Evaluating the effect of local monitoring on nuclear safety: evidence from France*

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Abstract

This paper empirically studies the deterrence effect of monitoring intensity on safety care and compliance with a self-reporting mechanism. To do so, we analyse the consequences of a policy requiring French Departments to subsidize local commissions whose role is to monitor nuclear stations and to communicate with local populations. Our analysis uses a dataset of safety incidents reported by French nuclear stations between 2008 and 2015, and data describing the annual budgets of their monitoring agency. We address the endogeneity of the indirect measurement of local monitoring intensity by using forecasting errors in Department-level operating budgets as an instrumental variable. Contrarily to a large part of the literature on enforcement and compliance, we also account for the possibility of non-detection of non-compliance by plant managers, and disentangle the effects of the policy on safety care and on non-compliance with self-declaration guidelines. We find that plant managers react to informational incentives: although we observe no significant increase in safety care, we find significant increases in compliance with declaration criteria: a 2.000 € increase in the annual budget of a local commission leads, on average, to a 1% increase in the total number of events reported.

Keywords: nuclear power, safety, threat of regulation, local monitoring, transparency, incident data.

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1 Introduction

In the context of environmental regualtion, informational policies such as public disclosure of information have been shown to increase the compliance of polluting firms with existing environmental regulations, and to decrease their levels of emissions (see e.g. Shimshack (2014) for a review). In this paper, we investigate whether these results carry forward to the nuclear industry, in which standard-based safety regulations are similarly implemented by centralized safety authorities, which deter non-compliance by conducting audits and levying penalties on non-compliant facilities. In addition to this classical command-and-control safety regulation, France implements since 2006 an informational policy by which Departments[1] hosting nuclear stations have to subsidize local commissions, who monitor the activity of their local nuclear station, and can communicate with the local population on the results of this monitoring.[2] We empirically study the effect of this monitoring policy on the decision of local plant managers to exert safety care and to comply with self-declaration criteria in the French nuclear industry.

Despite the importance of this question, it has remained largely unanswered by the literature. Its empirical evaluation is hampered by three major problems. The first one, inherited by the general specifics of empirical evaluation of nuclear safety, is the one of data scarcity. In particular, severe nuclear accidents are very rare, so that proper statistical analysis in this context is hardly available. The literature has dealt with this issue by either using Bayesian methods in the context of technical probabilistic risk assessment (Rangel and Lévêque, 2014), or by using extended sets of accidents from both nuclear power plants and fuel-cycle facilities (Sovacool, 2008; Hofert and Wüthrich, 2011; Burgherr and Hirshberg, 2014; Wheatley et al., 2016). The second problem stems from the unobserved nature of non-compliance. Non-compliance is economically meaningful only if perfect observability of the behaviour of the agent by the principal is not feasible. A first solution to this problem is to study detected non-compliance, as is done in

[1] France's administration is organized in several levels below the national government. The French territory is first divided into thirteen administrative regions. Regions are then divided in a total of a hundred Departments, which are divided in over thirty-six thousands counties.

[2] Most of these Departments had already created such agencies before 2006, on a voluntary basis. The law made the existence of these agencies mandatory in all Departments hosting either nuclear reactors or fuel-cycle facilities.

Feinstein (1989). In our case, detected non-compliance is not observable to the econometrician. This implies that the information contained in observed reporting behaviours is ambiguous, as it is affected by both safety care and non-compliance. Finally, the intensity of the monitoring of an agent may be partially determined by how safe the agent is perceived by the principal. As a result, safety care and non-compliance are determined jointly with the intensity of the monitoring, which might induce a simultaneity bias in the estimation.

We contribute to the literature on nuclear safety and non-compliance in several ways, with a particular focus on the three aforementioned problems. First, we use a rich novel dataset on declared safety incidents in French nuclear power stations. These incidents, although of small magnitude, consist in deviations from the safety standards and operation guidelines set by the French safety authority. They are therefore considered as significant for nuclear safety.[3] The declaration of these events by plant managers to the safety authority is mandatory. Yet, these events may remain undetected, and managers face countervailing incentives when choosing whether to report detected events. Reporting an event may be costly to the manager, for instance if his salary is based on the safety performance of the plant, or if he has to incur some cost after the declaration in order to redeem compliance. Not reporting an event can be costly as well, in case of a public backlash or in case of more stringent regulations. To perform our analysis, we also use data on the monitoring exerted by local commissions between 2008 and 2015. This local monitoring can be more or less thorough, as Departments in charge of subsidizing local commissions provide them with very heterogeneous levels of resources. As a result, the intensity of the monitoring performed by these commissions may vary from organizing meetings with local managers where safety issues are discussed, to hiring independent experts to assess, for instance, the environmental impact of the operation of the power station. We use the annual budget of each commission as a measure of the intensity of their monitoring activities. The rich heterogeneity in the size of these budgets provides a powerful source of identification.

[3] Through probabilistic risk and reliability analyses - a process of case-by-case scenario analysis performed by the operator and the regulator - an incremental probability of nuclear core meltdown is associated to each of these events.

Second, to disentangle the effects of local monitoring on safety care and non-compliance with declaration guidelines, we present a formal model for the behaviour of plant managers adapted from the environmental literature (see e.g. Evans et al. (2009); Gilpatric et al. (2011)), in which the decisions to exert safety care and to comply with declaration guidelines are jointly determined by the perceived sanction incurred by the manager when reporting an event, and the expected penalty faced when non-reporting. We derive testable hypotheses from this model and test these by using several observables such as specific or general counts of reported safety events, and nuclear reactor reliability indices. In particular, in a strategy related to Hausman (2014), we look at automatic shut-downs of reactors, a type of events that is perfectly detected by managers and reported to the authority due to the resulting changes in the production of electricity. As non-compliance with declaration guidelines is not possible for this subset of events, the effect of local monitoring on the sanction perceived by managers is identified. In a second step, the estimated effect of monitoring on safety care can be measured by observing evolutions of the reliability of nuclear power plants. Finally, conditionally on the results of the former regressions, we can identify the effect of monitoring on compliance by measuring the effect of monitoring intensity on the reports of significant safety events.

Third, we address the endogeneity of the measurement of monitoring intensity by using an instrumental variable (IV). Our instrument is based on the difference between the forecast and the realized annual operating revenues of the French Departments. This forecasting error has several attractive features. First, a forecasting error, once realized, might lead to a reassessment of the forecast for the current or coming fiscal year, and thus induce a change in the budget of the monitoring commissions. Second, such a forecasting error is almost per definition unanticipated, which prevents endogenous forward-looking behaviour of the local authorities. Finally, the source of the error is simply a financial miscalculation due to overall uncertainty or human failure related to tax returns, and thus it can be argued that it is not related to the unobserved factors affecting compliance and safety at the level of nuclear power stations. The second and the third property of these errors qualify them as a quasi-natural experiment. This instrumental variable is similar in spirit to the natural experiment used in Bressoux et al. (2009), who utilise random administrative mistakes to instrument for the endogenous assignment of teachers to schools in France.

To the best of our knowledge, Davis and Wolfram (2012), Hausman (2014) and Feinstein (1989) are the only papers that analyse the impact of economic incentives on nuclear safety and non-compliance. Davis and Wolfram (2012) and Hausman (2014) identify the effect of market deregulation in the U.S. on the reliability and safety levels of some US nuclear reactors. The proxy used in Hausman (2014) for safety consists of automatic reactor shut-downs and is thus closely related to our identification strategy. Likewise, our use of reliability indices is similar to the empirical assessment performed by Davis and Wolfram (2012). Our main focus, however, is on non-compliance instead of safety and we use the reliability indices and counts of automatic shut-downs only to disentangle the effect of monitoring on safety care from its effect on non-compliant behaviours in a back-door-identification-type strategy. Feinstein (1989) uses data on inspections of US power plants to study the factors of non-compliance and the effect of non-compliance on safety. His identification depends crucially - much in the spirit of the time in which his paper was written - on strong parametric assumptions on the distribution of the unobservables. These assumptions, however, are not guided by economic theory and are in this sense rather arbitrary.

More generally, within the literature dedicated to monitoring on compliance, our paper is closely related to the work of Duflo et al. (2013) and Telle (2013), who use randomized controlled trials to assess the effectiveness of monitoring programs on self-reporting behaviours. Telle (2013) studies the effect of deterrence on self-reporting, and shows that whereas specific deterrence (e.g. fines) does increase self-reporting, an increased frequency of audit does not. Duflo et al. (2013) show that preventing conflicts of interests in audit mechanisms leads to less non-compliance and more mitigation efforts. In the environmental literature, another related paper is Lin (2013), who assesses the effect of increases in the probability of being monitored on mitigation efforts and truthful self-reporting, using rainfalls as an instrument for the monitoring probability. Compared to these three papers, we investigate similar questions in a different industry, and use an instrumental variable different from the one used in Lin (2013), and instead of a randomized experiments. We also contribute to this literature by introducing possible non-detection of events by the firm and imperfect audit results for the regulator.

Our main results are that nuclear plant managers react to informational incentives provided by this French local monitoring program. These incentives do not induce increases in safety care, but significantly reduce non-compliant behaviours. In particular, a 2.000 €increase in the annual budget of a commission leads local managers, in expectation, to increase by 1% their level of compliance with declaration guidelines. Our results are robust to a variety of specifications. While the non-significant impact of monitoring intensity on safety care contradicts the findings of Hausman (2014) and Duflo et al. (2013), the positive effect on compliance is in line with the findings of Feinstein (1989); Telle (2013) and Duflo et al. (2013).

2 Institutional setup

2.1 Nuclear-power safety in France

The French nuclear fleet is constituted of 58 reactors, located in 19 sites, owned by a single utility, EDF. Nuclear safety is regulated by the Nuclear Safety Authority (ASN in the following) who sets technical and procedural standards regarding the construction, operation and maintenance of the nuclear reactors. In addition, the safety authority sets declaration criteria. Each criteria corresponds to a class of situations considered by the authority as significant for safety. The detection of any of these situations has to be declared to the authority by the power station managers. This declaration mechanism aims to foster knowledge spillovers across reactors, and to detect generic design weaknesses or organizational failures.

Non-compliance with this self-reporting mechanism is deterred by the use of periodic and random inspections by ASN inspectors. During these inspections, inspectors access the paperwork describing the many situations detected by plant managers but not considered significant enough for self-reporting. The firm can be prosecuted for failing to declare significant safety events. Anecdotal evidence confirms the fact that failing to declare safety events can be costly for plant managers, as the French station Fessenheim was invaded by Greenpeace activists in 2014, after it became public that its managers had understated the magnitude of an incident that happened earlier that year.

These safety events are interesting to the econometrician in many respect. First, reports have been consistently stored in a unique dataset since 1972[4]. In addition, safety incidents are much more numerous than large scale accidents, although their consequences are much less severe. These events thus offer the possibility to conduct more robust statistical analyses than previously available sets of nuclear events, which were either restricted to a small number of similar events (see e.g. Rangel and Lévêque (2014)) or extended to a larger quantity of events of various nature occurring in both power stations and fuel cycle facilities (see e.g. Sovacool (2008); Burgherr and Hirshberg (2014); Wheatley et al. (2016)). Finally, reports of safety events capture the incentives faced by nuclear plant managers, who have to decide how much effort to dedicate to the limitation of their numbers, and whether to report them to the safety authority.

Though, the incentives faced by plant managers to exert effort to limit the occurrences of safety events, and to declare these occurrences truthfully when detected, are unclear. Managers first face the consequences of the sanctions they may incur when they declare safety events, for instance if their salary is indexed on the safety performance of the station, or if reporting an event requires to invest money or time in order to comply with the safety authority's standards. On the other hand, not declaring a safety event may also be costly to the manager, due to the possibility of undergoing prosecution if the authority discovers the event covered up, or in the event of a public backlash against the power station due to the lack of transparency of its managers. The existence of these countervailing incentives is important in our set-up, as we aim to assess the effect of a monitoring policy on the behaviour of local plant managers. To address this obstacle, we first describe in the next paragraphs the organization of the French local monitoring commissions, and the way they may interplay with reporting of safety events. In the next section, we present a theoretical framework that formally captures local monitoring and incentives for self-reporting, and enables the identification of our estimation results.

[4]The dataset was constituted in 1995, but previous events were added to it progressively.

2.2 Local monitoring

In a note circulated in 1981 to local prefects[5], the French Prime Minister argued in favour of the creation of local commissions dedicated to the monitoring of risky energy generation facilities and to the information of the public regarding industrial activities prone to large risks[6]. At the time, this suggestion aimed to promote a sharing of responsibilities among local collectivities and the State regarding the information of populations about the nuclear risk[7]. In 2006, a law made the existence of these monitoring commissions compulsory in all French Departments hosting nuclear power reactors or fuel cycle facilities.

These monitoring commissions are composed of four groups of members: local elected officials (city mayors or regional counsellors), members of local environmental associations, members of the nuclear plant workers unions, and competent inhabitants, such as scientists, doctors or professors.[8] These members are not remunerated for their participation, and some restrictions regarding the composition of the commissions are set by the 2006 law. Elected officials must represent at least 50% of the commission, while each of the other three groups has to constitute at least 10% of the members.

Multiple activities are undertaken by these commissions. First, each commission organizes at least two meetings a year, during which plant managers and the safety authority present the main actions undertaken in the nuclear station to the commission. Commission members are provided with a set of documents regarding the operation of the nuclear facility to prepare the meeting, and may ask for specific topics to be addressed during the meetings. In particular, they receive an account of the occurrences of significant safety events within each reactor of their local station. Local commissions can also hire independent experts in order to carry out independent assessments of some aspects of the operation of the plant. Most frequently, these commissions investigate the

[5]Within the organization of the French territory, prefects are the local representatives of the State

[6]This occurred one year after the Saint-Laurent-des-Eaux partial core melt down, and two years after the Three-Mile-Island nuclear accident.

[7]The original note authored by Prime Minister Pierre Mauroy (in French) can be downloaded on this website: http://www.cli-gravelines.fr/Services-en-ligne/Espace-documentaire/Documents-a-telecharger/Les-textes-reglementaires/Circulaire-MAUROY-du-15-decembre-1981.

[8]Additional examples can be found on the website of the commission of the Paluel and Penly nuclear power stations.

environmental impacts of the operation of the station, for instance through radioactivity measurements in local water streams.

Monitoring commissions can also foster the diffusion of information by inviting the press to their meetings. Some commissions also publish contents on dedicated websites, or by distributing journals in city halls, or by mailing information letters to neighbouring populations. A minority of commissions even organize additional open meetings for interested local inhabitants, and invite local populations from neighbouring countries[9]. These commissions can finally make public statements regarding decisions made by the plant managers or by the safety authority.

These commissions are funded by the French Departments, as well as by the Nuclear Safety Authority. The law does not set any requirements on the amount of money granted to these commissions. Therefore, the ASN's policy regarding these funding consists in matching, for each commission, the endowment granted by its Department. Hence, local commissions obtain very heterogeneous budgets, which span between 5,000 €/year to more than 190,000 €/year. Due to these variations in endowments, some commissions can afford to mandate costly, independent investigations on the environmental impacts of the operation of the station, and to advertise their results to local populations, while other commissions can barely afford to organize two meetings a year.

By exerting monitoring and information disclosure activities, local commissions may modify the costs faced by nuclear plant managers when reporting, or failing to report, safety events. Yet, as has been shown in the literature dedicated to environmental regulation through self-reporting mechanisms, the change in incentives induced by increased sanctions (e.g. the cost of reporting a non-compliant situation) or increased penalties (e.g. the expected cost of hiding a non-compliant situation) can be quite different. In particular, if increases in sanctions and penalties should theoretically lead to unambiguous increases in safety care, they may have countervailing effects on the decision to comply with self-reporting guidelines. Therefore, the aim of this empirical paper is twofold. First, we want to assess whether the activities of this commissions, measured by their annual

[9]Since 2015 and France's new energy transition law, the organization of a third meeting, open to the public, is mandatory for each commission. But as this law has not been implemented yet, the existence of these public meetings is out of the scope of our study.

budgets, influences the behaviours of nuclear plant managers. If so, we also want to investigate how they influence these behaviours. In particular, we want to disentangle the effort exerted by managers in order to improve the safety of their power station from their decision to comply with declaration guidelines when they detect significant safety events.

2.3 Data collection

In order to shed light on these questions, we gathered data from three sources: the French Nuclear Safety Authority, the French utility EDF, and fourteen local commissions in charge of the monitoring of the nuclear power stations. Our unit of observation is set at the level of the reactor-year. In other words, our variables describe the operation of a reactor during a particular calendar year. Our dataset consists in an unbalanced panel of 234 observations of reactor-years, spread across 50 different nuclear reactors and the years 2008 to 2015. As the French fleet contains 58 nuclear reactors, the largest possible dataset that we could have gathered over the same time period would have contained 464 observations. This missing data issue is mostly due to the fact that many commissions could not provide us with financial data prior to 2010. The following paragraphs describe our different variables as well as their sources.

We first gathered data describing the activities of local monitoring commissions. This dataset was constituted based on the annual activity reports of these commissions, which contain information regarding their annual budgets, e.g. the endowment received from the Department councilw and the subsidies granted by the ASN. We also retrieved information regarding the administrative statuses and composition of the commissions. We finally gathered data regarding the frequency of their meetings, and whether these meetings are open to the press or the public. We also counted the independent studies mandated by these commission. Finally, we identified the commissions which have multiple facilities to monitor, as some nuclear sites in France host more than one nuclear facility.

The annual budgets of local commissions is used in order to capture the intensity of their monitoring activities. We deem this variable to be a good proxy for the intensity of the commissions as these budgets are used to finance environmental impact assessments by independent experts, in order to train commission members, or to widen the diffusion of the information gathered by these commissions. All of these actions suggest an increase in the potential cost for the manager of the monitoring activities conducted by these commissions.

As a proxy for nuclear safety, we use a dataset obtained from the French Nuclear Safety Authority which contains the significant safety events reported by plant managers. Although these events only have minor consequences, their number is substantially larger than the number of nuclear accidents. This dataset indeed contains over 19.000 safety events, declared between 1972 and 2015 in currently operated power stations. Nevertheless, we will restrict this dataset to the period 2008-2015, in order to match our data regarding the local commissions' activities.

Within this dataset, we focus on counts of events annually reported in the French reactors. In order to implement the identification strategy described in the following section, several counts of events will be considered: the count of all events declared during a reactor-year (ALL), and specific counts of events declared during a reactor-year, such as automatic shut-downs (ASD) or unplanned uses of safeguard mechanisms (SFG). These two types of events were identified jointly with the safety authority as being subject to perfect detection and declaration, a property which we will use to disentangle the effect of monitoring intensity on safety care and compliance with declaration guidelines. Automatic shut-downs have an impact on the electrical output of the power station, and are thus impossible to hide. Events requiring the use of safeguard mechanisms are deemed particularly severe and easy to detect by the authority.

In order to control for the various differences across reactors that may also explain the occurrences of safety events, we rely on two datasets obtained from the Nuclear Safety Authority and the French utility EDF. These datasets contain detailed information regarding the annual production levels, as well as information regarding the reliability of nuclear reactors. In particular, we use data on the annual length of maintenance activities conducted in each reactor, and data on the quantities of electricity lost due to unplanned maintenance or fortuitous stops.

In addition, we construct several variables that account for the history and technological design of the reactors. We first construct an age variable that describes the age of a reactor during the calendar year of observation. Age is defined here as the duration between observation and the year of connection of a plant to the electricity grid.[10] We also construct three design-fixed-effects dummy variables that match the three power plant designs that coexist in the French fleet. In order to capture possible learning-by-doing effects, we finally construct dummy variables which identify the first reactors built within each nuclear site and the first reactors built within the groups of reactors sharing a common plant design.

In the following section, we describe the identification issues that prevent us from directly assessing the effect of observed budgets on observed declarations of significant safety events, and describe a strategy allowing to overcome these issues.

3 Identification strategy

3.1 Safety care and compliance

3.1.1 Some stylized facts

In the following paragraphs, we propose a theoretical model that captures the incentives faced by a plant manager when deciding to exert safety care and to comply with self-reporting criteria. We only model the best response of the manager to an exogenous regulation mechanism embodied by a sanction for reporting and an expected penalty faced when deciding not to report a significant safety event. Contrarily to the existing theoretical literature, we do not model explicitly the optimization problem of the regulator, or that of the public planner deciding on the budget to grant to local monitoring commissions. This second part of the problem is irrelevant in our context, as our empirical estimation will consist in using an instrumental variable to assess the effect of exogenous changes in monitoring intensity on the behaviour of plant managers.

Hence, suppose first that an agent (the manager) operates a nuclear power reactor

[10] Other possible definitions of the age of a reactor is the time since the beginning of its construction, the time since the first divergence of its nuclear core, or the time since its first sale of electricity.

subject to safety standards and to a self-reporting mechanism enforced by a principal (the safety authority). Upon the detection a situation of non-compliance with a safety standard, the agent can declare this situation, and face a sanction for non-compliance. In the environmental literature, this sanction is usually thought of as a tax on reported emissions. In the context of nuclear power, this sanction may for instance consist in the cost of repairing equipments or adapting procedures in order to redeem compliance.

The manager may also decide not to declare the detected non-compliant situation, to avoid the sanction. In order to deter this behaviour, the safety authority audits the agent with a given probability, and levies a penalty when unreported situations are found. The probability of inspection can be thought of as the frequency of planned audits, or as the probability of undergoing unplanned inspections. The penalty embodies the consequences of non-declaration, such as public backlashes, increases in regulatory oversight, or a temporary shut-down of the power station. In addition, as inspectors have limited time to perform their inspections, we will assume that audits do not perfectly reveal all unreported situations.

Finally, the agent may fail to detect some non-compliant situations that occur in his power station. This may be due to imperfect knowledge of his equipment, or to limited time spent trying to detect these situations. We will consider here that the agent knows that he fails to detect some events and that these undetected events may be discovered by the principal during audits. Yet, given the nature of the reporting mechanism, we assume that the agent cannot report an event which he did not detect.

It is to be noticed that we forego the fact that all nuclear plant managers work for a single firm. We neglect this feature because many decisions related to the operation and safety of French power stations are delegated to the management of each nuclear station. For instance, it is the case for the decision to report the detections of significant safety events. Likewise, the inspections conducted by the safety authority are organized by seven regional subdivisions of the regulator, which are responsible for at most 4 stations. Investigating the existence of collective incentives affecting each manager's decisions is left for future research.

3.1.2 A formal framework

Formally, let E_{tot} be a continuous variable capturing the total number of events that occur during a year in a nuclear power reactor. For tractability of the model, we forego the count nature of these events, and assume that this quantity E_{tot} decreases when the manager increases his level of safety care. In other words, we assume that the operator can choose the number of events E_{tot} that occur each year in his nuclear reactor. We further assume that safety care is costly, but provides of private benefits, such as increased reliability of the power station. Hence, we assume there is a function $B(E_{tot})$, concave in E_{tot} with $B'(0) > 0$. In the absence of regulation, the agent would choose a level of care associated with a total number of detected events $\bar{E}$, satisfying $B'(\bar{E}) = 0$. $B(E_{tot})$ thus captures the costs avoided by the agent when letting safety events occur in his power station.[11]

Second, when E_{tot} events occur, we assume that a number of events $E = \rho E_{tot}$ are detected by the manager. ρ captures the ability of the manager to detect events. In the following, ρ will be assumed to be exogenous. We relax this hypothesis in the appendix. Now, Let zE be the quantity of events the manager decides to report to the regulator. Thus, z is the proportion of observed events declared to the principal. Let u be a random variable distributed according to a cumulative distribution F and density f over $[0; 1]$. The value taken by u represents the fraction of E_{tot} detected by the principal during audits. When u takes values between z and 1, the audit reveals a number of events larger than what the manager publicly reported. When u takes values between ρ and 1, the audit reveals a number of events larger than what the manager privately detected. This captures the possibility of non-detection of safety events by the agent.

For the tractability of the model, we finally assume that marginal sanctions and penalties are constant, e.g. there is α such that the sanction associated with reporting zE_{tot} events is $\alpha z \rho E_{tot}$, and the expected penalty associated with audits is $q\beta E_{tot} \int_{z\rho}^{1}(u - z)f(u)du$. Under this self-reporting mechanism with imperfect audits, a risk-neutral agent

[11]We implicitly assume that the B is a concave function that reaches its maximum, e.g. that $\bar{E}$ is finite.

maximizes the following quantity:

$$\max_{E_{tot},z} B(E_{tot}) - \alpha z\rho E_{tot} - q\beta E_{tot} \int_{z\rho}^{1} (u - z\rho) f(u) du \tag{1}$$

This model is adapted from the literature on audit mechanisms when audit are imperfect and firms have to self-report non-compliant situations (see e.g. Evans et al. (2009) and Gilpatric et al. (2011)). The main novelty in our setting is the introduction of the possibility of a detection by the principal of events which have not been detected by the agent. Usually, parameter ρ captures a possible lack of precision in the auditing technology, which could lead auditors to overestimate the true quantity of emissions released by the audited firm.

Let $\mu(z) = \alpha\rho z + q\beta \int_{z\rho}^{1} (u - z\rho) f(u) du$. From Evans et al. (2009) and Gilpatric et al. (2011), one can derive the following first-order condition characterizing the existence of an interior solution for the agent's choice:

$$\begin{aligned} z^\star &= \frac{1}{\rho} F^{-1}(1 - \frac{\alpha}{q\beta}) && (2) \\ B'(E^\star_{tot}) &= \mu(z^\star) && (3) \end{aligned}$$

Provided $\alpha < q\beta$, the existence of an interior solution for $z^\star$ is ensured. Likewise, provided $\mu(z^\star) < B'(0)$, then there exist an interior $E^\star_{tot}$ satisfying condition (3).

Following this, we can derive the following comparative statics on the effect of a change in the value of parameters α and $q\beta$ on safety care $E^\star_{tot}$, compliance $z^\star$ and the total observed quantity of reports $z^\star \rho E^\star_{tot}$, which we note $z^\star E^\star$ for simplicity.

Proposition 3.1 *Comparative statics At an interior solution, the following results hold:*

- *a marginal increase (decrease) in α leads to a decrease (increase) in $E^\star$, to a decrease (increase) in $z^\star$, and thus to a decrease (increase) in the observed quantity of reported events $z^\star E^\star$*
- *a marginal increase (decrease) in $q\beta$ leads to a decrease (increase) in $E^\star$ and to an increase (decrease) in $z^\star$*

Proof: The effect of a change in α or $q\beta$ on $z^\star$ derives directly from equation (2). Using the envelope theorem, we can differentiate $\mu(z^\star)$ with respect to either α or $q\beta$, which yields the second part of the result.

A direct corollary from this proposition is that a marginal change in $q\beta$ has an ambiguous effect on the observed quantity of reports $z^\star E^\star$. To see this, we can write:

$$\frac{\partial z^\star E^\star}{\partial q\beta} = E^\star \frac{\partial z^\star}{\partial q\beta} + z^\star \frac{\partial E^\star}{\partial q\beta} \tag{4}$$

The first term in the right-hand side of (4) is positive, while the second term is negative. Therefore, the variation in observed reports induced by a marginal change in $q\beta$ is determined by the relative size of these two terms, and in particular by the relative amplitude of the variations in compliance and in safety care. For instance, if $\frac{\partial E^\star}{\partial q\beta}$ is small enough, then an increase in $q\beta$ should be followed by an increase in the quantity of observed reports.

3.1.3 The channel identification problem

Equation (4) embodies our first identification issue, which we will refer to in the following as the *channel identification problem*. Indeed, assuming that our empirical estimation indicates that managers report more significant safety events when local commissions are endowed with larger budgets, it is impossible at this stage to claim that the effect is due to either changes in safety care (e.g. changes in E) or changes in compliance with declaration criteria (e.g. changes in z).

To identify the effect of monitoring intensity on observed reporting behaviours, we first need to identify whether the activity of local commissions affects the sanctions perceived by plant managers, or the expected penalty faced when choosing not to report safety events.

To do this, we identify within the reports of significant safety events a subset of events which are perfectly detected by managers and necessarily declared to the authority. These events first contain automatic shut-downs of reactors (ASD), which are perfectly detected and declared due to the fact that they instantaneously stop the electrical production of a reactor. They also contain events labelled "abnormal uses of safeguard systems" (SFG).

These rare events are considered particularly severe by the safety authority, and are particularly simple to detect during audits.[12] We refer to these events as PDD events (for Perfectly Detected and Declared), and note their total yearly number per reactor E_{PDD}. For this subset of events, we have $z = 1$ and $\rho = 1$. Hence, assuming that perceived sanctions and expected penalties are constant across all types of events, the first order condition defining the optimal effort exerted by the manager to prevent these events is the following:

$$B'(E_{PDD}) = \alpha \tag{5}$$

Therefore, if variations in the intensity of the activity of local commissions lead to a change in the occurrences of these perfectly detected and declared events, then we can conclude that the activity of these commissions do induce a change in the sanction perceived by the plant managers, and that this change in sanction led to a change in the safety effort exerted by plant managers. Conversely, the absence of an effect of the monitoring performed by local commissions on the occurrences of PDD events, combined with a significant effect of local monitoring on the overall quantity of events reported to the authority will be consistent with the hypothesis that local monitoring affects the expected penalty faced by plant managers when failing to report an event.

Conditionally on the result of this first step, we can disentangle the effect of the monitoring performed by the local commissions on both safety care (E_{tot}) and compliance (z). The level of non-compliance is per definition not observable in the reports of the managers. On the other hand, one possible proxy for the level of care E_{tot} is the reliability of a nuclear reactor. Indeed, the main private benefit of exerting safety care is the increase in the expected production of the reactor, which may be obtained for instance by limiting the need for maintenance works or the occurrences of fortuitous stops.

Therefore, we also estimate the effect of the monitoring performed by local commissions on the reliability of local reactors. Reliability is measured by two proxy variables: the annual ratio of lost electricity due to unplanned maintenance, and the annual ratio of lost electricity due to fortuitous stops. These proxies capture the quantity of electricity that was not produced due to unplanned maintenance works or fortuitous stops. As both

[12] The selection of these two categories of events was performed during informal discussions with the nuclear safety authority.

unplanned maintenance and fortuitous stops are related to the safety of a nuclear plant, we argue that a manager provided with incentives to increase safety care will first do so, if possible, in a way that increases his profit.

As an example, assume that the first step of the analysis indicates that local monitoring affects expected penalties, and that the effect of local monitoring on reported events (zE) is positive. Then, according to our framework, this observation can only be explained by two phenomena:

- an increase in expected penalties $q\beta$, leading to an increase in safety care (e.g. a decrease in E) and an increase in the level of compliance z
- a decrease in expected penalties $q\beta$, leading to an decrease in the level of compliance z, and to a decrease in safety care (e.g. an increase in E)

Then, one of these solutions can be ruled out by looking at the effect of monitoring on safety care. If local monitoring increases reliability, then we can conclude that local monitoring increases expected penalties and, as a consequence, the level of compliance of local managers with declaration criteria.

More generally, we can use this reasoning to combine the results of the estimation of the effect of local monitoring on general reporting, on reporting of PDD events, and on the reliability of power stations. The first two estimations indicate whether local monitoring affects perceived sanction (α) or expected penalties ($q\beta$). The third estimation indicates the direction of the effect of monitoring on safety care. Conditionally on the results of the first two estimations, this third estimations allows to identify the direction of the effect local monitoring on either perceived sanction or expected penalties. Finally, if this third estimation fails to reject the hypothesis that local monitoring affects safety care, then we can interpret quantitatively the results of the second estimation as the size of the effect of local monitoring on compliance (z).

3.2 Endogeneity of the monitoring intensity

Another identification problem that formally and logically precedes the Channel problem is the identification of the total effect (that is, regardless through which mediation channel) of the activity of the commissions on $z^{\star}E^{\star}$. This problem stems from two potential endogeneity sources. First, the budget of these commissions, which we use as a proxy for the intensity of their monitoring activity, is potentially endogenous due to reverse causality: a local commission may have a high level of activity because the Department council - which allocates their budget - is aware that the power station has an abnormal level of declaration of events. Second, the incentives provided by the regulator to the plant managers might be related to the intensity of the local monitoring. In a period of intensified political or public debate regarding nuclear power, for instance, both the threat of new regulation and the expenditures for local monitoring might be increased. Since we do not measure the intensity of the regulatory oversight, the intensity of the commissions' activity could be endogenous due to an omitted variable bias (OVB).

In order to solve the two endogeneity issues mentionned above, we use an instrumental variable method. Our instrumental variable, *shock*, is based on a natural experiment triggered by forecasting mistakes. More precisely, we use primitive budget data published every year by Department councils, in which a forecast of the balance of their revenues and expenditures for the upcoming year is provided. We also use *ex post* data on the Departments realized financial revenues in order to compute the forecasting errors made by the Departments. These errors are attractive in many respects. They are first, by nature, unanticipated, which precludes endogenous forward looking behaviours of local authorities. Second, as these errors are the results of a failure from the local officials to predict accurately the revenues levied by local taxes, it seems fair to argue that this error will be independent from the unobserved factors influencing the commissions' budgets. Finally, failing to predict accurately their revenues may lead local officials to reassess the funding provided to local monitoring commissions. As was mentioned in the introduction, this instrument is similar to the natural experiment used in Bressoux et al. (2009).

The instrument *shock* is defined using public financial data from French Departments[13]. More precisely, we used the detailed reports describing both the anticipated and realized budgets for each Department hosting a nuclear power station. These budgets include two main sections: revenues and spendings, whose total are equal. Within each sec-

[13]Yearly datasets are publicly available on the French website dedicated to the finances of local territories. This website is accessible here

tion of these budgets, one can find two main categories: investment revenues/expenditures, and operating revenues/spendings. Both categories are separated: investment revenues can only finance investment expenditures, while operating revenues are used to finance operating expenditures. Operating budgets account for approximately 85% of the budget of the French Departments. Yet, it appeared from a careful analysis of these datasets that the total forecast error is mostly driven by the investment revenue forecast error. Though, subsidies granted to the monitoring commissions are part of the operating budgets of the Departments. Therefore, the *shock* variable was defined for each reactor and every year between 2008 and 2015 as the two-year lagged value of the forecast error on Department-level operating revenues. The two-year lag is introduced because real budgets are usually published with a one-year delay. This suggests that forecasting errors made in year Y are only known at the end of year Y+1, and may affect the decision to subsidize local monitoring commissions at year Y+2.

4 Empirical estimation and results

4.1 Descriptive statistics

Table 1: List of variables and descriptive statistics

Variable		Mean	Std. Dev.	Min.	Max.
Event counts	ALL	12.856	4.778	2	27
	SDD	1.017	1.13	0	5
	ASD	0.809	0.955	0	5
	SFG	0.208	0.492	0	3
Commission controls	$budget$	52.415	48.146	4	198
	$meet$	2.271	0.446	2	3
	$multiple$	0.169	0.376	0	1
	$SaintLaurent$	0.051	0.22	0	1
Instrument	$shock$	20.6	21.8	-	-
Reactor controls	age	28.169	5.659	8	37
	$size$	3.966	1.38	2	6
	$FOAS$	0.559	0.498	0	1
	$FOAK$	0.008	0.092	0	1
	$production$	6.866	1.747	2.165	11.622
	$maintenance$	67.568	49.839	0	279

236 observations in 50 reactors from 2007 to 2015 (522 possible)

The variables constructed based on the data described in section 2.3 are presented in table 1. The first four lines of the table describe the counts of events reported per reactor and per year. These variables will be used in the next section as dependant variables. They respectively describe the total number of declaration per reactor.year and the number of declaration of specific categories of events. It is to be noticed that we have $SDD = ASD + SFG$.

The next four lines of table 1 describe the activity of the local commissions. As was announced earlier, the budgets of the commissions varies in the data from 4 000 €/year to 200 000 €/year. Notice also that most commissions only organize two meetings a year, and that only 15% of them have multiple sites to monitor. The next line considers our instrumental variable, *shock*, and shows that Departments, on average, are too optimistic in their operating revenues forecasts.

The final six lines describe our control variables for the local specificities of each nuclear reactor. We can see that the age of the reactors considered in this dataset ranges from 8 to 37, that sites include from 2 to 6 reactors, each of which produced an average of 7 TWh per year over the elapsed period of time. We can finally see that, on average, reactors undergo 68 days of maintenance every year.

Table 2: Declaration of events as a function of local commissions' budgets

	$budget \leq 50k€$		$50k€ \leq budget \leq 100k€$		$100k€ \leq budget$	
	mean	N	mean	N	mean	N
ALL	13.5	148	12.4	56	10.6***	32
SDD	1.08		0.8		1.06	

***difference between subgroup-means is highly significant

In table 2, we present the mean levels of declaration for the two categories of events of interest, for different subgroups of reactors defined with respect to the budgets of their local commission. We run simple mean difference test between the three proposed subgroups. We can observe that reactors overseen by a commission endowed with larger budgets tend to declare less events in general, whereas there seems to be no significant differences in the declaration of systematically detected and declared events across the commissions' budgets. These two suggestions are somehow contradictory, as the latter suggests the existence of a positive impact of threat on safety whereas the former does not suggest any significant effect. This first statistical observation calls for an in depth analysis of the determinants of the declarations of safety events, which is performed in the next two sections.

4.2 Econometric framework

A linear specification allowing to estimate the formal model presented in the identification section is the following:

$$Y_{it} = \beta \cdot X + \beta_{budget} \cdot budgets + \eta_i + \delta_t + \epsilon_{it} \tag{6}$$

where indices i and t respectively refer to the reactor and the year of observation. The dependant variable Y_{it} will be defined in turn as the number of declarations (per reactor and per year) of events perfectly detected by plant managers and declared to the safety authority (ASD and SFG), as the performance indicators describing the reliability of nuclear stations (K_{ipr} and K_{if}), and as the total number of events reported per reactor and per year (ALL). δ_t represents year fixed-effects, and controls for potentially varying declaration guidelines, or particular time-varying factors, such as generic efforts exerted by EDF at a national scale. η_i represents reactor fixed-effects, which capture potentially varying local factors influencing the safety of nuclear reactors. In all regressions, control variables X include reactor age, electrical production[14] and the overall number of days of maintenance during the year.

Given the possible endogeneity of the *budget* variable, we estimate equation 6 using our instrument *shock* and a generalized method of moments(GMM-IV) estimator with robust standard-errors.[15] We choose to use a GMM-IV estimator as it is known to be approximatively unbiased and to achieve close to perfect nominal coverage in the just-identified case (see e.g. Angrist and Pischke (2009b,a)).

Estimation results are presented in the following way. We first present in table 3 the

[14] Production can be seen as a form of exposure, as all power stations do not produce the same amount of energy each year.

[15] As we only have one endogenous regressor and one instrument, the GMM-IV, two-stage least-square and limited information maximum likelihood estimators are equivalent, see for instance p.189 in Wooldridge (2002), or chapter 8.6 in Hayashi (2000).

Table 3: Monitoring intensity, perceived sanctions and safety care

VARIABLES	ASD	SFG	Kipr	Kif
budget	0.00463	-0.0276**	-0.000106	-0.000322
age	-0.0859*	0.0419*	-0.00134	0.00122
production	-0.285**	-0.202**	-0.0104*	-0.0158**
maintenance	-0.00252	-0.00149	0.000289***	-0.000282**
Year-FE	Yes	Yes	Yes	Yes
Reactor-FE	Yes	Yes	Yes	Yes
Observations	234	234	234	234
KP rk LM	8.197	8.197	8.197	8.197
KP rk Wald	10.05	10.05	10.05	10.05

*** p<0.01, ** p<0.05, * p<0.1

four regressions in which the dependant variable Y is defined as, respectively, the annual number of reports (per reactor) of automatic shut-downs ASD, the annual number of reports of unplanned uses of safeguard systems SFG, the rate of lost production due to unplanned prolonged maintenance works K_{ipr} and the rate of lost production due to fortuitous stops K_{if}. The first two regressions test whether increased monitoring intensity induce a change in the sanctions perceived by plant managers. The last two regressions test whether increases in monitoring intensity lead to changes in safety care.

Second, table 4 contains the results of four regressions. In the first two regressions, the dependant variable Y_{it} is defined as the number of reported significant safety events. In the last two regressions, carried out as a robustness check, Y_{it} is defined and as the logarithm of this quantity. In both cases, regressions differ by the inclusion or exclusion of reactor-fixed effects. These regressions aim to measure the effect of increased monitoring intensity on the overall number of events reported by local managers. The results of these regressions can then be interpreted conditionally on the results obtained in table 3.

The results of the first-stage regressions are reported in the appendices. These first-stage regressions support our instrument as the coefficient of the *shock* variable is positive and significant. In addition, the test statistics reported in tables 3 and 4 support our instrumental variable.

Table 4: Monitoring intensity and reports of significant safety events

VARIABLES	ALL	ALL	log(ALL)	log(ALL)
budget	0.0571**	0.132*	0.00353*	0.00862
age	0.178	-0.473**	0.0209	-0.0417**
production	-1.137*	-0.942	-0.0835**	-0.0723
maintenance	0.0124	0.0135	0.00113	0.00117
Status	9.356***		0.641***	
multiple	-2.353**		-0.172*	
meet	7.510**		0.514**	
Saint-Laurent	-1.949		-0.217	
size	1.554**		0.109**	
FOAS	-0.481		-0.0552	
FOAK	-0.556		0.0264	
1300MW	9.189***		0.681***	
1450MW	20.20***		1.552***	
Year FE	Yes	Yes	Yes	Yes
Reactor FE	No	Yes	No	Yes
Observations	234	234	234	234
KP rk LM	17.32	8.197	17.32	8.197
KP rk Wald	26.86	10.05	26.86	10.05

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

4.3 Estimation results

4.3.1 Monitoring, perceived sanctions and safety care

The first two regressions presented in table 3 are based on the set of perfectly detected and declared events. It appears that the intensity of the commission's monitoring activity has no significant impact on the quantity of automatic shut-downs, and a small but statistically significant effect on the occurrences of unplanned uses of safeguard systems.

Conditionally on the assumptions made in the identification section, the results obtained when using ASD events as a dependant variable suggest that local monitoring has no impact on perceived sanctions. This result is contrasted by the results obtained when using SFG events as a dependant variable, where the results indicate a small but significant increase in the sanctions perceived by local managers.

In the last two regressions of table 3, we find no significant effect of the commissions' monitoring activity on the on reliability of nuclear reactors. As reliability is assumed to be correlated with safety efforts, these two regressions fail to reject the hypothesis that significant additional safety care remains constant when the intensity of the local monitoring increases. Overall, we conclude from the results gathered in table 3 that the intensity of the monitoring performed by local commissions has a small effect on perceived sanctions, but no significant effect on safety care.

The first two regressions also show mixed results regarding the age of nuclear reactors, which has a significant positive impact on the declarations of SFG events, but a small negative impact on automatic shut downs. Conversely, the last two regressions show that age has no significant effect on reliability. In all four regressions, these results on age are small when compared to the results on production which significantly decreases the quantity of reports and the reliability of nuclear station. The results on reliability are coherent, given the fact that production and reliability ratios are closely related. The relation between production and declarations of PDD events is also coherent with the fact that significant safety events seldom occur when the power station is producing electricity at its nominal capacity.

4.3.2 Monitoring and compliance

Second, the regressions presented in table 4 show that increased intensity of local monitoring leads nuclear managers to increase significantly the number of safety events declared. Given the results presented in table 3, observing an increase in the total number of events can only be consistent with an increase in the expected penalty faced by nuclear plant managers when deciding not to report a safety event. Indeed, under constant expected penalties, the small increase in perceived sanctions identified previously can only be consistent with a decrease in total reports. Moreover, under the previous observation that safety care remains constant when monitoring intensity increases, the only way to observe an increase in reports is to have an increase in expected penalties, leading to an increase in compliance.

Given the result that safety care is constant when monitoring intensity increases, the coefficient β_{budget} obtained in the second table can be interpreted as the total effect of monitoring intensity on compliance. If we note i this intensity, we have $\beta_{budget} = \frac{\partial zE}{\partial i} = z\frac{\partial D}{\partial i} + E\frac{\partial z}{\partial i}$. Then, since $\frac{\partial E}{\partial i} = 0$ due to the results obtained previously, we have that

$\beta_{budget} = E\frac{\partial z}{\partial i}$. Quantitatively, we conclude from the second column of table 4 that a budget raise of 1.000 € leads to a 1% increase in compliance with declaration guidelines (assuming that the average number of declaration per reactor and per year is 13 events). It is interesting to remark that if $\frac{\partial E}{\partial i} \neq 0$, then the quantitative interpretation of β_{budget} is a lower bound on the effect of monitoring intensity on compliance, as we showed that $\frac{\partial E}{\partial q\beta} < 0$.

The comparison of this coefficient with the result of a simple OLS regression shows that endogeneity biases the estimation downwards, leading to a negative and significant coefficient for the *budget* variable. The sign of this bias can be interpreted as the consequence of the reverse causality between the commissions' budgets and the declarations of safety events. For instance, a local commission conscious of the relative lack of information provided by plant managers may ask for larger budgets in order to challenge the plant managers in a more thorough way, leading to this downward bias.

Finally, the results presented in table 4 show that higher levels of production lead to smaller number of declarations of events. The technological design of the reactors is significantly related to the declaration of events. Reactors sharing the $1300MW$ or $1450MW$ reactors tend to declare a significantly larger number of events. Finally, year fixed-effects suggest that there is a learning by doing effect at the fleet level over time, while there is no evidence of learning-by-doing among types of reactors sharing the same design.

5 Conclusion and policy implications

This paper empirically studies the effect of a French informational policy that organizes the monitoring of nuclear power stations by dedicated local commissions. These commissions can provide no monetary incentives to local plant managers, but can communicate the results of their monitoring activities to local populations and to the safety authority. This paper investigates whether this policy induces changes in the behaviour of nuclear plant managers.

To do so, we design an original empirical strategy to identify the causal impact of this policy on the choices of local managers regarding both safety care and compliance with self-reporting guidelines. We first clarify the incentives faced by managers when exerting safety care and reporting significant safety events: the two main drivers of these decisions are the perceived sanctions incurred for reporting a safety event, and the expected penalty faced when an unreported event is discovered by the safety authority. Using this formal model, we estimate the effect of increased monitoring on safety care and compliance using an instrumental variable method. Our instrument, defined as budget forecasting errors at the Department level, aims to correct the possible biases induced when considering annual budgets of local commissions as a proxy for the intensity of their monitoring activities. This instrument exhibits several interesting features that qualify it as a quasi-natural experiment.

Empirically, we study the effect of monitoring intensity on three observables: the annual level of reliability of nuclear reactors, the quantity of events declared per reactor and per year, and the quantity of events declared that belong to a certain category of events, characterized by perfect detection and declaration. Using this latter observable, we identify the effect of monitoring intensity on perceived sanctions. Results suggest that the sanctions perceived by plant managers only marginally increase under increased monitoring intensity. Second, we find that increased monitoring intensity leads to an increase in the total number of declarations of safety events, and to no significant changes in the reliability of nuclear reactors. We conclude from these observations that local monitoring significantly increases the expected penalty faced by managers who decide not to comply with reporting schemes, which in turn induces an increase in their compliance with self-reporting criteria. Quantitatively, a budget raise of 2.000 € leads to a one percent increase in the number of events reported.

These results rely on several strong assumptions. First, we neglect the fact that all French plant managers work for a single firm, which could provide them with collective incentives that are not captured in our formal model, or accounted for in our empirical estimation framework. Second, we assume that safety care cannot be specific to a particular type of event, and that the ratio of the number of events undetected by the operator to the total number of events occurring in a power station is independent from the level of care exerted by the operator[16]. When relaxing this assumption, our empirical evidence

[16]This is different from saying that safety care as no impact on the detection of safety events. In

can still be interpreted as a positive and significant impact on the overall *transparency* of nuclear managers, where transparency is defined as the combination of a manager's ability to detect safety events and his propensity to declare them.

Regarding policy implications, we believe this paper's results call for optimism, as they suggest potentially cost-effective ways of improving the institutional design of nuclear safety regulation. At a national level, there has been a debate in France regarding the subsidies given to local monitoring commissions. Indeed, the French law passed in 2006 mentioned that Department ought to provide their local monitoring commissions with a fixed share of the special tax imposed on nuclear installations. As of this writing, this article of the law is yet to be implemented. Our findings suggest that implementing this measure could foster significant improvements in the level of compliance of nuclear operators. More generally, our results suggest that informational policies such as this French local monitoring policy could be used as efficient complements to traditional command-and-control nuclear safety regulation mechanisms, in France or abroad.

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our model, exerting safety care diminishes both the total number of events and the number of events undetected. Yet, we assume that the ratio of these two quantities remains constant.

Appendix 1: First-stage regression results

Note: In the table presenting the first stage regression results, only columns 3 should be considered. Other columns refer to an earlier version of the paper, which used other instrument sets.

Table 5: First-stage results of the regressions presented in the result section
FSCLI

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	budget	budget	budget	budget	budget	budget
green	2.591***	2.591***			2.070***	2.070***
shock			0.783***	0.783***	0.452***	0.452***
Status	-19.45**	-19.45**	-5.968	-5.968	-11.40	-11.40
meet	-67.46***	-67.46***	-83.57***	-83.57***	-72.50***	-72.50***
multiple	21.98***	21.98***	29.34***	29.34***	24.34***	24.34***
SaintLaurent	-100.6***	-100.6***	-107.8***	-107.8***	-119.7***	-119.7***
age	5.597***	5.597***	7.099***	7.099***	5.589***	5.589***
size	-23.00***	-23.00***	-19.91***	-19.91***	-25.36***	-25.36***
production	0.629	0.629	3.392	3.392	1.275	1.275
maintenance	0.0302	0.0302	0.0742	0.0742	0.0418	0.0418
FOAS	-8.622*	-8.622*	-11.96**	-11.96**	-9.345**	-9.345**
FOAK	36.19***	36.19***	38.81***	38.81***	38.23***	38.23***
1300	-28.10***	-28.10***	-24.63***	-24.63***	-32.20***	-32.20***
1450	-20.89	-20.89	-2.021	-2.021	-27.37	-27.37
2008	7.805	7.805	16.42	16.42	19.46**	19.46**
2009	-4.999	-4.999	-7.279	-7.279	2.156	2.156
2010	-19.18***	-19.18***	-23.86*	-23.86*	-11.73	-11.73
2011	-27.20***	-27.20***	-6.045	-6.045	-11.62	-11.62
2012	-28.04***	-28.04***	-31.52**	-31.52**	-25.99**	-25.99**
2013	-34.18***	-34.18***	-34.97**	-34.97**	-30.82***	-30.82***
2014	-40.69***	-40.69***	-29.24*	-29.24*	-28.94**	-28.94**
2015	-10.50	-10.50	-32.21*	-32.21*	-3.176	-3.176
Constant	125.6***	125.6***	101.2***	101.2***	130.3***	130.3***
Observations	274	274	274	274	274	274

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
green no FE

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