c + \bar{\mu} - 2Q)Q + p(c + s + \bar{\mu} - Q) + p(1 - p)(c + s + \bar{\mu} - Q) + \bar{\mu}(1 - p)^2 = EC(S) - 2p(c + s - Q) - p^2(c + s - Q) + \bar{\mu} \quad [9]$$

If we compare $EC(S)$ and $EC(S)$ we can see that the advantage of a “weak-control” practice under a monopolistic situation gives not as clear results as in the previous case. Thus, we study conditions for having:

$$EC(S) > EC(S) \text{ or } EC(S) \leq EC(S).$$

Considering $EC(S) > EC(S)$, this means that:

$$2p(c - Q) + \bar{\mu} > 2p(c + s - Q) - p^2(c + s - Q) + \bar{\mu}$$

Or, still after simplifying:

$$p > \frac{2s}{(c + s - Q)} \quad [10]$$

(With $c + s - Q > 0$).

Then, $EC(S) > EC(S)$, this is true if $(c - Q) > s$. We can establish proposition 2:

Proposition 2: *Under assumption 1 to 5, the level of the opportunity costs is essential to determine whether a strict controlled monopolistic organization generates higher expected costs than a decentralized structure. Consequently:*

i) If $p > \frac{2e}{(c+e-Q)}$, then a weak control incurs lesser costs than a monopolistic organization.

ii) If, in the opposite, $p \leq \frac{2e}{(c+e-Q)}$, the monopolistic organization involves smaller costs.

The proof results from the above argument.

2.3 Decentralized vs centralized organization

This section studies the efficiency of both types of organization. This consists in comparing each costs structure according the nature of control. This analysis borrows some feature to the instruments of the contestable market theory in Baumol, Panzar and Willig (1982) because we refer to the sub-additivity of costs. However, our approach is different because we refer here to expected costs and we do not examine the sustainability question, i.e. the possibility for potential entrants to compete on prices. The question we deal with is to know whether it is more costly organizing monopolistically ultra-hazardous activities, or conversely, decentralizing it with independent operators. Here, the cost structure corresponds to the cost of civil liability.

2.3.1 The case of weak control

It is important to note that the insurance premium plays a fundamental role. Indeed, in what follows we shall study the conditions for which the expected cost of the decentralized

structure is either higher or lesser than the monopolist one, i.e: $\sum_{i=1}^n E_i C(\bar{S}) \geq EC(\bar{S})$

or the reverse. $\sum_{i=1}^n E_i C(\bar{S}) < EC(\bar{S})$. It is obvious that the value at which the insurer fixes the level of the premium is determinant for having either the cost of monopolistic organization higher than the decentralized one or the reverse.

Let us assume that: $\sum_{i=1}^n E_i C(\bar{S}) < EC(\bar{S})$. In what follows we consider that the level of the insurance premium of the decentralized organization is given and is equal to $\mu = pQ$.

From the previous definition we deduce that: $\sum_{i=1}^n E_i C(\bar{S}) = 2pc$ and consequently:

$$\sum_{i=1}^2 E_i C(\bar{S}) < EC(\bar{S}) \Rightarrow 2pc < 2p(c - Q) + \bar{\mu}$$

or,

$$\bar{\mu} > 2pQ = 2\mu$$

Then, the condition for the monopolist operator to meet a higher expected cost of accident than under a decentralized structure is that his premium insurance should be more costly than for the individual operators. Otherwise, if $\bar{\mu} = 2\mu$, then, both organizations, monopoly or the decentralization one are equivalent.

Proposition 3: Under a weak control, under assumptions 1 to 5, if insurance premiums are defined proportionally for each plant ($pQ = \mu$ for each individual operator and $\bar{\mu} = 2pQ$, for the monopolist), then the monopolistic and the decentralized organizations generates the same expected costs:

$$\sum_{i=1}^2 E_i C(\bar{S}) = EC(\bar{S}) \quad [11]$$

Proof comes from the previous argument.

We have to note that this result is similar to the case in which insurance is not compulsory and may be set up at $\mu = \bar{\mu} = 0$. Then, it is equivalent to exploit a ultra-hazardous risky park of plants under a monopolistic organization (unique operator) or under a decentralized organization (two independent operators).

2.3.2 The case of strong control

We analyze now the cost structure of the decentralized structure highly controlled. As before, we consider:

$$\sum_{i=1}^2 EC_i(S) = 2(p(c + e) - ep^2) \quad [12]$$

And we compare it with [9] and we determine the conditions for having:

i) Either $\sum_{i=1}^2 EC_i(S) \geq EC(S)$, or

ii) $\sum_{i=1}^2 EC_i(S) < EC(S)$.

Then, let us analyze the relationship $\sum_{i=1}^2 EC_i(S) < EC(S)$, this is equivalent to:

$$2(p(c + e) - ep^2) < 2p(c + e - Q) - p^2(c + e - Q) + \bar{\mu}$$

After developing, this relationship is true if there is $\bar{\mu} > 0$, such that¹⁶:

$$\bar{\mu} > 2\mu + p^*(c + s - Q)$$

This expression means that if the insurance premium of the monopoly is higher than the sum of both the individual operators' premium plus $p^*(c + s - Q)$, which is positive. That means, that it is only if the monopoly gets adverse insurance premium that the relationship

$$\sum_{i=1}^2 EC_i(S) < EC(S)$$

, is verified. Or, putting it otherwise, it is only if the insurance premiums are detrimental for the monopoly compared to the decentralized facilities that the centralized organization incurs higher costs. This is sufficient to establish proposition 4:

Proposition 4: *Under strong control and under assumptions 1 to 5, if insurance premiums are defined proportionally for each plant (i.e. $pQ = \mu$ for each individual operator and $\bar{\mu} = 2pQ$, for the monopolist), then the monopolistic organization incurs lesser costs than the decentralized organization:*

$$\sum_{i=1}^2 EC_i(S) < EC(S)$$

[13]

With a monopolist insurance premium proportionally less than the one of the individual operators (i.e. $\bar{\mu} \leq 2\mu$), then the advantage of the centralized situation is obvious, but this is an “unnatural” position and this result is not in the spirit of this model.

3 Insurance and effort

The above results are reached under the assumption that probabilities of a major accident are given. However, by increasing or decreasing the effort dedicated to improving safety, the operators may influence the level of risk: the operators may lower the accident probability by taking due care.

To deal with this point we adopt the Shavell (1986)'s presentation. Let x be the operator's level of safety effort, $x \geq 0$. The probability of accident modifies as x varies: $1 > p(x) \geq 0$, $p'(x) < 0$ and $p''(x) > 0$. In the following, the analysis is restricted to the more realistic situation of a strong control.

¹⁶ Remember that $2pQ = 2\mu$

The counterpart to the purchase of liability insurance is that the insurance company demands to the operator the highest level of care. Because of the specificity of the electro-nuclear production, it is not unrealistic to assume that asymmetric information between the operator and the insurance companies are almost impossible. Indeed, at all moment the insurance company can check the level of safety. The expected costs functions are modified, considering that the operators are risk neutral we represent the cost structure of a facility owned by a single operator by the following table:

Cost structure, strict control, one facility and one operator		
States of nature	Cost	Explicit probabilities
$H_1 = (A, A)$	$c + \mu + x - Q$	0
$H_2 = (A, B)$	$c + \mu + x - Q$	$p(x)$
$H_3 = (B, A)$	$\mu + s + x$	$p(x)(1 - p(x))$
$H_4 = (B, B)$	$\mu + x$	$(1 - p(x))$
Sum		1

Table 5

And, the second one, the monopolistic cost structure:

Cost structure of a strongly controlled monopolistic operator		
States of nature	Cost	Explicit probabilities
$H_1 = (A, A)$	$2c + x + \bar{\mu} - 2Q$	0
$H_2 = (A, B)$	$c + x + s + \bar{\mu} - Q$	$p(x)$
$H_3 = (B, A)$	$c + s + x + \bar{\mu} - Q$	$p(x)(1 - p(x))$
$H_4 = (B, B)$	$\bar{\mu} + x$	$(1 - p(x))$
Sum		1

Table 6

We assume that the monopolist spends the same amount x for care in for the whole park. From each one we draw the expected cost of civil liability. Consequently, for the “decentralized” operator:

$$\begin{aligned}
 EC_d(x) &= p(x)(c + x + \mu - Q) + p(x)(1 - p(x))(\mu + s + x) + (\mu + x)(1 - p(x)) = \\
 EC_d(x) &= x + \mu + p(x)(c + s - Q) - sp(x)^2
 \end{aligned} \tag{14}$$

And for the monopolist operator:

$$\begin{aligned}
 EC_m(x) &= p(x)(c + x + s + \bar{\mu} - Q) + p(x)(1 - p(x))(c + x + s + \bar{\mu} - Q) + (\bar{\mu} + x)(1 - p(x)) = \\
 EC_m(x) &= x + \bar{\mu} - (c - Q)(-2 + p(x))p(x)
 \end{aligned} \tag{15}$$

We can check that these functions are convex. They decrease for low values of x and increase as x grows because $1 \geq p(x) \geq p(x)^2 > 0$ and for high values of x , $p(x)$ and $p(x)^2$ tend to 0. This element is important to determine what structure will give the highest level of safety. This can be done directly by considering that the level of the premium is identical for both organizations i.e. $\bar{\mu} = 2\mu$. To make a fair comparison between these structures, we assume that the two plants in the decentralized structure are gathered but keep their management autonomy. We study then two conjectures. Concerning the first one, the insurance premium is given and the operators have to adapt x to it. Concerning the second one, while in the second one, the insurance policies is adapted to the care level supplied by operators, i.e; $\bar{\mu}(x) = p(x)Qn$, (for $n = 1,2$).

3.1 The insurance premium is given

We can set up the following proposition:

Proposition 5: *Under assumptions 1 to 5, when civil liability is ruled by a capped liability regime, a monopolistic organization induces a higher level of care than a decentralized one in so far that the value of the cap is such that $c - e - Q > 0$. If x_f^* and x_ϕ^* , represent respectively the optimum effort level of the decentralized and the centralized organization, then $x_f^* < x_\phi^*$.*

Proof:

We replace the expected costs functions respectively by

f and φ such that:

$$f(x) = EC(x) = x + \mu + p(x)(c + e - Q) - e [p(x)]^2, \quad i = 1,2.$$

For the decentralized structure, and:

$$\varphi(x) = EC(x) = x + 2\mu - (c - Q)(-2 + p(x))p(x)$$

for the monopolist organization.

We can check that $\varphi(x)$ and $f(x)$ are related each other:

$$\varphi(x) = f(x) + \mu - (c - e - Q)(-1 + p(x))p(x)$$

Then, considering that if x_f^* is that level of effort such that cancels $f'(x_f^*) \leq 0$, with equality for $x_f^* > 0$, then:

$$\varphi'(x_f^*) = 0 + (c - e - Q)(1 - 2p(x_f^*))p'(x_f^*)$$

If $x_f^* < x_\phi^*$ where x_ϕ^* is that optimal effort level which minimizes $\varphi(x)$ it sufficient to show that $\varphi'(x_f^*) < 0$. This means that the monopolist situation supplies a higher optimal level of effort than the decentralized situation and the reverse if $x_f^* \geq x_\phi^*$. Indeed, as $\varphi(x)$ and

$f(x)$ are increasing functions, if $\varphi'(x_f^*) < 0$ when $f'(x_f^*) = 0$, then $\varphi(x_f^*)$ has not yet reached its minimum level. This will be done for $x_\phi^*, x_\phi^* > x_f^*$.

Now, we examine the conditions for which:

$$\varphi'(x_f^*) < 0 \rightarrow \varphi'(x_f^*) - (c - s - Q)(1 - 2p(x))p'(x_f^*) < 0$$

this expression is verified if $1 - 2p(x) > 0$, this means that $\frac{1}{2} > p(x)$, this by knowing that $c - s - Q > 0$ (the cap is supposed to be higher than the cumulated value of the opportunity cost and the level of the coverage) and $p'(x_f^*) < 0$ (assumption on the density of the probability distribution). This last condition is easily checked because $p(x)$ is very small. Nobody will take the risk to invest in the electro-power generation with a risk of major failure such that $\frac{1}{2} \leq p(x)$. Hence, $\varphi'(x_f^*) < 0$, for $\frac{1}{2} > p(x)$. As a consequence, $x_\phi^* > x_f^*$ and the proposition 5 is verified.

3.2 Variable insurance premium according the level of care

Now we consider the situation in which the insurance adapts its premium to the level of effort of the agent: $\mu(x) = Qp(x)$ and $\bar{\mu}(x) = 2Qp(x)$. we apply the same argument as previously. That means that the insurance premium depends on the level of effort achieved by the operators. We draw the following proposition:

Proposition 6: Under assumption 1 to 5, under a capped liability regime, and when the insurance premium is defined proportionally to the level of care x , where $\mu = Qp(x)$ and $\bar{\mu} = 2Qp(x)$, then the monopolistic organization induces a higher level of care than the decentralized organization, i.e. $x_f^* < x_\phi^*$, where x_f^* and x_ϕ^* , are respectively the optimum effort level of the decentralized and the centralized organization.

Proof: As previously, we define respectively the following functions $\varphi(x)$ and $f(x)$ as:

$$\varphi(x) = p(x)(c + x + s + 2Qp(x) - Q) + p(x)(1 - p(x))(c + x + s + 2Qp(x) - Q) + (2Qp(x) - Q)p(x)$$

$$f(x) = p(x)(c + x + Qp(x) - Q) + p(x)(1 - p(x))(Qp(x) + s + x) + (Qp(x) + s) \mathbb{1}(1 - p(x))$$

As previously, we express $\varphi(x)$ as a function of $f(x)$:

$$\varphi(x) = f(x) + cp(x) + sp(x) - cp(x)^2 + Qp(x)^2$$

and we seek for the first derivative function:

$$\varphi'(x) = f'(x) + cp'(x) + sp'(x) - 2cp(x)p'(x) + 2Qp(x)p'(x)$$

As before we calculate $\varphi'(x_f^*)$ with x_f^* such that $f'(x_f^*) = 0$:

$$\varphi'(x_f^*) = 0 + (c + e - 2(c - Q)p(x_f^*))p'(x_f^*)$$

It can be shown that this value is negative. Indeed, $p'(x_f^*) < 0$, and $(c + e) - 2(c - Q)p(x_f^*)$ is positive. To see that, let us note that $p(x_f^*)$ is always positive or null, hence we have to define, the conditions for which:

$$c + e > 2(c - Q)p(x_f^*) \Rightarrow \frac{c + e}{2(c - Q)} > p(x_f^*)$$

This condition is always verified because $c > Q$, and $c, e > 0$, the insurance company cannot allocate more than the cap. Consequently, $\varphi'(x_f^*) < 0$, and $\varphi(x)$ has not reached its minimum, at x_f^* then $x_f^* < x_\phi^*$. The centralized structure ensures a higher level of safety compared to the decentralized organization.

Remark : The insurance premium question: The previous results have been reached without specific assumptions on the level of the insurance premium. More precisely, it has been assumed that the level of insurance is identical whatever the competitive structure. This subject is becoming highly sensitive between authors who think that the level of insurance premium is considerably too high, taking account of the level of effective coverage (Faure and Fiore (2008)) and authors who considers that this premium is too low because of an insufficient level of exposure from the insurance company side (Caroll, and Froggart, (2007)). Implicitly, we have admitted that the premium is equal to $\bar{\mu} = p Q n$, where n is the number of station as in Faure-Fiore (2009). However, we are not led to bring some judgment about the actual level of insurance premium of real companies. Indeed, our analysis considers only that under similar and proportional insurance premium the cost of safety is lesser under a centralized system than under a decentralized one. Our results are depending on the relationships between the amount of c, e and Q . Two of these values are depending on decisions of the Authorities, the amount of the ceiling c and on the combined choices of the insurance market and the insurance corporations i.e. the level of Q . Hence, if the lag between c and Q is sufficiently thin such that $c - e - Q < 0$ then $\varphi'(x_f^*) > 0$ and with the same argument than above, $x_\phi^* < x_f^*$, i.e. the decentralized structure insures a better safety. This point is important. Indeed, it means either that the insurance companies accept to increase their share in compensation or that the level of the ceiling is diminishing. We recall that this level may be such that $0 \leq c \leq D$. Hence, the lesser the level of the cap, the larger is

the road for a decentralized organization. However, as seen in the first paragraph (see also Carroll, and Froggart, (2007)), the landslide tendency is to increase the level of caps.

The question of the negative value of $(c - Q) - e$, however, has to be considered seriously. Indeed, it corresponds to the increased resort to private insurance due to the pooling of insurers as Pelzer (2007, p.55) shows it by underlining the US and the German experiences. We can quote it: *“The operators’ pooling systems established in Germany and in the US prove their capacity to deploy many times the amounts required under the revised nuclear liability conventions and in particular the amounts offered by the insurance industry. The money will be provided to cover the legal liability of the operator liable without excluding certain risks from coverage”*.

Consequently, when the lag between c and Q diminishes (for e given), then the decentralized structure may become more efficient than the centralized one.

4. Conclusion and Policy recommendations

The objective of public authorities is to insure the best safety coverage of populations against the risks of the electro-nuclear industry. We limited our model to assess the cost of safety only, letting aside the working costs of this industry. We show that a natural monopoly organization generates higher care level than a decentralized management. This involves inducing dispersed operators to cluster them together. It is then the interest of the new structure to minimize its expected global safety and damage costs. This is done by increasing the level of safety expenses (proposition 6). As a corollary, the condition for increased safety is a high level of control from the regulatory authority side. Hence, the more stringent are becoming the Regulatory Authority, the more they favor scale economies (proposition 4). The above results are independent of a privatization concern because in the nuclear sector, many ways can be invoked to privatize the production park. For instance, the stations can be privatized as separate entities, which may not be a viable competitive scheme. The safer scheme is then to consider that privatization may be achieved through the transfer of shares of a unique portfolio to different partners. Hence, this analysis has specifically focused on the question of the advantages of splitting the exploitation of a nuclear park independently of the question of privatization of assets.

If it is impossible to maintain a centralized structure, then a decentralized organization should be accompanied by deep changes in the insurance infrastructure. Indeed, this one

should favor an increase of the involvement of insurances and re-insurance companies. This is shown in the final remark of section 3. This result joins the contemporaneous trend that tends to extend the cover by insurance companies in this ultra-hazardous sector.

These proposals could bring some confusion without more explanation. Indeed, the previous results do not mean that considering concrete present situations, the safety level of decentralized structures shows inefficiencies in so far that they comply perfectly with the actual norms of the regulatory authorities. Precisely, our argument means that if, for instance, safety standards have to increase, then as a consequence, they require more care effort (this lead to diminish theoretically the probability of an accident) whereas safety costs are near the equilibrium level x_f^* . Then the centralized monopolistic organization generates lower equilibrium costs compared to a decentralized one.

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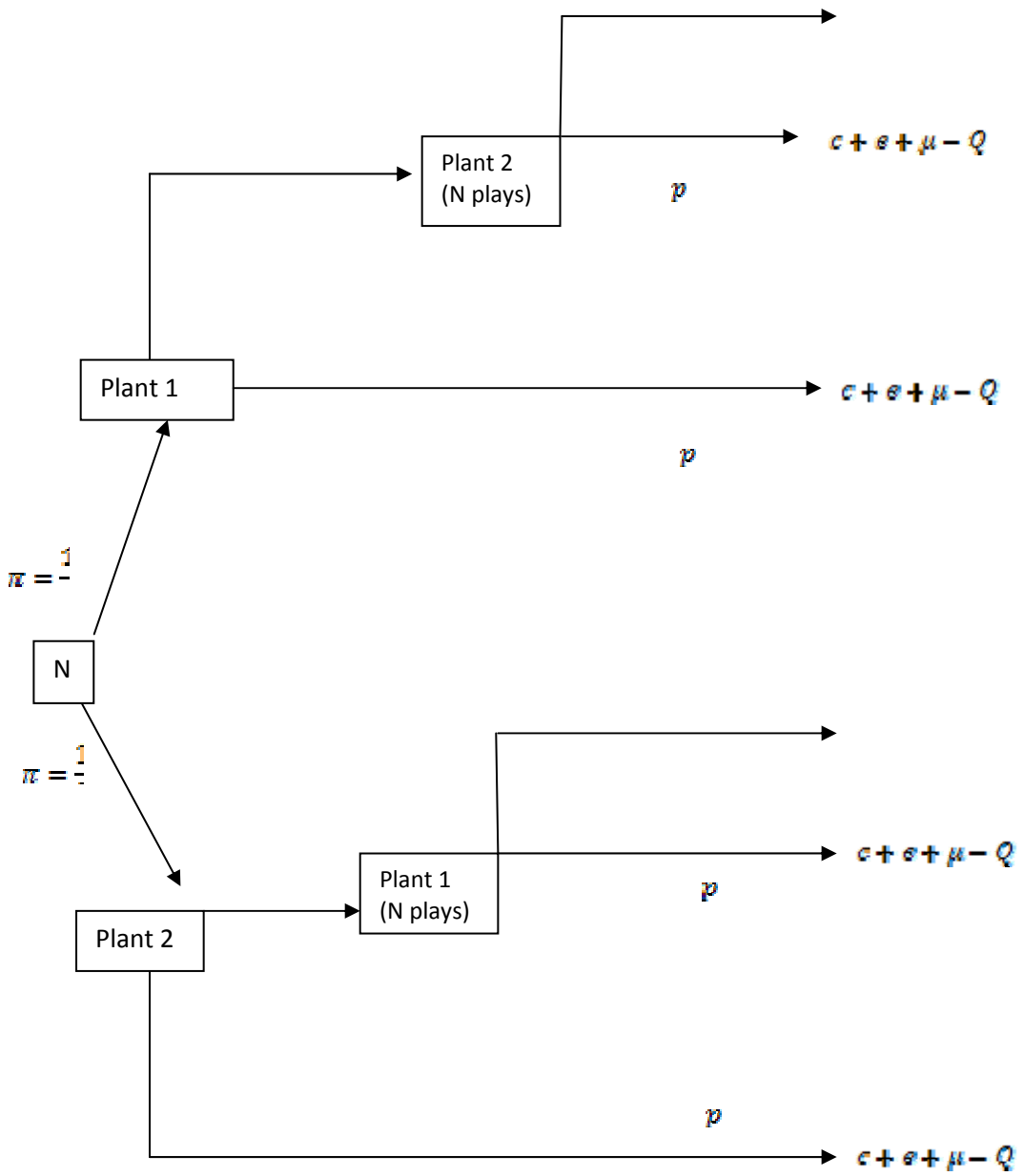
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