

Accountability feedback assessments for improving efficiency of nuclear regulatory institutions



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HIGHLIGHTS

- A general introduction to regulatory accountability is given.
- A definition of an effective accountability system is proposed.
- A method to assess accountability systems is proposed.
- A simplified simulation of a regulatory system demonstrates the method's capabilities.

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ABSTRACT

The Fukushima-Daiichi Accident demonstrated the need of assessing and strengthening institutions involved in nuclear safety, including the accountability of regulators. There are a few problems hindering the path towards a greater understanding of accountability systems, the ensemble of mechanisms holding to account the nuclear regulator on behalf of the public. There is no consensus on what it should deliver and no systematic assessment method exists.

This article proposes a method of assessing institutions based on defence in depth concepts and inspired from risk-assessment techniques used for nuclear safety. As a first step in testing the proposal, it presents a simple Monte-Carlo simulation, illustrating some of the workings of the method of assessment and demonstrating the kind of results it will be able to supply. This on-going work will assist policy-makers take better informed decisions about the size, structure and organisation of a nuclear regulator and the cost-effective funding of its accountability system. It will assist in striking a balance between efficiency and resilience of regulatory decision-making processes. It will also promote the involvement of stakeholders and allow them to have a more meaningful impact on regulatory decisions, thereby enhancing the robustness of the regulatory system and potentially trust and confidence.

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1. Introduction

Prior to the Fukushima-Daiichi nuclear accident, both the nuclear operator and the regulator were seemingly aware that the plant would be unable to withstand a very large tsunami having predicted by some of having a credible frequency of occurrence. The failure of the operator to make the necessary improvements was caused by institutional shortcomings including in the regulatory system.

The commission charged by the Japanese government with investigating the causes of the Fukushima-Daiichi accident not only found that the plant was ill-defended against tsunamis with

waves above 10 m but also that such powerful tsunami have far from negligible frequencies of occurrence in the region (NAIIC, 2012). Despite these studies showing the risks for the plant of the tsunami hazard to be unacceptable, TEPCO did not make the necessary improvements and the regulator failed to force its hand.

In its comprehensive report on the accident (IAEA, 2015), the IAEA argues that the Nuclear and Industrial Safety Authority (NISA) lacked the authority to have the operator make these changes and traces this issue to several institutional failings. First, NISA lacked independence from both the nuclear industry it was charged to oversee and the ministry promoting nuclear power. Second, it lacked formal authority due to the complexity of the regulatory framework. Finally, the government staffing policy and the rule requiring job rotation every few years in particular hindered NISA staff from gaining the expertise needed (IAEA, 2015).

In 2007, the Japanese Government welcomed an IAEA team of expert to review its governmental, legal and regulatory

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framework. There were several unaddressed issues raised in the IAEA review report that were pertinent to the Fukushima accident. In particular, issues related to the independence and the competences of the regulator (IAEA, 2007). However, Japan resisted international calls for regulatory reform (Convention on Nuclear Safety, 2008).

Despite these deep-rooted institutional failings being identified as one of the root causes of the accident, the international nuclear community has so far focused predominately on engineering and operational lessons.

To address these needs, a three barrier defence in depth institutional model for national nuclear systems has been proposed, consisting of a strong self regulating industry, a strong independent regulator, both of which are held to account by the third barrier: strong, diverse and well-informed stakeholders (Weightman, 2015). The role of nuclear stakeholders is of the utmost importance to prevent and mitigate against dual failures of the regulator and operator such as the one which occurred in Japan. However, little attention has so far been given to their role in ensuring that both the operator and the regulator are adequately performing their duties. The article thus focuses on stakeholders and the diverse mechanisms which hold the nuclear regulator to account on their behalf. Collectively, these mechanisms will be referred to as the system of accountability for the nuclear regulator.

The first section provides some background on regulatory accountability. The following section outlines the literature on regulatory accountability and argues that progress in the field is held back by a lack of a systematic approach to assess the effectiveness systems of accountability. The article then proposes a novel method based probabilistic safety assessments to quantitatively evaluate the effectiveness of accountability systems. In the final section, a Monte-Carlo simulation depicting a much-simplified version of the method of assessment is presented. Its aim is to illustrate the inner workings of the method of assessment and demonstrate the kind of results it will be able to supply. This work is part of a wider development of using nuclear safety assessment techniques to assess institutions systems that may well have wider policy implementations beyond those for nuclear regulatory systems.

2. Background

2.1. Definitions

2.1.1. Stakeholders

The International Nuclear Safety Group defines stakeholder as those who have a specific interest in a given issue or decision. There are two types of stakeholders: internal stakeholders, who are directly involved in the decision making process; and external stakeholders comprising any organisation or individual that has a legitimate interest in the decisions taken (INSAG, 2006).

The stakeholders are very diverse. They include members of the nuclear industry, the general public, its governmental representatives such as the national and local governments, and non-governmental entities such as NGOs and other interest groups.

2.1.2. Regulatory accountability

The definition of regulatory accountability that will be used in this paper is the following: for a regulator, to be considered accountable it is required to justify both its decisions and actions and to make the necessary changes should the explanation given be judged unsatisfactory (see House of Lords Select Committee on the Constitution (2004), Bird (2012)).

2.1.3. Accountability mechanisms

An accountability mechanism can be broadly defined as any structural control that is used to meet the challenge of an organisation's accountability (Ogus, 1994). In OECD countries, the mechanisms through which a regulatory body is held to account typically include the following (OECD, 2002):

- Stakeholder consultations such as NGO forums public consultations, public meetings, consultation with the nuclear industry etc.
- Parliamentary oversight in the form of annual reports, committee hearings, parliamentary questions etc.
- Oversight by the executive branch (i.e. by a ministry or a governmental agency).
- Financial and performance audits.
- Appeal processes.
- Appointment process for leadership role within the regulatory body.

2.2. Stakeholders and regulatory accountability

Whilst stakeholders may not know what the regulatory framework should look like or how the regulator should manage its activities, they can always provide valuable input on its decisions as they are directly affected by them and thus may perceive issues the regulator overlooked.

The House of Lords' Select Committee on the Constitution (2004) identifies three key elements to allow the stakeholders to have an impact on a regulator's actions:

- *The duty to explain*: Regulators must provide information on its activities to interested parties and explain the basis of the decisions they take.
- *Exposure to scrutiny*: Regulators must provide the means through which stakeholders can enquire about regulatory activities and decisions.
- *The possibility of independent review*: Stakeholders must be able to ask for an independent review of a regulatory decision so that it may be overturned or altered.

3. Problem description

Regulatory accountability is not a very active field of study. Accountability is mentioned in myriads of books and articles on public administration (Bishop, 1990; Chandler, 1996; Deleon, 1997; Harlow and Rawlings, 1997; White and Hellingsworth, 1999; Woodhouse, 1997) and on regulation (Baldwin and McCrudden, 1987; Baldwin, 1995; Baldwin and Cave, 1999; Ogus, 1994) as it is seen as a democratic requirement and a necessity to ensure an effective public administration and effective regulators. However the chapters dedicated to accountability only skim the surface and readers must content themselves with a basic explanation of its concept and brief descriptions of the various accountability mechanisms in place in the country in question.

The OECD (2002) provides details on what constitutes an effective system of accountability. These can be divided into two parts.

Firstly, a strong set of legal requirements for regulators to uphold is needed to foster transparency and accountability. It must include:

- A law setting explicitly the objective(s) of the regulator.
- Laws on information disclosure and requirements on responsiveness to information requests.
- Requirements for the regulator to seek the opinion of the

stakeholders on regulations that affect them.

- Requirements governing regulation-making processes to ensure fair and transparent regulatory procedures.

Secondly, an effective system of accountability comprises the following features.

- An appeal process that is clear, predictable, consistent and independent from the original decision-maker.
- An audit office that is in charge of checking the quality of the implementation of the regulations.
- Oversight of the regulator's activities by the parliament.
- A regulatory oversight body in charge of regulatory reform.

Only a few studies focus exclusively on systems of accountability. Bird (2012) writes on the accountability of two financial regulators in Australia and Graham (1998) and the Select Committee on the Constitution of the House of Lords (2004) study the UK system of accountability.

Although each work describes the system of accountability of interest with clarity, they do not provide substantial additions to the field of regulatory accountability. Bird (2012) argues for incremental changes for several accountability mechanisms to find the best balance among accountability, independence and efficiency. Graham (1998) proposes the implementation of a common set of regulatory procedures. The Select Committee on the Constitution of the House of Lords (2004) similarly seeks the implementation of legal requirements codifying the appropriate behaviour of regulators as well as more balanced appeal mechanisms and parliamentary oversight.

Furthermore, these studies use different methods of assessment, each lacking a systematic approach. They also use few, if any, quantitative performance indicators to assess the systems of accountability. As a result the studies cannot be used to compare these systems to inform policy makers. Additionally, the degree of subjectivity involved is detrimental to the accuracy of the assessment.

Finally, the focus of these studies is not on the system of accountability in question but rather on its individual parts. The objectives the system of accountability should achieve are never clearly stated. As a result these studies are unable to consider neither the relative importance of each mechanism in achieving them nor the combined effects of all the system's parts put together. Whilst the importance of balancing accountability with efficiency is recognised, neither the OECD nor the three studies talk about the costs of the various accountability mechanisms.

The most relevant study regarding the accountability of the nuclear regulator is the review of the British nuclear regulatory environment requested by the Government and conducted in 2008 (Stone, 2008). Even though the accountability system is not the main focus of the report, it does offer recommendations on accountability to improve the effectiveness of the regulatory framework. Two propositions are of particular relevance: First, the report recommended that a board of directors, composed of people with relevant industry experience and representatives of various stakeholders, lead the nuclear regulator and hold it to account for its performances. Second, it proposed the introduction of an extended appeal process.

However, regulatory accountability is not the main thrust of the report. The system of accountability is not discussed in its entirety, nor are the costs and efficiency of various proposals analysed.

4. Proposal for a new method of assessment

The objective of this work is to take the first step towards providing a systematic quantitative approach to assess institutions that is flexible and addresses the need described earlier. It seeks to

evaluate different systems of accountability and provide quantitative results allowing their comparisons.

4.1. Objective of an accountability system

In order to build a method of assessment on strong foundations, it is necessary to first address the basic issue that has never been tackled head on: How is the effectiveness of a system of accountability to be defined? In a report entitled *The Characteristics of an Effective Nuclear Regulator*, the Nuclear Energy Agency proposes the following definition for a nuclear regulatory body: 'Effectiveness is about how well an organisation is achieving its fundamental purpose'.

Using past work on regulatory accountability and consulting with nuclear regulators, staff of accountability mechanisms and stakeholders, it was found that the fundamental and overarching purpose of a system of accountability is to ensure that the nuclear regulator is achieving its objective, that is, ensuring that nuclear licensees operate their facilities in a safe manner (NEA, 2014).

4.2. New approach

4.2.1. Introduction

The approach proposed to provide a sound basis to the method of assessment revolves around two key ideas. The first is to use risk assessment techniques used in the nuclear industry for nuclear safety as an inspiration for the assessment method as the two issues share similar traits.

Indeed, in recent years, risks assessment methods have been used in an increasing number of fields - Nepal and Jamasb (2013), Nepal and Jamasb (2015a, 2015b), for instance, use them to evaluate the multi-faceted high impact risks the European electricity network faces. Similarly, the aim here is to assess the effectiveness of an accountability system by evaluating the effect regulatory failures have on the frequency of high-impact events in nuclear plants taken as reactor core damage which are extremely rare but could lead to deaths or injuries or disruption of energy supplies. (The Fukushima-Daiichi Accident had a significant impact on energy supplies and the Japanese economy (Hosoe, 2015) but no immediate deaths from ionising radiation and it has been predicted that there will be no discernible increase in stochastic deaths (UNSCEAR, 2013)).

The nuclear safety case, which has long been used in the nuclear industry to demonstrate the safety of a nuclear facility or activity, is of particular interest. Based on solid scientific foundations, it uses a systematic approach and offers both a deterministic and quantitative probabilistic risk-assessment approach to demonstrate that the risks posed by the facility or activity in question have been reduced to reasonable levels and as low as reasonable practicable (ALARP). The techniques involved in such assessments provide the basis for the new approach to the assessment of institutions introduced here.

The second idea is to model accountability mechanisms and nuclear regulators as well as their decision-making processes, looking at how faults can propagate through the system and events build up to eventual significant failure. The assessment of systems of accountability would thus rely less heavily on the observable behaviour of these organisations and would be able to assess the contribution of each individual accountability mechanism in the achievement of the system of accountability's fundamental objective. Indeed, as most countries rely on similar mechanisms to provide some regulatory accountability, and as real-life experiments are not a possibility, modelling how they function is the only approach that can accomplish this goal.

4.2.2. Nuclear safety risk assessment

Nuclear safety risk assessment normally goes through the following steps (ONR, 2013):

- Identify all the possible hazards using systematic and thorough identification processes.
- Identify all possible faults that could trigger an undesirable event using systematic and thorough identification processes. For instance combustible material is a hazard, and a spark is a fault associated with it as this would ignite the material and start a fire.
- Identify the failure modes of the plant using systematic and thorough fault sequence identification processes
- Perform both deterministic and probabilistic analyses of the plant design against these failure modes. The analyses must demonstrate that the facility conforms to sound safety principles such as defence in depth and that equipment important to safety is going to work during its expected lifetime so as to prove the design's strong tolerance against these failure modes.

4.3. Structure and rationale of the method

4.3.1. Effectiveness of systems of Accountability

The IAEA (2016) provides a list of requirements for nuclear regulators to follow whilst the NEA (2014) details the characteristics they must possess. As both organisations compiled these results thanks to substantial research on regulatory effectiveness, it can be inferred with some confidence that any deviation from these standards would impede regulators from performing effectively.

Ensuring the effectiveness of the regulatory authorities can thus be thought as an effort to systematically detect and fix these deviations, or regulatory failures, and mitigate the negative impact these may eventually have on the safety of nuclear facilities. This occurs when the regulator fails to undertake its regulating duties adequately, such as taking decisive action when an unacceptable risk arises.

As a result, the assessment of the effectiveness of a system of accountability can be done by evaluating the response of the nuclear regulator to combinations of regulatory failures. In particular, the negative impact the nuclear regulator has on safety can be used as a scale of effectiveness for its system of accountability.

4.3.2. Analogy with the nuclear safety risk assessment

Table 1 presents the different analogies that can be drawn between the nuclear safety risk-assessment method and the method for assessing the effectiveness of a system of

accountability.

These analogies suggest that the proposed method should have the following steps:

- Systematic identification of regulatory failures
- Systematic identification of failure sequences
- Modelling the regulatory processes associated with each regulatory activity
- Using research on human and organisational factors in probability safety - assessments to infer the impact regulatory failures have on regulatory processes
- Modelling the processes of accountability mechanisms
- Identify measurable indicators for the principles for effective accountability
- Using research on human and organisational factors in probability safety assessments to infer the performance of the processes of accountability mechanisms using the data gathered

The first step deals with identifying the undesirable events that may occur within a regulatory body. The second, third and fourth aim at exploring the potential consequences these events may have on the regulator's performance and thus on the safety of the facilities it oversees. The three final steps look at the 'safety systems' and their characteristics.

Once these steps have been carried out and all the necessary data on the regulator and the system of accountability have been collected, we can then assess the robustness of the entire system – nuclear regulator and its system of accountability – against regulatory failures.

Modelling the processes of both the regulator and the mechanisms that hold it to account will allow us to perform a simulation of the nuclear regulator's behaviour over the years, after it has been afflicted with a combination of regulatory failures. We will thus be able to observe, year after year, the spread of regulatory failures, and their growing impact on the quality of the regulator's output. Most importantly, we will be able to assess the capacity of the system of accountability to prevent the regulator from degrading the level of safety in nuclear facilities.

5. Test-case Monte-Carlo simulation

The work presented here is a test case for the development of the proposals for quantitative assessment of institutions using a Monte-Carlo simulation run on MATLAB.

5.1. Institution modelling

For the simulation, five institutional components were modelled: a nuclear regulator, one stakeholder and three accountability mechanisms. For simplicity, and to ensure rapid convergence of the Monte-Carlo simulation, all the components but the regulator are modelled as a single-working unit. Each possesses a set of characteristics which impact how well it performs the tasks it has been assigned.

5.1.1. Nuclear regulator modelling

5.1.1.1. Basis. The nuclear regulator in this simulation is composed of 22 staff, 20 junior staff and 2 senior staff. They carry out two activities: developing new regulation and inspections. Half the staff deals with inspections whilst the other half focuses on safety standards.

The inspection process and the regulation-making process are displayed in Fig. 1. Fig. 1a displays the inspection process whilst Fig. 1b displays the rule-making process. Actions in green cases are performed by individual junior staff, in blue cases by a group of

Table 1.
Analogies between the risk assessment for nuclear safety and the proposed method for assessing the effectiveness of a system of accountability.

Dimension	Safety case	Accountability
Source of danger	Hazards and associated faults	Regulatory failures
Impact on system	Fault sequences	Failure sequences ^a and their impact on regulatory processes
Consequences for safety	Probability of incident/accident Damages incurred	Probability of poor regulatory decision-making Increase in risk incurred
Safety systems	Protective safety measures Mitigating safety measures	Mechanisms detecting and fixing regulatory failures Appeal mechanisms

^a Failure sequences describe how regulatory failures may trigger or worsen the gravity of other regulatory failures.

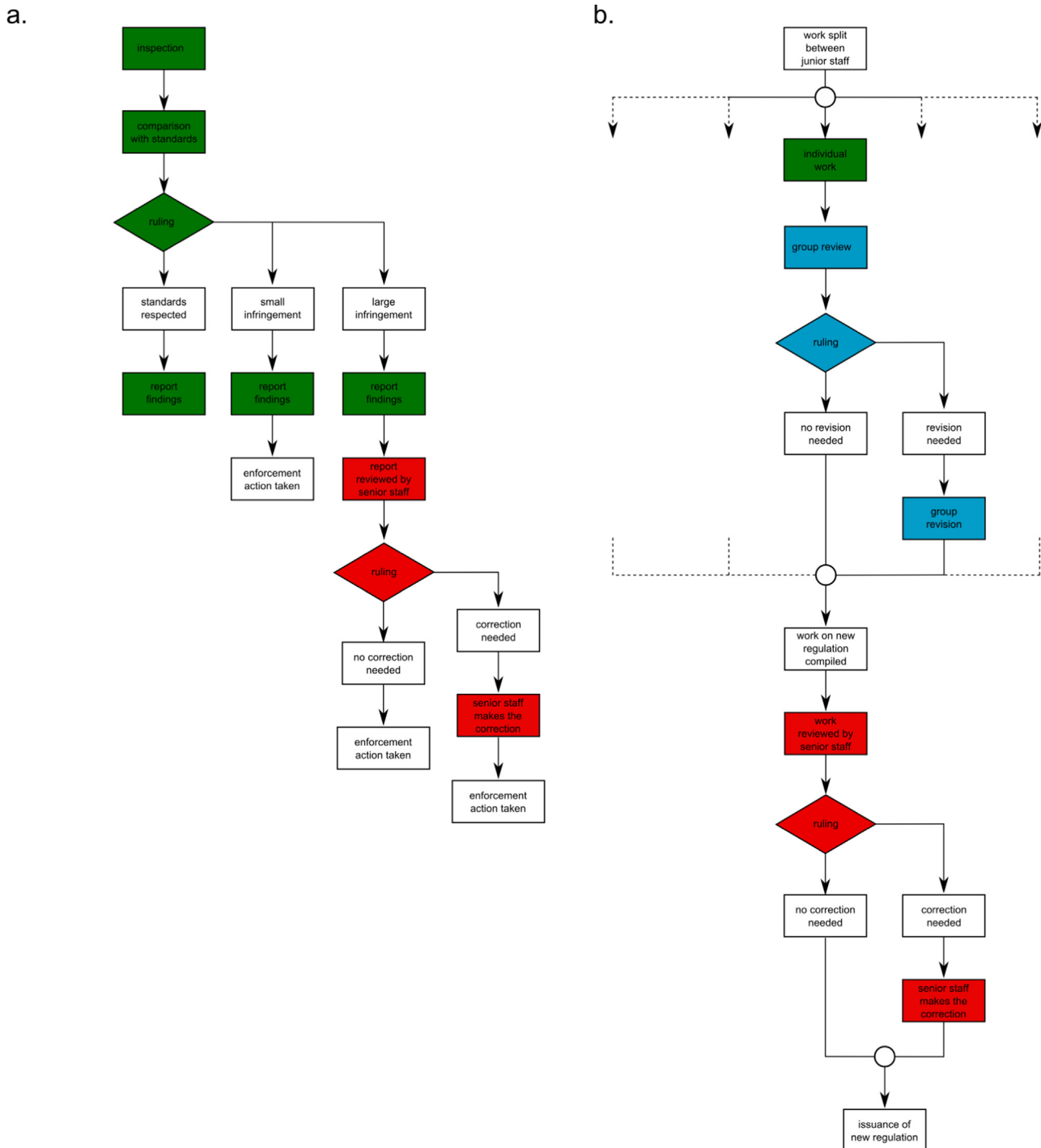


Fig. 1. Decision-action diagrams describing the two activities of the nuclear regulator inspections (a) and rule-making (b).

junior staff and in red by senior staff.

Each junior inspector is in charge of one nuclear plant. The regulation-making junior staff on the other hand, works all together to develop new regulation.

5.1.1.2. Regulator's performance and safety. For the simulation, we assume regulatory staff possesses only one characteristic impacting their ability to ensure safety: expertise.

Each inspection has a chance to focus on an area where the operator fails to comply with the regulations. It is assumed that any safety standard violation is associated with an increase in risk, expressed in reactor core damage frequency, from ALARP levels.

Thus the role of the inspector is to detect such lack of compliance and take action.

In the United States, plant inspectors perform on average 33 inspections per plant year (NRC, 2005). In addition, in 2012, 5 reactors out of 104 were found to have degraded performances (NRC, 2013). Thus, in the model, it is assumed that junior inspectors perform 33 inspections per year and each inspection has a 5% chance to be in an area where the operator does not comply with the regulations.

The chosen probability density distribution for the associated risk increase is displayed in Fig. 2. It is constant for risks comprised between 0 and R_0 and then decreases exponentially:

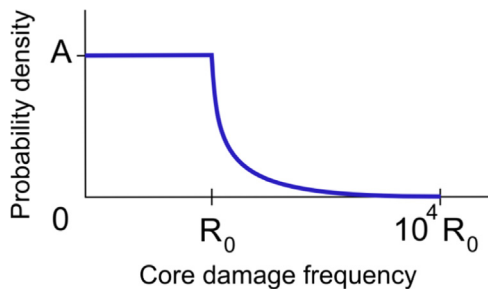


Fig. 2. Probability density distribution of risk.

$p(R)=Ae^{-B(R-R_0)}$. B is a constant chosen so that the probability for the risk R to be below R_0 is 90%. A is the normalisation constant ensuring $\int p(R)dR=1$. R_0 was chosen to be $10^{-7} \text{years}^{-1}$.

In the simulation, the expertise of each inspector impacts the probability for him/her to detect the full extent of the operator's lack of compliance. Therefore the impact on safety an inspector has can be quantified by the difference between the risk increase due to the operator's lack of compliance and the risk increase prevented by the inspector.

The aim of developing new regulations is to improve safety and therefore reduce the risk posed by nuclear plants. In the simulation, the expertise of the staff affects their ability to identify the areas where safety standards could be strengthened and to gather international experience, expert opinion and new scientific findings in order to maximise the risk reduction.

Rule-makers develop four new regulations per year aimed at reducing the risks to ALARP levels. The risk reductions these can potentially achieve follow the same probability distribution as the one used for inspections. R_0 was chosen so that the contribution of rulemaking and inspections to risk reduction is the same on average. A and B were chosen to satisfy the same conditions used for inspections given the same level of expertise of junior staff. Table 2 provides the numerical values for A , B and R_0 for both inspections and rule-making.

The impact on safety of the rule-making staff is therefore the difference between the risk reduction the new regulations would ideally achieve and the risk reduction actually obtained.

There is a probability for junior staff to fail to adequately perform the task they have been assigned. It is equalled to $k \times \frac{\text{expertise}}{R}$. R is the ideal risk reduction the regulatory task could achieve and k is a constant chosen so that for $R=R_0$ and for an expertise of 65%, the probability is equalled to 0.1%. Should they perform the task, the probability of success is equalled to its expertise whilst the probability of failure is equalled to one minus its expertise. In case of success, the risk reduction achieved by the task is equalled to R . In case of failure the risk reduction achieved by the task is equalled to $R \times \text{expertise}$.

There are several instances when the tasks done by a junior staff are reviewed. If the risk reduction achieved by an inspection is above R_0 , the senior inspector reviews the work. The entire junior rulemaking staff reviews the work made by each rulemaking staff and the regulation draft is reviewed by the senior

Table 2. Constants used for the probability density distribution of risk for inspections and rulemaking.

	Inspections	Rulemaking
$R_0(\text{years}^{-1})$	10^{-7}	4.1×10^{-7}
A (years)	9×10^6	2.2×10^6
B (years)	9×10^7	2.2×10^7

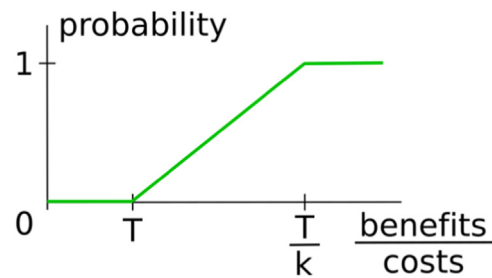


Fig. 3. Probability of the stakeholder appealing a decision as a function of benefits over costs.

rulemaking staff. There is a probability that the review is not performed. It is equalled to $k \times \frac{\text{expertise}}{R}$. k is chosen so that for $R=R_0$ and for an expertise of 88%, the probability is equalled to 1%. For the group review, the average expertise of the junior rulemaking staff is taken as expertise. If the task was done correctly, the work is left unchanged. If it was not, the probability for the review to successfully notice the flaws of the work is equalled to the expertise of the reviewer. If the flaws are noticed, the work is done again and successfully, if they are not, the work is left unaltered.

5.1.2. System of appeal (accountability mechanism 1)

The first accountability mechanism is a system of appeal stakeholders can call on to overrule a regulatory decision they find improper. The mechanism follows the process described in Fig. 4a. Its characteristics are expertise, time and resources which impact its capacity to judge accurately regulatory decisions.

The main simplification for the appeal mechanism is that it can either uphold a regulatory decision or replace it with a better one but cannot take a decision that would make matter worse than the initial decision taken by the regulator (worse, in terms of negative impact on safety).

Its final attribute is ease, which provides information on how easy it is for a stakeholder to win an appeal. For instance, restricting the grounds on which an appeal may be filed is particularly effective to reduce the probability of a successful appeal.

Stakeholder modelling

In the simulation there is only one stakeholder. The main simplification made is that the stakeholder is completely informed of the activities undertaken by the regulator.

It reviews each regulatory decision made, and based on this assessment, it decides whether to appeal the decision using the first accountability mechanism.

The stakeholder possesses one main characteristic, expertise, which affects the accuracy of the assessment it makes of regulatory decisions. In addition it is allocated a yearly budget which sets a limit to the amount of appeals it can sue for.

Fig. 3 shows the probability for the stakeholder to appeal a decision as a function of benefits to costs ratio. The benefits are the perceived difference between the maximum core damage frequency reduction the regulator could achieve and the reduction actually obtained times the likelihood of winning the appeal given by the ease of the system of appeal. The costs are the appeal costs to the stakeholder. If the benefits to costs ratio is below a certain threshold T , the stakeholder does not appeal, above T , the probability to appeal rises linearly and is equalled to 1 when the benefits over costs reaches the value $\frac{T}{k}$ where k is constant between 0 and 1.

5.1.3. Audit office (accountability mechanism 2)

The second accountability mechanism is an audit office. It deals with management and organisational failures of the regulator and

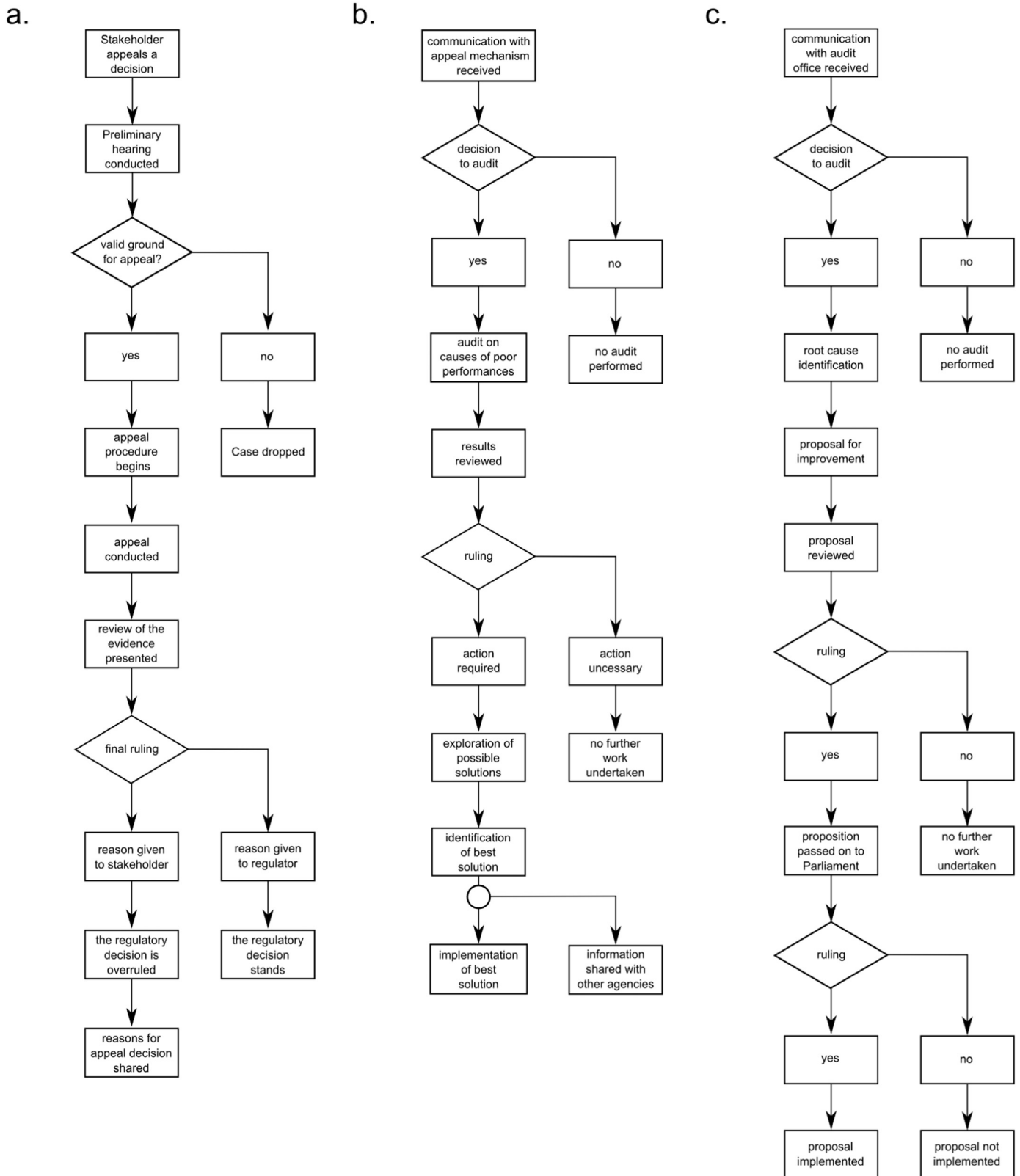


Fig. 4. Decision-action diagrams describing the processes through which the regulator is held to account.

aims at boosting its performance by detecting and finding solutions against these failures. It follows the process displayed in Fig. 4b. In the simulation, the only way to trigger an audit is for the audit office to become aware of poor regulatory performance thanks to the appeal mechanism records. The probability of the

audit office starting an investigation is proportional to the amount of regulatory decisions having been repealed during the year.

The attributes of the audit office are similar to the first accountability mechanism: expertise, time and resources all impact the office's capability to identify both the source of the problem

and an adequate solution. There are two additional characteristics: focus, describing how much a priority is the nuclear regulator for the audit office; and communication with the first accountability mechanism which gives a measure of the extent of information exchange between the two institutions.

5.1.4. Parliamentary scrutiny (accountability mechanism 3)

The third accountability mechanism deals with regulatory failures that can only be tackled through an act of the parliament. Thus this mechanism is the combination of a body (such as a Parliamentary Select Committee) whose role is to detect these failures and find adequate solutions and the parliament, whose role is to make the former's proposals a reality. The process followed is shown in Fig. 4c.

As the body in charge of detecting regulatory failures share similar features with the audit office, it is modelled in the simulation using the same characteristics. They are namely, expertise, time, resources, focus and communication with the second accountability mechanism. The parliament is described by only one characteristic: political risk which is a measure of the capacity of members of parliament to set aside politics and take the necessary actions.

5.2. Regulatory failure modelling

The sequence of regulatory failures chosen for the Monte-Carlo simulation is displayed in Fig. 5. It shows the effects deep cuts of the nuclear regulator's budget have on the training quality of the regulatory staff, which over time impacts its expertise.

5.3. Simulation

Time is discretised in time steps of 1 year. The state of the system at time t is represented by the expertise score of each regulatory staff, the quality of the initial training and the status of continuous training.

Initially the regulator is effective. Each staff is assigned an initial expertise score using a probability density function presented

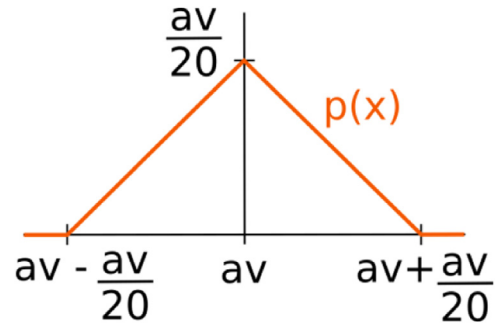


Fig. 6. Triangular probability density function.

in Fig. 6. Where, av is the average expertise score and it is set at 65% and 88% for junior and senior staff respectively.

There are two mechanisms which impact the evolution of the expertise of the regulatory staff.

The first is staff turnover: each year, every junior staff has a probability of 8% to leave whilst every senior staff has a probability of one sixteenth to leave. Thus, on average, 1.6 junior staff leaves per year and one senior staff leaves every eight years. A junior staff leaving is replaced by a new recruit. A senior staff leaving is replaced by one of the three best junior staffs of the appropriate field (inspection or regulation), chosen at random. The junior staff taking over as senior staff is in turn replaced by a new recruit.

New recruits are trained and assigned an expertise score using the same triangular probability density function, with the average expertise equal to the quality score of the initial training.

The second mechanism is continuous training. All regulatory staff are continuously trained to ensure they progressively gain expertise. Every year, the expertise score of each regulatory staff changes by a certain amount, assigned using the triangular probability density distribution displayed in Fig. 6. The average expertise variation is dependent on the status of the continuous training described below.

It is assumed that the initial training is run by the junior regulatory staff, thus the quality of the training is impacted by the expertise of the junior staff. The quality of the initial training is set at 75% of the average expertise score of the junior staff. When the budget reduction is introduced, the quality of the initial training drops to 45%. It remains there until 75% of the average expertise score of the junior staff falls below this value, at which time the former relationship between the two variables is restored.

Both senior and junior staff expertise score cannot drop below 15%.

The status of continuous training can assume several possible discrete values displayed in Table 3 along with the associated average yearly expertise score variation.

The simulation runs for 60 years. At $t=0$ the budget reduction is introduced, causing an immediate drop in the quality of initial training and the continuous training status is switched to failing.

The stakeholder can appeal any regulatory decisions made during the year whilst poor regulatory performance may trigger an audit the same year or several years in the future.

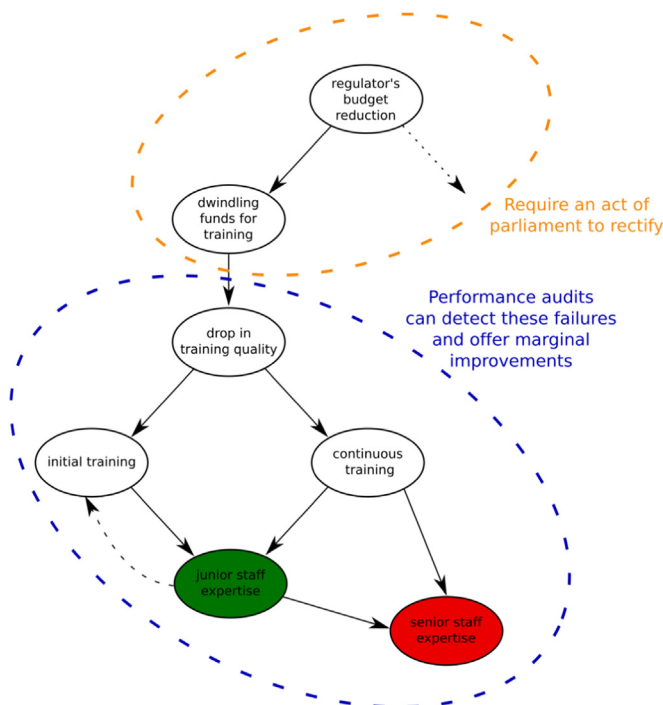


Fig. 5. Diagram displaying the failure sequence the regulator is afflicted.

Table 3. Status of the continuous training and the associated average yearly variation in expertise.

Status	Average variation
Failing	-1%
Less failing	-0.5%
Not failing	+1.5%
Boosted	+6%

If the audit office determines the cause of the regulator's poor performance and successfully implements tangible improvements, the status of continuous training switches from *failing* to *less failing*. In addition, the regulatory staff must attend an intensive course which increases their expertise score by 10%.

Should the audit office solutions be found insufficient to adequately restore the effectiveness of the regulator, the third appeal mechanism may launch a more in-depth investigation which may eventually result in an act of parliament solving the budget issue.

When the budget issue is solved, the continuous training status changes from *less failing* to *boosted*, as training becomes a priority. Only when the average junior expertise score reaches 65% does its status switch to *not failing*.

6. Results and discussion

10,000 independent iterations were performed to reduce the statistical errors of the results. However, as this simulation is merely a proof of principle, statistical uncertainties will not be discussed in this work.

6.1. Impact of accountability systems

Figs. 7–9 illustrate the impact of the three different systems of accountability (SoA) on regulatory expertise and on nuclear safety. System A is only made of an appeal mechanism, system B is made of the appeal and the audit mechanisms whilst system C is made of all three accountability mechanisms.

Figs. 7 and 8 present the probability density function (pdf) of the average expertise of the junior regulatory staff, at three times, 20, 40 and 60 years for accountability systems B and C respectively. The pdf is used to calculate the probability $P(t)$ that for a random simulation run, the regulator will have an average junior expertise at time t between E_1 and E_2 :

$$P(t) = \int_{E_1}^{E_2} p(E, t) dE \tag{1}$$

Where $p(E,t)$ is the pdf of the average expertise of the junior regulatory staff.

Only equipped with an appeal mechanism, the accountability system A cannot impact the expertise of the regulatory staff. As a result, in Fig. 7, the pdf of the average junior expertise is the same as for a failing regulator without an accountability system. Expertise decreases continuously until it reaches its lower limit of

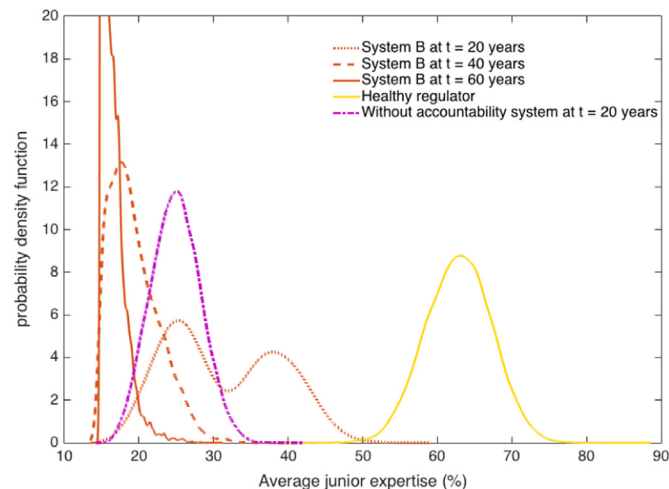


Fig. 7. Pdf of the average junior expertise for accountability system B, at time 20, 40 and 60 years.

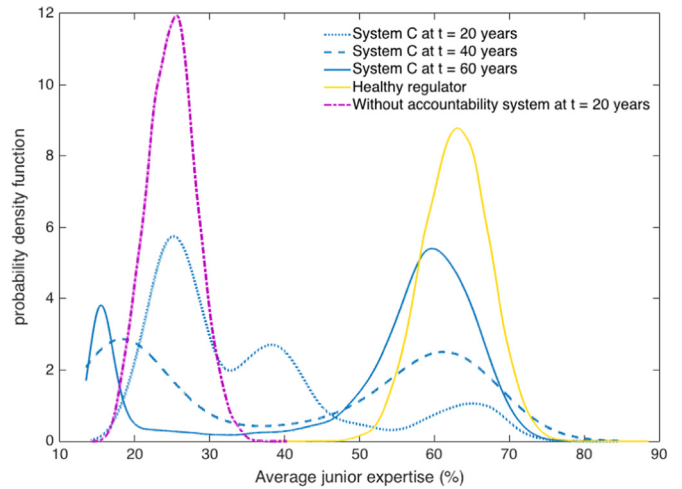


Fig. 8. Pdf of the average junior expertise for accountability system C, at time 20, 40 and 60 years.

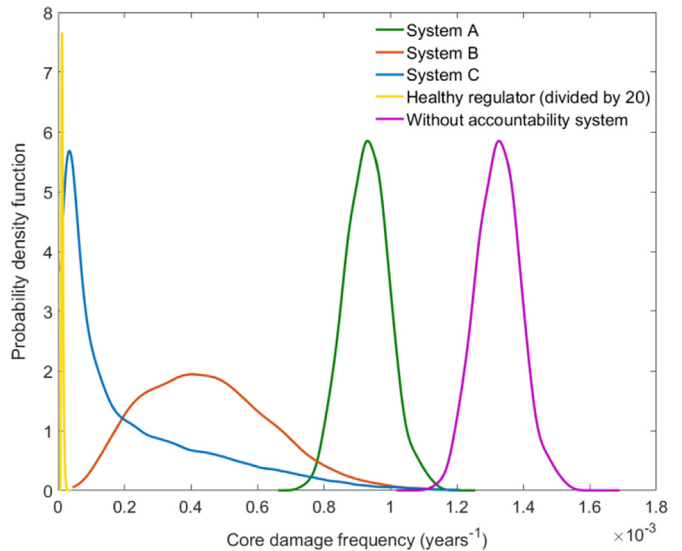


Fig. 9. Pdf of the cumulative difference between ideal and actual decrease in risk per plant achieved by the regulator.

15%. After 20 years, the average expertise of the junior regulatory staff is comprised between 15% and 35%. At later times $t=40$ and 60 years, in all the simulation run, the staff has the minimum possible expertise and the pdf of the average expertise is thus a Dirac delta function.

With system B, at time $t=20$ years, the pdf is formed of two bell curves, one with a peak at 27%, and another, with a smaller peak at 39% but larger width. This shows that in the simulation, one of these two scenarios happened: either the audit office detected the failings of the regulator and took action to resolve the issue which resulted in an average junior expertise between 32% and 50%. Or the audit office failed to detect any regulatory failures, and the average junior expertise continued to fall as with system C. Using Eq. (1), the probability of each scenario was found to be 50:50. At time 40 and 60 years, the pdf is only formed of one bell curve that becomes growing taller and thinner with time and whose peak gradually approaches 15%. At $t=60$ years, the pdf peaks to 94 at an average junior expertise of 15%. This emphasises that the audit office, as it does not possess the power to tackle the real root cause of the issue, can only slow down the inexorable loss of regulatory expertise. This may have implications for policy makers.

With system of accountability C, at time $t=20$ years, the pdf is formed of three bell curves. The first one is identical to the one found for system B. This is hardly surprising as their respective audit office have the same characteristics and thus have the same chance to have detected the regulatory failure during the first 20 years. The second bump in the pdf peaks at 39% whilst the third and smallest peaks at 66%. The shape of the curve indicates that three possible scenarios can occur, either the audit fails to identify any regulatory failures, either the audit office does act but the third accountability mechanism does not, or both mechanisms act and the root cause for the poor performance of the regulator is found and fixed. Using the pdf to calculate the probabilities of each outcome, the split was found to be 50:40:10. Pdfs at times 40 and 60 years indicate that the chances for the regulatory failure to go unnoticed becomes slimmer as time goes by, as might be expected. After 60 years, there is still a 15% chance that the accountability system has yet to resolve the issue however.

Fig. 9 shows the pdf of the cumulative difference between ideal and actual core damage frequency decrease achieved by the regulator.

As expected, the system A is the least effective. The cumulative core damage frequency increase per plant has a 95% chance to be between 0.8 and $1.1 \times 10^{-3} \text{ years}^{-1}$. Compared with the pdf obtained without any accountability mechanism, it is simply shifted $4 \times 10^{-4} \text{ years}^{-1}$ to the left, which gives the direct impact of the appeal mechanism on nuclear safety.

With system B, the spread of the cumulative core damage frequency increase is much wider. There is a 90% chance for it to be between 2 and $7 \times 10^{-4} \text{ years}^{-1}$. Indeed the faster a successful audit is made, the more impact it will have. Its action marginally improves the regulator's continuous training program thus attenuating the yearly drop in expertise which in turn impacts the quality of its work.

With a full accountability system, there is a 8% chance for the cumulative core damage frequency per plant to be at the level of a healthy regulators at $10^{-5} \text{ years}^{-1}$, and a 45% chance to be below $10^{-4} \text{ years}^{-1}$, less than the most optimistic scenario for a failing regulator with accountability system B. The probability density then decreases slowly between 0.2 and $1.0 \times 10^{-3} \text{ years}^{-1}$. Again, the explanation for this behaviour is that the sooner the audit office and the third accountability mechanism successfully act to resolve the regulatory failures, the greater the impact on the core damage frequency increase.

These numbers may seem quite high, especially for a healthy regulator, but in the simulation, it is assumed that a regulatory error cannot be rectified later on. As a result, even after the accountability system resolves the budgetary issues of the regulator, the damage done cannot be undone.

6.2. Costs of accountability systems

Figs. 10–12 provide the details of the average costs of each accountability system. The costs of individual accountability mechanisms are given without using a discount rate so as to offer a good indication as to when they are being used. For the total cost of a system of accountability, both the undiscounted and discounted costs are shown. A constant discount rate of 5% was used for the simulations.

The activities of system A are straightforward. As the regulatory expertise tumbles, the quality of its work suffers and the stakeholders appeal decisions more and more frequently. As the result, the cost of the appeal system increases sharply. The stakeholders have limited funding however. Thus, demands for appeals plateaued after 20 years.

The appeal mechanism in system B is marginally less used than

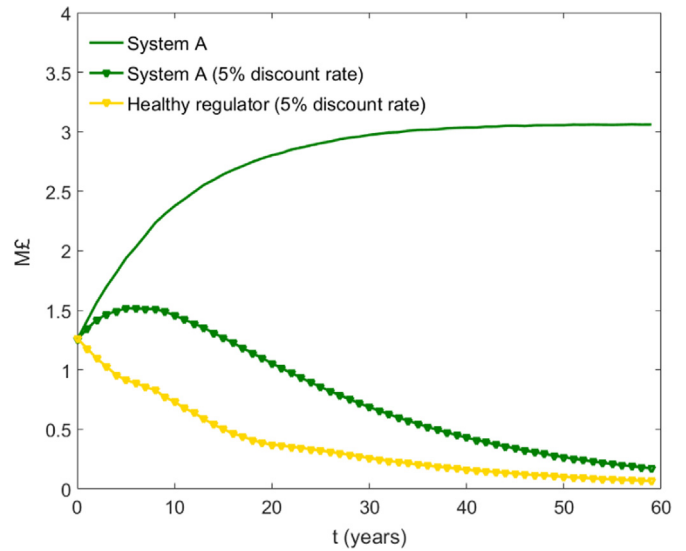


Fig. 10. Costs of accountability system A.

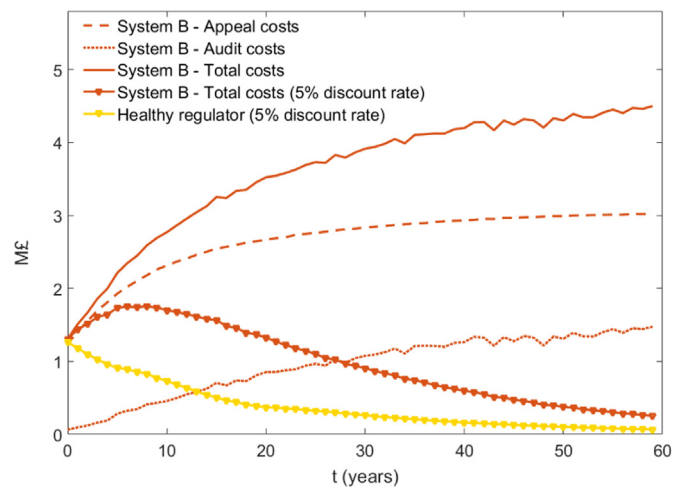


Fig. 11. Costs of accountability system B.

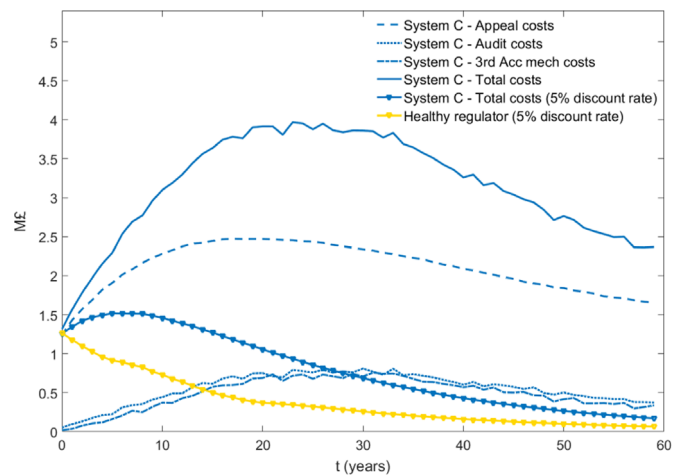


Fig. 12. Costs of accountability system C.

in system A as the regulatory expertise is, on average, raised by the actions of the audit office. The cost of the audit office increases with time, mirroring the rise in the appeal cost. Indeed, the probability of an audit being launched is proportional to the

amount of regulatory decisions having been appealed during the year. The first successful appeal offers marginal and temporary improvements to the regulator. The audit office can conduct more audits, but without the third accountability mechanism, these will have no impact on regulatory expertise. Thus the cost of audits eventually plateaus instead of decreasing.

With system C, the audit office costs are tightly linked to its system B counterpart during the first 20 years. In addition, during this time period, the cost curve for the third accountability mechanism is of the same shape as the audit office cost, only shifted by about 5 years. After 20 years, both the cost of the audit office and of the third accountability mechanism decreases at the same pace. This means that, on average 5 years after a first audit, the third accountability mechanism takes action and resolves the regulatory issue. Due to its actions, the chances for the regulator to be failing decreases with time. This ultimately results in the slow decrease of the average costs of all three accountability mechanisms.

6.3. Comparison of costs and benefits of accountability systems

The simulation also provides the means to compare average costs and benefits of the different systems of accountability.

The costs of the system are simply the sum of the costs of each accountability mechanisms.

In order to provide an estimate of the benefits, the increase in risk experienced due to the poor performances of the regulator were multiplied by the cost of an accident. In this simulation, it was assumed that this cost is merely the loss of revenue for the operator due to the plant's early closure. Thus, the cost of an accident is, on average, the average revenue of a nuclear plant per day times the average time left before closure.

It was assumed that the 10 plants in the simulation have a lifetime of 60 years, that they all have been constructed 6 years apart and that every time a plant closes, a new one comes online. The average revenue of a plant per day was chosen to be £1,000,000.

The results are displayed in Table 4. It displays the average cumulative cost for the system of accountability, the average cumulative risk increase per plant and the average cost due to early plant closures over the duration of the simulation. Finally, it displays the cost benefit ratio where the cost is the cumulative cost of the accountability system while the benefit is the avoided costs due to early plant closures thanks to the accountability system.

Based on these numbers – which are not meant to be taken literally – each additional accountability mechanism results in a better value for money.

The cost benefit ratio drops from 0.59 with only one appeal mechanism to 0.3 with all three accountability mechanisms.

As previously mentioned, the simulation does not allow the regulator to rectify errors it has done in the past. It results in a higher risk increase, especially for healthy regulators as they are more likely to notice a past regulatory error and take the necessary actions. Thus the increase in core damage frequency and in cost due to early plant closures are overestimated.

6.4. Discussion

This section highlights that this very simple Monte-Carlo simulation can be used for studying a wide range of scenarios. For instance, one could explore the effect of stakeholder funding on the performances of the system of accountability, or compare a system of accountability having a quick and inexpensive appeal mechanism with a system having a long and expensive one. Indeed, it can provide useful information to policy makers in determining a new regulatory system of enhancing an existing one.

However, it is important to note that some the simplifications used reduce the potential uses of the simulation in its current form, although the further work planned is anticipated to address such issues.

For example, since there is only one regulatory failure sequence, only one audit and one investigation performed by the third accountability mechanism are required to solve the problem. As a result, the simulation cannot be used to study the impact of different amounts of funding for the audit office and the third accountability mechanism.

In addition, the possibility of exploring the relative importance of each accountability mechanism is reduced by two key assumptions:

An audit can only be launched following the overturn of a regulatory decision by the appeal mechanism and an investigation by the third accountability system can only be launched once it has been warned by the audit office. In reality, these audits can be triggered by many other events, such as the claims of a whistleblower.

However, this simulation is a proof of principle, the developed method will be able to address these questions.

Other limitations include the simplicity of the decision-making process models used (such as the process determining whether the stakeholder appeals a regulatory decision) and the fact that the probability distributions were chosen using best judgement. There is extensive research on more elaborate and more realistic information processing and decision-making models (for example Rehner and McCauley (2016), Zhu et al. (2016). Kavvadias and Khamis (2014) describe the process to find the best fitted probability distributions for a Monte-Carlo simulation. These will be studied further to enhance the accuracy of the method of assessment.

Sensitivity studies were performed to analyse the impact of the average junior expertise for a healthy regulator and of the discount rate on the results. The results are in the appendix.

7. Conclusion and policy implications

7.1. The research

One of the major causes of catastrophic events such as the Fukushima-Daiichi nuclear accident and the collapse of banks that led to the 2008 financial crisis is the lack of an effective regulatory regime. To assure effectiveness, regulatory systems have to be backed up by an appropriate accountability system.

Table 4.
Costs and benefits of the three systems of accountability.

	No SoA	SoA A	SoA B	SoA C	Healthy regulator
Cost of the accountability system (M£) over 60 years	NA	48	58.5	58.9	22.7
Cumulative increase in risk per plant (10^{-3}yrs^{-1}) over 60 years	1.32	0.93	0.45	0.22	0.01
Cost due to early plant closures (M£) over 60 years	265	184	92.3	67.8	8.0
Cost benefit ratio	NA	0.59	0.34	0.30	NA

In this paper it was argued that the optimisation of regulatory accountability is held back by: (i) a lack of understanding of what the objectives of such systems should be and, (ii) the absence of systematic method to assess systems of accountability and allow their comparison.

This paper addresses the first of these issues by developing a definition of an effective accountability system through stating its fundamental aim and the necessary characteristics in order to achieve it. It goes on to address the second issue by presenting a method of assessment of accountability systems based on safety assessment techniques used in the nuclear industry.

A simple Monte-Carlo simulation is reported that demonstrates the principles of the method of assessment and illustrates the kind of information and results it will be able to procure on regulatory accountability systems.

7.2. Policy implications

Three distinct groups stand to benefit from this research. First, it will provide policy makers in governments tools to model the effectiveness and performance of nuclear regulatory systems of accountability, and evaluate the likelihood that regulatory failures lead to catastrophic failure of nuclear facilities. In turn this will help them make informed decisions on the most cost-effective way to fund each of their accountability mechanisms and help them determine whether greater changes to their accountability system is warranted. In addition, the results obtained will enable them to strike a better balance between independence and accountability of the regulator.

The research will also prove useful for nuclear regulatory bodies. Modelling regulatory activities will provide regulators with a tool to optimise the number of checks and balances each regulatory decision requires. This will in turn help them work toward decision-making processes that are both resilient to regulatory errors and efficient. In addition the modelling could use likely scenarios of future nuclear growth to inform regulators on their future human resource needs, training and organisational structures.

The last group that stands to benefit from this work is the nuclear stakeholders. It will provide them valuable information on their nuclear regulatory authorities and their decision-making processes as well as their system of accountability. This will ease and promote their involvement and enable them to have a more meaningful impact on regulatory decisions whilst reducing the amount of time they must devote to the task. In turn, this may lead to a greater trust and confidence in the regulatory systems.

Such uses of are particular relevance to policy makers in those countries (more than 30) who at present do not use nuclear power as part of their energy mix but are developing a programmes to do so to enhance energy security and address climate. Additionally, the work is anticipated to be beneficial to existing nuclear power states who are seeking to learn the lessons from the Fukushima-Daiichi Accident by enhancing their regulatory systems.

Finally work could also be used to improve cost-effectiveness of regulators regulating the safety of other energy related fields such as oil and gas and the chemical industry.

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Appendix A. Sensitivity studies

Impact of the average junior expertise for a healthy regulator

Method

Most variables used in the simulation were chosen arbitrarily as the research needed to make an informed choice has yet to be performed.

A sensitivity study was done to observe the impact of a change in the average junior expertise of a healthy regulator on the results obtained. The change thus affects both the initial average junior expertise and the average junior expertise after the regulator has been restored to its healthy condition by the system of accountability. For simplicity, in this section, the average junior expertise of a healthy regulator is referred as the initial expertise.

For the study, it was decided to maintain the average senior expertise of a healthy regulator constant at 88%. In order to satisfy the steady-state equations for junior and senior expertise of a healthy regulator however, both the average expertise of a new recruit, as well as the continuous training improvement rate for a healthy regulator had to be changed, alongside the average junior expertise.

Table A.1 summarises the values used in each simulation.

For each simulation, the regulator starts to fail at time $t = 0$, when the budget cuts are introduced. The system of accountability used for the sensitivity study is system C, comprised of all three accountability mechanisms.

Results

Figs. A.1 and A.2 display the probability density function for the average junior expertise at times $t = 20$ and 60 years respectively.

At $t = 20$ years, regardless of the initial expertise chosen, the pdf curves obtained have a similar shape. They are all formed of three bells that correspond to the three possible scenarios. Either the audit office fails to detect that the regulator is failing, either it does detect it but the third accountability mechanism has yet to investigate, or both have successfully acted. An increase in initial expertise has two main effects. First, it shifts the entire pdf to greater expertise. Second, it reduces the probability for the audit office to detect the regulatory failure in the first twenty years, from 55% for an initial expertise of 60% to only 25% for an initial expertise of 80%. Indeed, as the rate of improvement for a failing regulator is the same in all simulation, the greater the initial expertise is, the longer it takes the regulator to reach a level of deterioration that prompts the audit office to investigate, thus starting the 'healing' process.

At $t = 60$ years, the pdf curves are all formed of two bells which represent the two possible scenarios: If the third accountability mechanism has fixed the root cause of the poor performances of the regulator, it is either healthy or quickly improving and has an

Table A.1.
Expertise constants used for each simulation of the sensitivity study.

	Simulation	1	2	3	4	5
Healthy regulator characteristics	av. junior expertise (%)	60	65	70	75	80
	av. expertise of new recruit (%)	40.2	48.8	57.3	65.8	74.3
	av. rate of improvement (%/year)	1.9	1.5	1.2	0.9	0.5
	av. senior expertise (%)	88	88	88	88	88
Failing regulator characteristic	av. rate of improvement (%/year)	-1	-1	-1	-1	-1

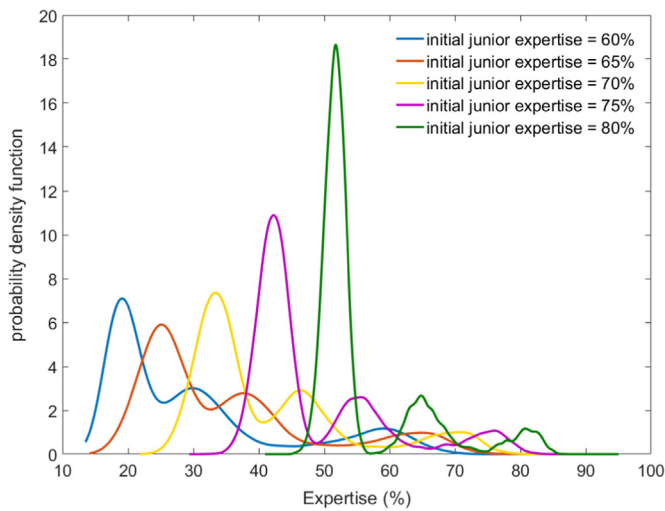


Fig. A.1. Pdf of the average junior expertise at time $t=20$ years for different values of initial junior expertise.

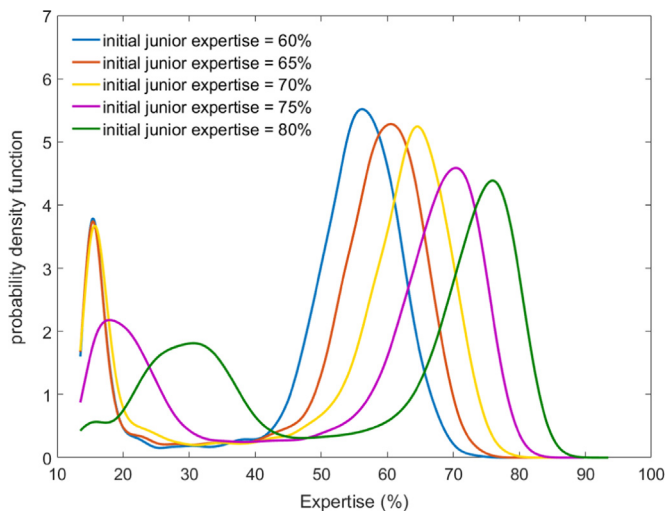


Fig. A.2. Pdf of the average junior expertise at time $t=60$ years for different values of initial junior expertise.

average junior expertise close to the initial one. If the third accountability mechanism has yet to resolve the budgetary issue, the average junior expertise is close to the minimum.

For an initial expertise between 60% and 70%, the pdf curves are nearly identical. All three have the same bell curve, centred at an average junior expertise of 17% and their second bell curve have the same shape, albeit centred on their respective initial expertise.

For higher initial expertise, the first bell curve becomes wider and shifts to higher expertise, from 19% for an initial expertise of 75–30% for an initial expertise of 80%. The second bell curve keeps the same width as for lower initial expertise and continues to be centred on the respective initial expertise; however the peak value of their pdf slowly decreases from 5.5 for an initial expertise of 70% to 4.3 for an initial expertise of 80%.

Regarding the probabilities for each scenario to happen, for an initial expertise between 60% and 70%, the probability for the third accountability system to have resolved the regulatory failure after 60 years is constant at 85%. For higher initial expertise, the probability drops sharply to only 65% for an initial expertise of 80%.

Fig. A.3 displays the impact of the initial expertise on the increase in risk for each plant resulting from the budget cuts imposed to the nuclear regulator.

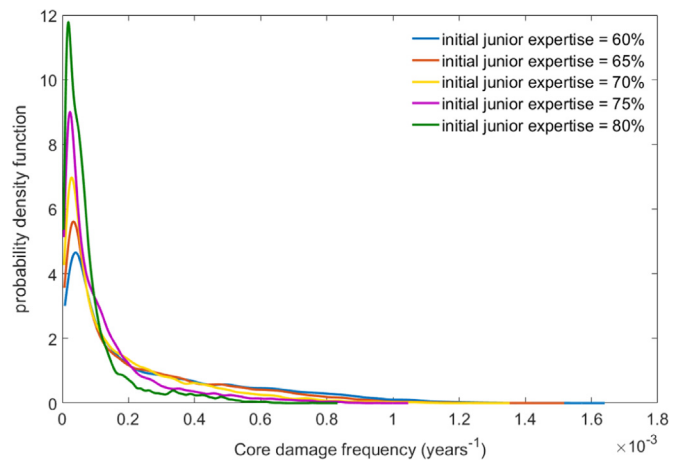


Fig. A.3. Pdf of the cumulative difference between ideal and actual decrease in risk per plant achieved by the regulator for different values of initial junior expertise.

The curves of all probability density functions have the same shape. They peak at a very low core damage frequency and sharply decrease with increasing risk.

The peak value of the pdfs rises and the peak position shifts to lower core damage frequency as the initial expertise is increased. With an initial expertise of 60%, the pdf reaches its maximum of 4.6 at $4 \times 10^{-5} \text{years}^{-1}$ and with an initial expertise of 80% the pdf reaches its maximum of 11.5 at $2 \times 10^{-5} \text{years}^{-1}$.

In addition, the higher the initial expertise is, the sharper is the fall in the value of the pdf with increasing core damage frequency.

In terms of probabilities, the cumulative increase in risk per plant has only a 50% chance of being smaller than at $2 \times 10^{-4} \text{years}^{-1}$ for an initial expertise of 60%. The probability reaches 90% for an initial expertise of 80%. There is a 99% chance that the cumulative increase in risk per plant is below $10^{-3} \text{years}^{-1}$ and at $5 \times 10^{-4} \text{years}^{-1}$ for the former and latter case respectively. Thus, increasing initial expertise from 60 to 80 on average halves the increase in risk due to budget cuts.

Table A.2 summarises the costs and benefits of the system of accountability for each simulation made. The cost of the system of accountability decreases only marginally when the initial junior expertise is increased. However both the cumulative increase in risk and the cost due to early plant closure plummet with an increasing initial junior expertise. Naturally, maintaining a higher level of expertise would incur greater expenditures for the regulator. However, this simple model only focuses on the effectiveness of the system of accountability, not the regulator itself. Thus, whilst the cost of the regulator should significantly rise with an increased junior expertise, the cost of the accountability system falls marginally.

This sensitivity study shows that increasing the initial junior expertise delays the action of the system of accountability. Thus, a regulator with higher initial junior expertise takes, on average,

Table A.2.

Costs and benefits of the system of accountability for different values of initial junior expertise.

Initial junior expertise	60%	65%	70%	75%	80%
Cost of accountability system (M€) over 60 years	60.4	58.9	56.8	53.5	49.9
Cumulative increase in risk per plant (10^{-3}yrs^{-1}) over 60 years	0.251	0.216	0.172	0.127	0.085
Cost due to early plant closures (M€) over 60 years	87.2	68.5	49.7	34.6	22.5

Table A.3.
Costs and benefits of the systems of accountability for different discount rates.

Discount rate		No SoA	SoA A	SoA B	SoA C	Healthy regulator
0%	Cost of accountability system (M£) over 60 years	NA	164	216	189	68
	Cost due to early plant closures (M£) over 60 years	2390	1673	787	508	42
	Cost benefit ratio	NA	0.23	0.13	0.10	NA
1%	Cost of accountability system (M£) over 60 years	NA	121	157	142	51
	Cost due to early plant closures (M£) over 60 years	1495	1056	495	328	29
	Cost benefit ratio	NA	0.28	0.16	0.12	NA
3%	Cost of accountability system (M£) over 60 years	NA	72	91	87	32
	Cost due to early plant closures (M£) over 60 years	610	426	206	144	14.5
	Cost benefit ratio	NA	0.39	0.23	0.19	NA
5%	Cost of accountability system (M£) over 60 years	NA	48	58.5	58.9	22.7
	Cost due to early plant closures (M£) over 60 years	265	184	92.3	67.8	8.0
	Cost benefit ratio	NA	0.59	0.34	0.30	NA
10%	Cost of accountability system (M£) over 60 years	NA	23.2	27.3	29.0	12.8
	Cost due to early plant closures (M£) over 60 years	44.2	30.4	17.4	14.5	2.7
	Cost benefit ratio	NA	1.68	1.01	0.98	NA

more time to recover from budgetary cuts. However, increasing the initial junior expertise has a very beneficial impact on the increase in risk and the cost due to early plant closure. Indeed, with an increase in initial junior expertise from 60% to 80%, the latter is divided by more than 3.

In the simulation, the simplification was made to have only one feature characterising the regulatory staff, one that therefore encompassed all characteristics that impact regulatory performance. This sensibility study hence emphasises how crucial it is to identify these characteristics and to choose their value to best represent a healthy regulator.

Impact of the discount rate

Five different discount rates were used in this study to investigate the sensitivity of the results to the constant discount rate chosen: 0%, 1%, 3%, 5% and 10%.

The results of the study are summarised in Table A.3. It displays the average cost of the accountability system over 60 years, the cost of early plant closures over 60 years and the cost benefit ratio for systems A, B and C using the five discount rates.

The results show that the cost due to early plant closure is slightly more affected by an increase in the discount rate than the cost of the accountability system is. This is because the undiscounted cost of systems of accountability increases fast for the first twenty years before slowing down and even decrease for system C. On the contrary, the cumulative risk due to poor regulatory performance can only increase with time since the model does not allow the regulator to correct past mistakes. As a result, the chances of a nuclear plant closing down early are highest at time $t=60$ years which in turn explains why an increase in the discount rate has a greater impact on the cost due to early plant closure.

As a result, the cost benefit ratio increases with the discount rate. However, increasing the discount rate has no impact on the relative efficacy of the different accountability systems. System C conserves the lowest cost benefit ratio regardless of the discount rate used. Thus, it can be concluded that for comparing the effectiveness of different systems of accountability, the choice of the discount rate has only a limited impact.

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