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Flexible decision making in the wake of large scale nuclear emergencies: Long-term response

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ABSTRACT

We develop a decision-making model that describes optimal protection and recovery strategies for a single economic location affected by radioactive release from the nearby Nuclear Power Plant. The initial period of release and deposition is characterised by high degrees of uncertainty, which is likely to lead to precautionary emergency measures being carried out regardless of the actual dangers to the public, and therefore it is excluded from the optimisation problem. Instead, the analysis is performed on the timescale of weeks, months, years and decades after the accident, implying that the problem is largely deterministic if one disregards long-term economic uncertainties. It is on these longer timescales that economically-driven decisions could be made on whether or not to implement various protection and recovery measures, which include relocation, remediation, repopulation and food banning. Our model allows one to find the joint cost-minimal strategy across the set of measures, providing certain spatial and temporal flexibilities are permitted. Several qualitatively different strategies are identified, including those with no relocation and delayed remediation. Which strategy is optimal depends on the initial radiation levels, the rates and costs of the individual actions, and the preferred economic valuation of the relevant health effects associated with radiation. Our main message is that in many possible settings relocation should be used sparingly and repopulation should be delayed to exploit natural decay of the radioactive elements. These findings could provide useful recommendations to regulators in civil nuclear industry and help devise better policies for implementing emergency response and recovery measures.

1. Introduction

1.1. Overview of the nuclear risk issues

Energy policy issues have remained high on the political agenda both on national and international levels since the turn of the century, driven by the common economic factors such as growing energy demand, scarcity of resources and volatility in the price of fossil fuels, as well as growing concerns over climate change (IEA-NEA, 2010; IPCC, 2013). Several countries around the world see nuclear power as an important route for cutting carbon emissions while meeting their energy demands in the future (IPCC, 2014), even though the viability of the nuclear option in a sustainable energy mix is being debated constantly (Kaygusuz, 2012; Mari, 2014; Mez, 2012; Verbruggen, 2008).

Nuclear power is often regarded to be amongst the safest forms of electricity generation, taking into account the complete worldwide electricity production chains, with some arguing that this result holds even after the possibility of large nuclear accidents is included in the analysis (Kearns, Thomas, Taylor, & Boyle, 2012). Nevertheless, it is evident from the accidents at Chernobyl, 1986, and Fukushima, 2011, that severe nuclear disasters can occur, and even though their probability is extremely low, there is a clear need to devise and implement adequate strategies aimed at reducing the radiological risks to public. A number of methodologies and software packages, often referred to as Decision Support Systems, have been developed to aid this (Bartzis et al., 2000; French, 1996; Geldermann et al., 2009; Hämäläinen, Lindstedt, & Sinkko, 2000; Hoe & Müller, 2003; Landman, Päsler-Sauer, & Raskob, 2014; OECD/NEA, 2000; Papamichail & French, 2005; Wex, Schryen, Feuerriegel, &

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Neumann, 2014). As one recent report puts it, "in order to effectively position nuclear power in the long-term energy mix, nuclear policy needs to highlight nuclear safety even more by developing advanced nuclear technologies and by upgrading nuclear safety standards continuously after Fukushima" (Fujii & Komiyama, 2015).

The preparedness stage for a nuclear accident focuses on assigning exclusion zones as well as optimally locating medical supplies (primarily iodine tablets) in potentially vulnerable areas. Given that there is already an extensive literature on disaster management that can be applied to solve this problem (see Paul and MacDonald, 2016, for an example of state of the art techniques), we do not consider the preparation stage in our model. The literature on dynamic decision making and economic optimisation in the response and recovery phases is, however, considerably less mature (Altay & Green III, 2006).

Immediate response to a nuclear accident involves procedures for evacuation, sheltering, iodine tablets distribution, whereas recovery measures include long-term relocation and remediation, as well as potential repopulation of the affected areas (Gering, Gerich, Wirth, & Kirchner, 2013; Higgins et al., 2008; Munro, 2013). The key difference between the response and recovery stages is, therefore, the timescale on which the relevant measures are implemented: while emergency response can take place on the timescale of minutes, hours and days in the immediate aftermath of a nuclear disaster, recovery measures often span over weeks, months and years (DECC, 2013). As a result, the degrees of uncertainty for the radiation rates and doses during the response and recovery stages differ greatly: the shorter timescales are characterised by potentially volatile changes in the release rates and in weather patterns affecting nuclear deposition, and this is likely to restrict flexibilities in the emergency decision-making. Short-term response, therefore, is expected to have typical features of emergency planning, when precautionary actions may not necessarily be justified in economic terms (Dana, 2002; Klinke & Renn, 2001).[1]

Long-term post-accident response and recovery planning, on the other hand, is characterised by significantly lower levels of radiological uncertainty, and requires multiple economic as well as non-economic factors to be taken into account (French, 1996; Geldermann et al., 2009; Hämäläinen et al., 2000). It is possible that governments are going to prioritise the economic factors by seeking to minimise the total cost of preventative and recovery measures (Munro, 2011; 2012). Such a strategy is expected to provide value for money as long as it accounts for the health costs of mortality and morbidity from radiation. However, the multiple non-economic factors associated with nuclear accidents imply that the initial relocation may still have to be carried out in many cases regardless of the costs involved, which shifts the focus to the long-term economic viability of remediation and eventual repopulation of the relocated area. The present paper is dedicated to finding cost-minimal long-term prevention and recovery strategies after a severe nuclear accident, given a hypothetical set of flexibilities specified by the regulators. To identify these flexibilities, we turn to the lessons learnt in the aftermath of the Chernobyl and Fukushima disasters.

Of the vast literature on Chernobyl, the two key studies on the long-term measures are (Lochard & Schneider, 1992) (contamination and population distributions, resettlement and health costs) and (Jacob et al., 2009) (remediation costs in rural areas); see also (IAEA, 2006; Karaoglou, 1996). These studies are based on the actual data from the affected populations and territories, and recommend a variety of cost-efficient strategies. The Fukushima disaster, on the contrary, occurred a relatively short time ago (in radiological terms) and was accompanied by considerable devastation caused by the earthquake and the tsunami, making it harder to quantify the long-term economic effects of the event itself. The existing studies on Fukushima have focused on providing contamination maps and summarizing early-stage radiological impacts on the environment (IRSN, 2011; 2012), analysing health effects for the affected populations (González et al., 2013; Harada et al., 2014; WHO, 2013), assessing economics of decontamination (Munro, 2013) and people's intention to return to their evacuated family homes (Munro & Managi, 2014). A comprehensive up to date review of the multiple consequences of the Fukushima disaster (Ahn et al., 2015) advocates that "scientific and academic communities should start efforts for establishing the scientific bases, both natural and social, for better societal resilience."

Central to the present study are the notions of *temporal* and *spatial flexibilities*, which have a very specific meaning in the context of nuclear emergency management. The temporal flexibilities involve the ability to implement various protection and recovery measures at different moments in time to ensure minimal radiological exposure while minimising the associated costs. The spatial flexibilities imply that it is possible to treat different locations in the vicinity of the nuclear power plant, often referred to as exclusion zones, differently depending on their radiological and economic conditions.

1.2. Temporal flexibilities

A considerable amount of research activities in the field of nuclear emergency planning has been dedicated to developing complex Decision Support Systems (DSS) such as ASTEC, ARGOS, RODOS, SPEEDY, COSYMA, COCO-1 and COCO-2. These software packages are capable of modelling various physical processes and decision-making scenarios as the accident unfolds, which includes the core meltdown and production of the relevant source term, transportation and deposition of the released radionuclides for given meteorological conditions and for a specified terrain, short-term emergency response measures, longer-term economic effects and recovery measures, and long-term health effects. The detailed input data for these packages can be obtained from economic and population databases such as GIS for many locations throughout the world (De Silva & Eglese, 2000), including those near the existing nuclear installations.

The DSS that is most relevant to the present study is COCO-2 (Higgins et al., 2008). It provides a great level of detail concerning post-accident economics, including estimates for health costs and remediation costs for each specified area of land, all depending on the initial contamination (generated separately by ARGOS, RODOS or any other suitable software package). The calculations are run on the timescale of up to two years after the accident. One downside, however, is that COCO-2 does not allow flexible decision making: it requires the user to select one particular strategy for which the relevant retrospective cost calculations are subsequently performed. Therefore, COCO-2 misses out on the *long-term temporal flexibility* in decision-making and makes no attempt to find strategies that are economically efficient at different points in time whilst complying to various regulations.

Finding the cost-minimal strategy through trial and error would be a vast undertaking as the number of different scenarios quickly escalates. However, these sorts of optimal control problems are commonly solved in Mathematical Finance and, more generally, in Operations Research (Sahebjamnia, Torabi, & Mansouri, 2015), and we are going to follow that framework here to identify the best post-accident recovery strategies. Such a framework will provide a superstructure to COCO-2.

[1] Indeed, several decision-makers in the relevant ministries in Europe, as well as senior academics working in this field, have stated that there are no and cannot be any monetary constraints while responding to a nuclear accident (private correspondence).

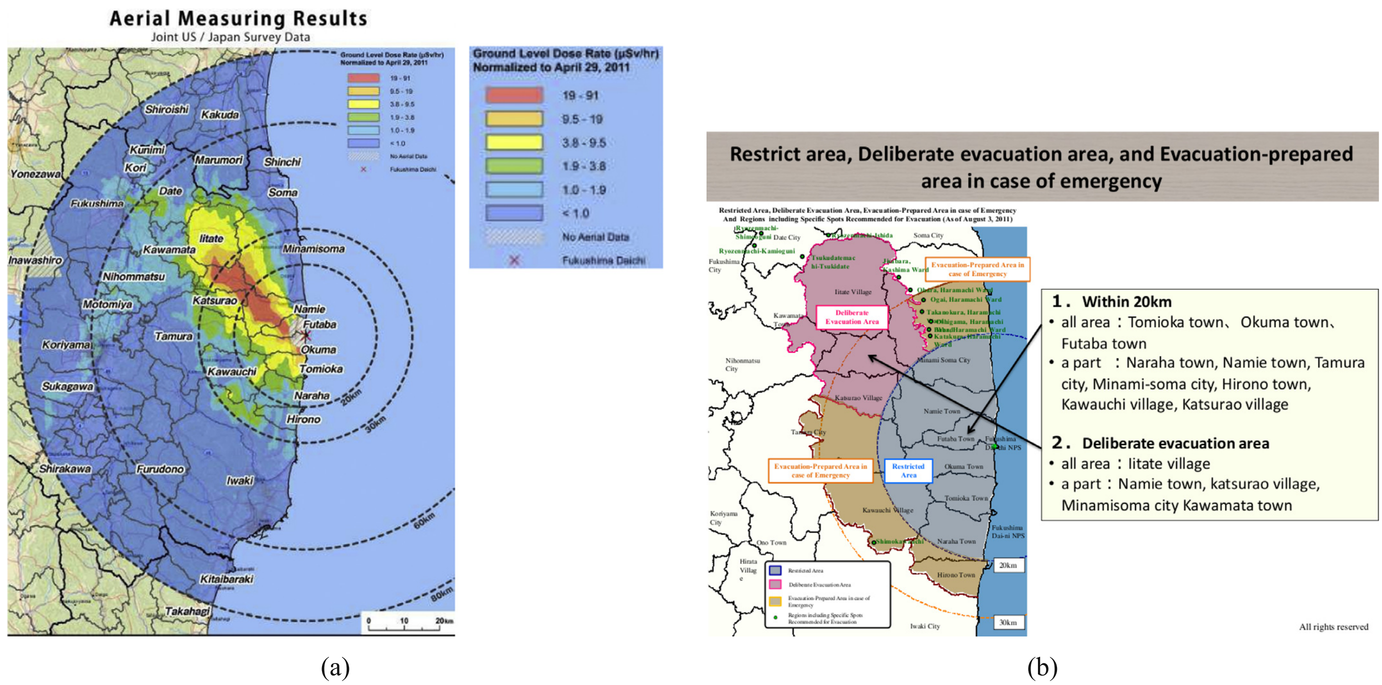

Fig. 1. (a) Radiation map and basic exclusion zones in the Fukushima area (MEXT and DOE airborne monitoring data); (b) Restricted area, Deliberate Evacuation area and Evacuation-Prepared area near Fukushima (from Akahane, 2013).

1.3. Spatial flexibilities

It is clear that choosing the location of each nuclear installation is a balancing act between various factors, most importantly the proximity of the sites to urban areas with significant population (Grimston, Nuttall, & Vaughan, 2014). Whilst the so-called semi-urban installations (for example, at Hartlepool and Heysham in the UK) could reduce operational and transmission costs, they pose a greater risk to the nearby population, and therefore require detailed emergency planning.

The radiological data from Fukushima (Fig. 1(a)) reveals extensive patches with high radiation (above the standard Emergency Reference Levels) beyond the 30 kilometres exclusion zone, while there remain significant areas inside the zone with very low or zero contamination.[2] It is possible that emergency evacuations and long-term relocations inside these relatively unaffected areas might have caused psychological and economic harm comparable to (or even exceeding) the potential radiological harm averted by these actions (Ahn et al., 2015), as arguably was also the case in for a number of evacuations in the aftermath of Chernobyl (IAEA, 2006; Karaoglou, 1996; Walinder, 1995). At the same time, the emergency response in the significantly affected settlements both within and beyond the 30 kilometres zone was delayed, and according to the (WHO, 2013) report, a substantial number of people in those areas received large doses, resulting in the Deliberate Evacuation area being installed in the relevant prefectures (Fig. 1(b)). This hints at the need for introducing *spatial flexibility* in the exclusion zones, possibly through creating further partition into sub-regions along the prevailing wind directions (wind roses) and around the main population centres. A dartboard-like structure (Gering et al., 2013) might be a good starting point, although a more detailed mosaic-like pattern tailored around the urban areas within the circular zones could provide a greater level of control (Fig. 2).

[2] See http://radioactivity.nsr.go.jp/en/contents/4000/3180/24/1304797_0506.pdf for more details.

The proposed alternative layouts of the exclusion zones raise specific social and societal issues in relation to their implementation, in particular along the border lines of zones with different treatment. Indeed, how acceptable by the public are decisions that involve (strongly) different treatments of two nearby neighbourhoods which end up in different zones based on radiological and economic assessment carried out? Similar issues will arise for any layout of the exclusion zones, including the commonly used circular structure, and call for the boundaries between the zones to avoid cutting through population clusters. The mosaic-like layout may, in fact, provide one of the best ways of addressing the problem of the boundaries by mapping the zones directly on population centres, as illustrated in Fig. 2. Ultimately, the feasibility of having different treatments within specified boundaries will depend on how densely populated the entire prototype exclusion zone is, which is part of a wider issue of siting for nuclear power installations (Grimston et al., 2014).

1.4. Joint optimisation based on minimising the costs

Considering the joint cost-minimal strategy across a number of measures is particularly important in the situations such as large accidents where a combination of individually justified actions may be deemed unacceptable as a whole due to high levels of disruption to society (ICRP, 2009). To address the need for the spatial and temporal flexibilities, we develop a decision-making model for a single economic location (say, a town, a village or an area of agricultural land) based on Bellman's Optimal Control Theory (Bellman, 1956), which is at the basis of the Operations Research (OR) methodology. The continuous-time optimisation is performed on the timescale of several half-lives of Cs-134 (2.07 y), which we refer to as the *mid-term problem*, or Cs-137 (30.17 y), referred to as the *long-term problem* (Section 2.1). The extended timescales imply that the initial contamination levels at a given area are expected to be known. As a result, the problem is largely deterministic, and it is only subject to the general long-term economic and demographic uncertainties that are beyond the scope of the present

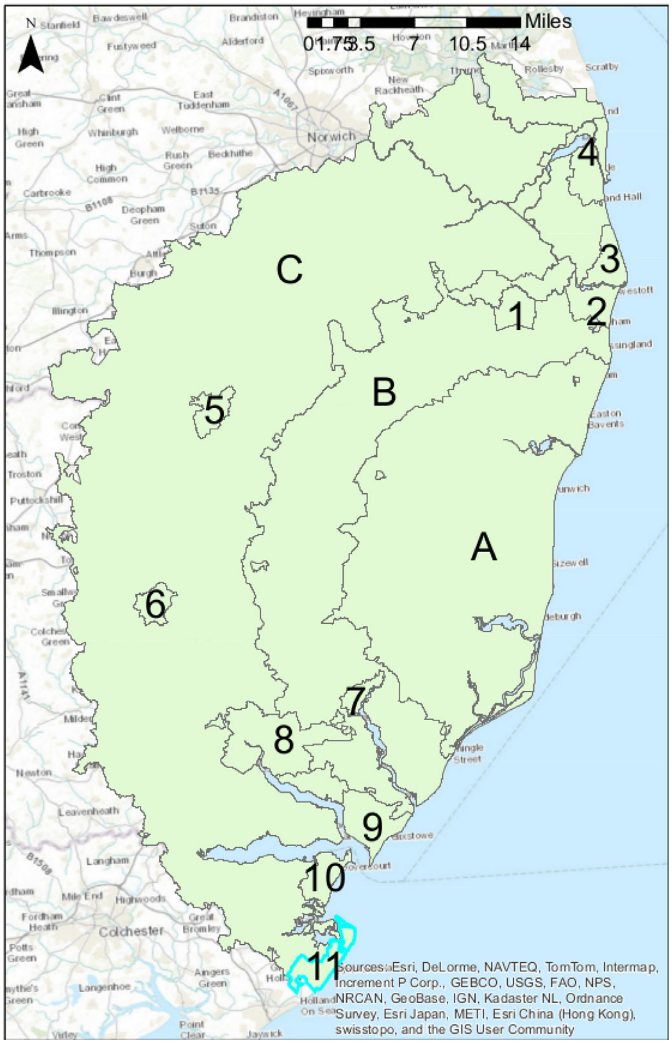

Fig. 2. Prototype mosaic-like exclusion zones around urban centres surrounding Sizewell NPP, UK (image courtesy of Dr. Steve Ashley, private correspondence).

study. Three dynamic controls are introduced: relocation and/or repopulation target, remediation rate and food production rate (the latter applicable to rural areas only), allowing one to find the joint optimal solution according to Bellman's principle of optimality.

Decisions on whether and when to trigger specific long-term preventative and recovery measures are expected to be made by local or national governments based on the initial assessment of the radiological situation in a given location during the deposition period, as well as on the estimated health costs and costs of implementing the selected measures. The long-term decisions should be made immediately after the end of the deposition period in accordance with the optimal strategy obtained for the given set of radiological and economic parameters over the entire optimisation period. The time horizon, which marks the end of the optimisation period, is set to 15 years in this paper as a compromise between the time required to implement various long-term measures such as remediation and repopulation, and the underlying long-term economic and political uncertainty. It is possible to re-run the algorithm at any point in time several days, weeks, months and even years into the original optimisation period as the new economic data becomes available, with the aim to refine the decisions further down the line. This is one of the possible ways of taking long-term economic uncertainties into account, given that they are not included in our fully deterministic model (Section 9); however, the length of the "time-step" between the refinements of the optimal strategy is a matter of subjective choice by the decision-makers, much like the time horizon of the optimisation problem.

We note that our methodology is based on minimising the combined cost of various protection and recovery measures, health effects of radiation and other relevant economic parameters. In reality, any long-term decision making takes into account a number of non-economic factors such as acceptance of a decision by various groups including the public, decision-makers, stakeholders and experts (Geldermann et al., 2009) alongside the standard radiological and economic evaluation methods. To accounting for these multiple factors in the context of nuclear emergencies, the so-called Multi-Criteria Decision Analysis (MCDA) methodology has been applied successfully (French, 1996; Hämäläinen et al., 2000). This methodology is more generic than the purely economic valuation considered in this paper, and therefore it could be used to extend the main insights gained in the present study with regards to the effect of temporal and spatial flexibilities on cost-minimal strategies. We see the economic evaluation as the necessary first step in long-term decision making, which then needs to be enhanced by accounting for the multiple non-economic factors.

1.5. Structure of the paper

The paper is structured as follows. Section 2 sets the problem by specifying the characteristic timescales and the spatial domain. The relevant types of radiological exposure are introduced in Section 3. This is followed by an overview of the available preventative and recovery measures in Section 4. Section 5 describes the costs associated with radiological exposure, prevention measures and recovery measures. Based on this information, a Bellman-type economic optimisation problem with controls for relocation, repopulation, remediation and food ban is formulated in Section 6, allowing one to investigate cost-minimal prevention and recovery strategies. This section also explores similarity criteria between different hypothetical settings, and the role of regulatory radiological constraints. Section 7 analyses historic data from Chernobyl and Fukushima to estimate the values of the input parameters that define the new model. This is followed by Section 8 which presents the case studies and discusses results of Monte-Carlo simulations for a wide range of values of the input parameters, allowing the reader to infer the likely strategies they would face under their own geographical and economic setting. Section 9 provides a critical review of the findings and outlines the limitations of the model. Section 10 concludes.

2. General problem setting: temporal and spatial domains

2.1. Characteristic timescales for response

Based on a number of reports concerning the past nuclear accidents (Ahn et al., 2015; Dorfman, Fucic, & Thomas, 2012; IRSN, 2012; Jacob et al., 2009; Lochard & Schneider, 1992; UNSCEAR, 2013) as well as the existing emergency regulations (DECC, 2013; Nisbet et al., 2009), it appears feasible to consider the following three characteristic timescales for decision making: short-term, mid-term and long-term (Table 1). These timescales correspond to the lifetimes of I-131, Cs-134 and Cs-137, which are the three radionuclides most commonly found in a nuclear reactor fallout; they also relate to the characteristic times of implementing evacuation, relocation, remediation, repopulation and other protection and recovery measures.

In our terminology *evacuation* means a short-term removal of people from a potentially hazardous environment pending later risk assessment based on better information, while *relocation* is essentially a resettlement of people to new areas for several months,

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Table 1
Characteristic timescales for response to a nuclear disaster. The terminology is explained further in Sections 3.1, 3.2, 4.1, 4.2, 4.3.

...	Short-term	Mid-term	Long-term
Timescale	minutes, hours, days	weeks, months, years	years, decades
Main radionuclides (half lives)	I-131 (8.02 d)	I-131, Cs-134 (2.07 y), Cs-137 (30.17 y)	Cs-134, Cs-137
Main radiation pathways	cloud shine, inhalation	ground shine, food	ground shine, food
Main uncertainty factors	source term, weather	local economy	local, global economy
Iodine prophelaxys	may be essential	not feasible	not feasible
Sheltering and masks	may be feasible	not feasible	not feasible
Evacuation	likely to be carried out as a precaution	only appears as a pre-condition	only appears as a pre-condition
Relocation	not feasible	may be feasible	may be feasible
Repopulation	not feasible	may be feasible	may be feasible
Remediation	not practical	may be feasible	may be feasible

years or permanently. Given the high values of uncertainty associated with the short-term problem ('state of emergency'), the flexibility in decision making is limited compared to that of the mid- and long-term problems. Even though some short-term temporal and spatial flexibilities in sheltering times, iodine prophylaxis and evacuation are also possible (Dillon, 2014; Gering et al., 2013), the present study only focuses on the largely deterministic mid- and long-term problem setting.

The lifespan of the volatiles such as I-131 (8.02 d) is comparable with the duration of the radioactive release in Chernobyl and Fukushima, and therefore the relevant dose dynamics needs to be coupled with the stochastic deposition model, which might be particularly relevant for the onset of the mid-term problem. In our model we shift $t = 0$ from the start of the accident to the end of the deposition period at a given location under consideration, and introduce corrections that account for the decay of the volatile elements during the deposition period and the hypothetical dose received during this period (see Electronic Supplementary Materials V for further discussion).

2.2. Single-location approximation

As mentioned previously, spatial flexibility in the exclusion zones could be achieved through partition into sub-regions along the prevailing wind directions (wind roses), around the main population centres, or through a dartboard-like structure (Gering et al., 2013). Having a flexible set of regions allows for better overall optimisation given the likely differences between the radiation levels as well as in the unique economic and demographic make-up of different areas within the zone.

The actual radiological contamination maps in Chernobyl and Fukushima differ significantly from the simplistic structure with co-centric circles (De Cort et al., 1998; IRSN, 2012). As a result, emergency regulators may want to consider a dartboard layout, or, even further, a mosaic layout, with multiple regions that form a prototype exclusion zone being fine-tuned to the wind-rose in the given area as well as the relevant population distribution (Fig. 2). Once the layout is created, various emergency evacuation and relocation strategies for moving people between different regions could be considered, based both on the results of the dedicated economic models and on the past experience such as that of Fukushima (Fig. 3).

Splitting the exclusion zone into a mosaic-like structure tailored around the urban areas also leads to an immediate advantage in terms of the simplicity of the resulting optimisation problem. If we assume that radiation levels are homogeneous within each small region, then it is possible to ignore various spatial distributions and consider 'single-location' problems that are independent from one another in the leading order. This is a reasonably good approximation if one wants to consider the effects of radiation on small towns and villages, as well as sparsely-populated agricultural areas and compact urban clusters. We note that there are always multiple socio-economic inter-dependencies between different regions (for example due to shared infrastructure and commuters), and also because emergency response resources such as machinery, transport and finance are often limited, which means that the single-location results should be seen as illustrative only. Running the single-location model for each region with its specific parameters and collating the results only produces a first approximation for the optimal decision-making throughout the extended exclusion zone; a fully-coupled optimisation problem should be considered in practical applications. It will be demonstrated in Section 8.3 that the decision-making at a single location could follow a number of distinct scenarios, therefore allowing for different recovery strategies in different regions in the zone.

3. Types of radiological exposure

Much of the mid-term and long-term radiation exposure, both in urban and in rural areas, comes from *ground shine*, defined as "external dose direct from radioactive materials deposited on the ground" WHO (2013), which is a result of the initial radioactive deposition (Harada et al., 2014; Lochard & Schneider, 1992). Additional doses could be received by consuming contaminated foods and water (ingestion) and breezing radioactive particles carried by wind (inhalation) WHO (2013). We restrict our analysis to ground shine and ingestion of contaminated food produce originated in rural areas, the two types of exposure most relevant on the longer timescales (Jacob et al., 2009).

3.1. Dose rates from ground shine

The deposition period could last several hours, days or weeks (Ahn et al., 2015; Katata et al., 2015), and the radioactive material will usually be carried in a plume of smoke or ash depending on the type of accident that has occurred. Once the deposition is over, the instantaneous effective dose rate $r(t)$ per person at the current moment t due to external exposure from ground shine could be expressed as

$$r(t) = c\,\frac{\gamma\,N_A}{\mu}\,M(t) \equiv c\,B(t)\,, \tag{1}$$

where N_A is the Avogadro constant, γ is the decay rate of a given radionuclide, μ is its atomic weight, $M(t)$ is its cumulative mass deposited per unit area as of time t (Katata et al., 2015) and $B(t)$ is the relevant surface radioactivity in becquerel/m^2. The latter is assumed to be known from real-time measurements. The dose rate is typically measured in mSv per annum (for biological tissue), and it is related to the area of contamination (in becquerel or Ci per square kilometre) by means of the dose conversion factor c. IRSN (2011) estimate the latter at $1\,\mu$Sv/h per 300 kbecquerel/m^2 per one person exposed to ground shine from *equal deposits* of Cs-134 and Cs-137, which is equivalent to $2.92 \cdot 10^{-5}$ mSv/y per

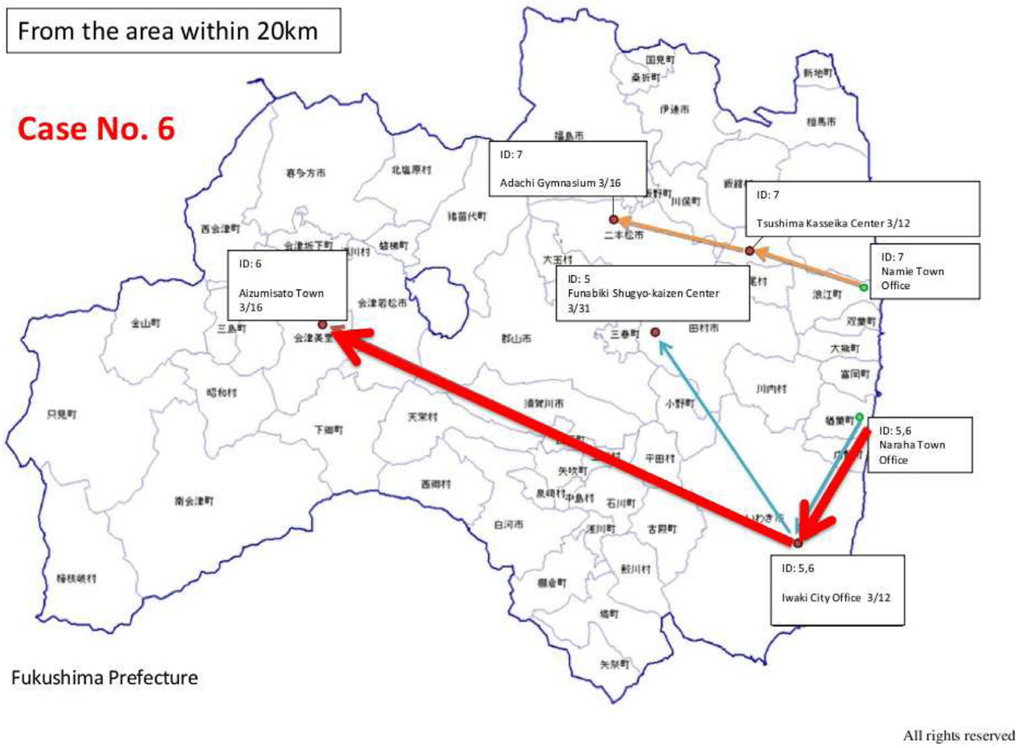

Fig. 3. Some of the multiple evacuation pathways in the aftermath of the Fukushima disaster (from Akahane, 2013).

1 becquerel/m^2 per person. The dose conversion factors for the individual elements could vary significantly depending on their decay energy: the factor for Cs-134 is around 9 times greater than that for Cs-137 (Yoo, Jang, Lee, Noh, & Cho, 2013).

To keep things simple we build our framework around a single radionuclide in the main part of the paper, but it is relatively straightforward to extend the model to multiple radionuclides (Electronic Supplementary Materials VI). Our results are obtained for the case when the three radionuclides most commonly found in a nuclear reactor fallout, I-131, Cs-134 and Cs-137, are deposited with the initial concentrations similar to those that have been measured in the aftermath of the Fukushima disaster (Katata et al., 2015; WHO, 2013).

3.2. Dose rates from ingestion of contaminated food produce

In rural areas with a significant agricultural industry, deposited radionuclides are gradually being transmitted from the agricultural land into complex food chains, causing doses through ingestion far beyond the contaminated area. This process is taking place on the timescales of months and years. Plant uptake is the major pathway of radiocaesium from soil to human diet (see Zhu and Smolders, 2000, for a review of the uptake mechanisms and transfer factors (TF)). The initial soil-to-plant transfer leads to radiocaesium flux into food not only through cereal crops and vegetables, but also through milk and meat produce in the subsequent plant-to-animal transfer.

The agricultural yield from contaminated areas (tons per Ha per year) could be controlled by implementing a food production ban, which we are going to refer to simply as *food ban*. If the mass flux before the accident was m_0, then its post accident value m will either remain the same or be reduced: $m \in [0,\, m_0]$. By definition, both m_0 and m are based on full workforce in place, which will be reduced (in some cases to zero) if relocation measures are implemented (4.1).

Denoting the radioactive transfer coefficient from soil to food as a (becquerel/kilograms in food per becquerel/m^2 on land *in a single growing season*, see Gillett et al., 2001), we express the annual flux of radiocaesium into food grown over area A as $mA \cdot aB$ for a given soil radioactivity B in that area (becquerel/m^2). This flux is measured in becquerel/year; when referred to the area A itself, it becomes simply $m\,a\,B$ with the unit becquerel/year per square metre of the agricultural land. The removal of radioactivity from land into food chains adds an extra rate of decay to B:

$$\frac{\mathrm{d}B}{\mathrm{d}t} = -(\gamma + \varkappa + \alpha)\,B, \tag{2}$$

where $\alpha = m\,a$ (yr^{-1}) could be referred to as agricultural extraction rate of the radionuclides (α^{-1} is their characteristic lifetime in the soil before entering food chains), and $\varkappa$ is the remediation rate for the agricultural land. The estimates for m, a and α are given in Section 7.3.

Assuming the food production and consumption cycle is much shorter than the characteristic extraction time and half-life of a given radionuclide (this is certainly true for one of the main long-term contaminating sources, Cs-137), the total instantaneous dose rate (millisievert/year) from food produced over a given area A and consumed elsewhere along the supply chains will be

$$(\alpha\, B(t)) \cdot A \cdot e\,,$$

where e is the ingestion dose coefficient (averaged across all age groups).[3] According to (Field, 2011), $e = 1.3 \cdot 10^{-5}$ millisievert/becquerel for Cs-137 among adults. The presence of radiocaesium in human body is short-lived, as it is eliminated through the urine within several days, but the resulting exposure is considerably more severe compared with ground shine.[4]

[3] Do not confuse the ingestion coefficient e with the 'e' number.
[4] http://www.epa.gov/radiation/radionuclides/cesium.html.

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4. Prevention and recovery measures

4.1. Relocation and repopulation

To protect the people from negative health effects from ground shine, *remediation* or *relocation* could be implemented depending on the severity of the contamination. Previously relocated areas could also be *repopulated* after a systemic clean-up aided by the natural decay of the deposited radionuclides. When the people are informed about the hazard but no specific relocation measures are being taken, voluntary evacuation might take place depending on individual perceptions of nuclear risk among the population. In this paper we ignore any voluntary movements as well as voluntary choices to remain at the contaminated area despite the orders to move.

As soon as the coordinated relocation (repopulation) measures are announced, people will be moved at a relative rate β_- (β_+) per person times the maximum population p_0 in the given area prior to the accident, and a certain target for the remaining population, $p_c \in [0, p_0]$, will be imposed. The amount of people remaining in (returned to) the area, $p(t)$, could be modelled according to

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \beta\,(p_c - p)\,, \quad \beta = \beta_- \quad \text{if} \quad \dot{p} < 0\,, \quad \beta = \beta_+ \quad \text{if} \quad \dot{p} > 0\,, \tag{3}$$

where β_- and β_+ are relative rates of relocation and repopulation, respectively. This functional form provides a very basic reflection on the possibility of having different relocation priorities for different social groups depending on their vulnerability, even though we do not explicitly distinguish between social groups (age, pre-existing medical conditions, etc.) by using the single variable p for the population. In addition, the exponential form (3) provides algorithmic simplifications when it comes to solving a Bellman-type optimal control problem to find the optimal strategies, since it reduces the number of dimensions (Section 6). We note that when the rates $\beta_\pm$ are large relative to other processes such as natural decay and remediation, the population dynamics is close to the step-like $p = p_c$.

If $p > p_c$, we are driven towards relocation ($\dot{p} > 0$), while for $p < p_c$ we have repopulation ($\dot{p} < 0$); p_c is, therefore, the main parameter that controls the population dynamics, providing the imposed rates of displacement $\beta_\pm$ are fixed. It is possible to control the values of β, too, but we are going to assume that they are given based upon the available resources to move people. The situations when $0 < p_c < p_0$ correspond to partial relocation or repopulation. We also ignore commuters who by definition either work or reside in a given area without staying there permanently.

4.2. Remediation

The dose rate due to ground shine in a given area is governed by

$$\frac{\mathrm{d}r}{\mathrm{d}t} = -(\gamma + \varkappa)\,r + c\,\frac{\gamma N_A}{\mu}\,q(t)\,, \tag{4}$$

where $q(t)$ is the deposition flux (Katata et al., 2015) and $\varkappa$ is the remediation rate, which is our second control parameter; it varies between 0 (no measures) and $\varkappa_0$ (maximum measures), and includes various clean-up techniques (Higgins et al., 2008; Jacob et al., 2009; Munro, 2013). If the half-life of the radionuclide and the characteristic duration of remediation ($\varkappa^{-1}$) is long enough compared to the duration of the deposition period t_0, the latter will be taking place very close to $t = 0$ on the longer timescale, and so $q(t)$ will effectively be a delta-function. This reduces the entire deposition to the initial condition for r, resulting in a simplified dose rate dynamics:

$$\frac{\mathrm{d}r}{\mathrm{d}t} = -(\varkappa + \gamma)\,r \quad \forall\, t > 0\,, \quad r(0) \equiv r_0 = c\,\frac{\gamma N_A}{\mu}\,Q_0\,; \tag{5}$$

$Q_0 = \int_0^{t_0} q(t')\,\mathrm{d}t'$ is the total radioactive mass deposited.

The models for relocation and remediation described by (3), (5) capture basic features of these processes whilst keeping the number of parameter to the minimum, which is sufficient for the purposes of the present scientific study. We note that should policy makers and regulators wish to use our methodology, they will need to give some thought to including more realistic features in these equations. In particular, equation (5) excludes the natural processes such as mixing by air and washing by precipitation that act to redistribute and, in many cases, reduce the radiation from ground shine. They could be accounted for on a case by case basis by making appropriate adjustments to the decay rate γ if sufficiently reliable data is available.

4.3. Restrictions on food production in rural areas

In the simplest case food restrictions could be imposed through banning food production in the affected area, as well as withdrawing the already produced contaminated foods from the market. We are going to consider the first option only since it appears to be the most efficient long-term measure. Thus, food restrictions could be described by varying the production rate α from 0 (complete food ban) to $\alpha_0 = m_0\,a$ (normal production rate without any ban and with full working population).

5. Costs associated with radiological exposure and prevention/ recovery measures

Let us now introduce the principal economic costs that are likely to be incurred at a given 'point' location during the medium- and long-term response to a large-scale radioactive release from a nuclear power plant. The timescales under consideration are several weeks/ months/ years after the release.

5.1. Overview of the economic factors and their relevance for different settings

The costs associated with radiological exposure and prevention/ recovery measures include monetised values of health effects due to radiological exposure, costs of relocation, resettlement and repopulation, economic productivity and disruption, added value from agricultural produce and land value. We do not consider insurance and re-insurance costs. The two state variables that define the problem are the current population density at the given area, $p(t)$, and the dose rate from ground shine, $r(t)$, with the relevant 'initial' values p_0 and r_0 corresponding to the end of the deposition period (Electronic Supplementary Materials V). All the costs are described in terms of at least one of these variables.

Our methodology is developed for rural and semi-urban areas that have significant population as well as farmland, referred to as *combined setting*. In this setting all of the protection and recovery measures introduced in the previous sections could be applied simultaneously. Agricultural production, responsible for the unique radiological exposure pathway through ingestion, will be treated separately from the general productivity term $F_p\,p(t)$ that constitutes the rest of the economic output (see below). It is assumed that all the workforce employed at the farmland comes from within the given region, and that there is no substitution for the lost agricultural output if the workforce is relocated. Thus, if the population drops below its pre-accident value p_0 as a result of relocation measures (4.1), the agricultural output will, in the simplest case, also drop proportional to $p(t)/p_0$. Finally, we assume

Table 2
Essential nomenclature.

p	population	t	time
r	dose rate from ground shine	F_r	health cost per unit dose per person
α	radiation decay rate through farming	F_α	revenue rate from farming per person
$\beta-$	relocation rate	$F_{\beta-}$	relocation cost per person
$\beta+$	repopulation rate	$F_{\beta+}$	repopulation cost per person
δ	interest rate	F_Δ	net annual economic disruption per person, including infrastructure depreciation
$\varkappa$	remediation rate	$F_\varkappa$	remediation cost corresponding to e-folding decrease in radiation
γ	natural radioactive decay rate	τ	characteristic timescale based on the maximum dose received
λ_z	characteristic scaled cost of recovery measure z relative to the health cost	C_z	NPV of the cost of implementing recovery measure z over the entire optimisation period
$F(p, r, t)$	cost rate function (combination of the individual costs)	$V(p, r, t)$	"remaining" cost referred to as *value function*
T	optimisation horizon		

that farmland only constitutes a certain fraction $\omega \in [0, 1]$ of the given region's area, with the rest occupied by towns and villages; the total food produce from this area has to be scaled proportionally.

In subsequent sections we go on to describe how our model can be calibrated to the data from historic nuclear accidents, and how it could be used to help establish the best course of action in the aftermath of a hypothetical future nuclear accident. Chernobyl, the biggest nuclear disaster in history, provided extensive information on the economics of a severe nuclear accident (Jacob et al., 2009; Lochard & Schneider, 1992). The economics of nuclear decontamination and assessment of policy options for the management of land around Fukushima is described in Munro (2013); see also (Munro, 2011; 2012) and the relevant WNN reports.[5]. The key principles for modelling the economic costs that are expected to arise off-site in the aftermath of a hypothetical nuclear accident in the UK are described in great detail in the COCO-2 report (Higgins et al., 2008).

Since many of the actual costs and rates associated with relocation, remediation, repopulation and food production may vary greatly between different settings, we provide results for a wide range of values of the input parameters and not just the values corresponding to Chernobyl or Fukushima. This allows the reader to infer the likely scenarios they would face under their own geographical and economic setting, while also accounting for possible differences between the preferred methods of describing the health effects in economic terms. In the case of Chernobyl, due to a very specific political and economic environment that existed in the Soviet Union at the time of the disaster, the relevant data is not readily transferrable to present-day conditions in countries like UK or Japan.

Let us now describe the individual costs in detail, before introducing the total cost associated with the long-term preventative and recovery measures in the very end of the section. A brief summary of the relevant notations is given in Table 2 for the reader's convenience.

5.2. Health costs

The doses received by the population result in a loss of life expectancy and morbidity, both of which can be quantified in economic terms to a varying degree of success. There is some discussion in the literature about what the true costs of exposure to radiation are, and (Cuttler & Pollycove, 2009) is just one example of the relatively recent point of view that low levels of exposure to radiation can in fact provide some benefit to the recipient. According to (Walinder, 1995), "it is impossible to predict, by means of a mathematical expression, the specific outcome of a low radiation dose".

As is evident from Fukushima, even in a large-scale nuclear disaster it is unlikely that general population is going to be exposed to very high levels of radiation capable of causing the so-called *deterministic* health effects such as acute radiation sickness (WHO, 2013), often triggered above a certain radiation threshold. Moreover, based on the current ICRP and IAEA guidance dose thresholds (Electronic Supplementary Materials I), as well as on the general public perception of radiation, dose rates above 20 millisievert/year are likely going to trigger emergency measures such as relocation regardless of any economic considerations. We, therefore, restrict our analysis to relatively mild initial dose rates between 10 and 20 millisievert/year in the *baseline setting* and between 50 and 100 millisievert/year in the *high radiation setting*. These radiation levels are well below the known thresholds for the deterministic effects, and tend to cause *stochastic* effects on human health (Choi, Costes, & Abergel, 2015), including cancers. The stochastic nature of the health effects allows one to employ the commonly held (and, at the same time, much criticised) assumption of the linear-no-threshold (LNT) health response to radiation dose (see Little, Wakeford, Tawn, Bouffler, & Berrington de Gonzalez, 2009; Tubiana, Feinendegen, Yang, & Kaminski, 2009, for the discussion regarding the applicability of the LNT model).

By making the LNT assumption one could say that the loss of life expectancy (LLE) due to radiation is proportional to cumulative dose received. As a result, the loss in life expectancy due to exposure to ground shine in the period from t to $t + \mathrm{d}t$ when the relevant dose rate is $r(t)$ can be thought to be proportional to $r(t)\,\mathrm{d}t$. If F_r is the corresponding economic loss per person per unit radiation dose received (estimated below), the resulting rate of economic losses due to radiation exposure from ground shine at time t of the remaining $p(t)$ individuals is $-F_r\, r(t)\, p(t)$ (£ per unit time per unit area). As mentioned earlier, we do not differentiate between different age groups.

Exactly the same approach could be used to express the rate of economic losses associated with radiation exposure through ingestion of the food that had been grown in the region under consideration. The latter is characterised by dose rate r from ground shine, which can be converted into dose rate due to ingestion of the food produced in this particular location. Assuming the agricultural production in the contaminated area is proportional to the remaining workforce p relative to the initial workforce p_0, the relevant health cost is $-F_r \frac{\alpha e}{c} \frac{p}{p_0} r$ (see Section 3.2 for the definition of the parameters). Therefore, all the health-related costs can be expressed in terms of the dose rate from ground shine in the area under consideration.

To estimate F_r, which is economic loss per unit dose per person regardless of whether the dose comes from ground shine, ingestion or both, we use the following expression from (Dreicer, Tort, & Manen, 1995) for the monetary gain C (£) associated with collective averted dose D (man Sv) across all the radiological pathways

[5] http://www.world-nuclear-news.org/RS-UN-reports-on-Fukushima-radiation-0204141.html.

under consideration:

$$C = D P_{\rm f} \,(1 + w_{\rm nf} + w_{\rm h})\, L \nu \,. \tag{6}$$

Here $P_{\rm f}$ ((man Sv)$^{-1}$) is the probability coefficient for fatal cancer induced per unit collective dose received (either ground shine, ingestion or both), $w_{\rm nf}$ is the weight of non-fatal cancers relative to fatal cancers, $w_{\rm h}$ is the weight of hereditary consequences relative to fatal cancers, L (years) is the average LLE from a fatal cancer and ν (USD/life year) is the monetary value of a statistical life year (VSLY).

Using (6), the health cost term F_r can be expressed as

$$F_r = P_{\rm f} \,(1 + w_{\rm nf} + w_{\rm h})\, L \nu \,, \tag{7}$$

We note that our model does not use the concept of collective averted dose D directly because of the need to treat the population and the dose received per unit person separately when implementing different prevention and recovery measures. Collective averted doses are only introduced when it is required to link the model with the literature that utilises this concept, as is the case here.

IAEA quotes the values $L = 13$ years, $P_{\rm f} = 0.05$ per (man Sv), $w_{\rm nf} = 0.01$ and $w_{\rm h} = 0.013$ in Eq. (6). Arguably the biggest challenge is in estimating VSLY (ν).

The concept of VSLY was developed in public policy making to put monetary value on the reduction of risk of death for an average 'statistical' individual (Higgins et al., 2008). VSLY could be estimated based on a number of existing approaches, including Human Capital (HC) and Willingness to Pay (WTP), applied in various contexts such as road accidents and public healthcare. The IAEA's regulations are based on HC approach, also used in COCO-1. It estimates the benefits of reducing radiation exposure through the associated health benefits, valuing life in terms of the saved economic output (productive capacity) from preventing a death/illness. COCO-2 implements WTP approach, which values life in terms of the amounts that people are prepared to pay to reduce risk of death/illness (NHS and private medical insurance are good examples Higgins et al., 2008). Compared with HC, WTP accounts for subjective welfare costs in addition to the loss of productivity, and therefore it tends to give higher values than HC. The drawback is that welfare costs are often harder to quantify.

A realistic estimate for ν (VSLY) based on the WTP approach should account for range of factors such as loss of economic output from an average person per year based on the loss of life expectancy from cancer, the reduction of output from the sick individuals and costs associated with cancer screening and treatment of the affected individuals. According to (Miller, 2000), VSLY can be estimated as the value of statistical life (VSL) divided by average life expectancy (LE), with VSL set to be 120 times the GDP per capita in a given year. Since LE is equal to around 80 years in the UK, VSLY is 1.5 times higher than the current GDP per capita of around £27, 000 per year, yielding $\nu = £40,500$ per year. This estimate is in line with the WTP-based calculations in Jones-Lee, Loomes, and Spackman (2007) who use alternative metrics called value of life year (VOLY) and value of preventable fatality (VPF) specified for multiple age groups. Munro (2013) quotes considerably higher values for VSLY: 3–8 times the GDP per capita in the US and 3 times the GDP per capita in Australia. In the UK context the "3 times the GDP per capita" evaluation is equivalent to $\nu = £81,000$ per year.

For the purposes of this study, which is based on a deterministic model that neglects long-term economic and radiological uncertainties, we set ν to be equal to the average between the lower-end estimate (£40, 000 per year) and the upper-end estimate (£80, 000 per year) obtained above, yielding $\nu = £60,000$ per year. Plugging this into Eq. (7), we get the value $F_r = £39,900$ per man Sv (around € 50,000 per man Sv for the GBP/EUR exchange rate of 1.25), which is used as the default value in this paper. We note that the value of F_r is the same for all the radiological exposure pathways; the dose can come from either ground shine, ingestion or both.

The HC and WTP approaches, along with the VPF, VOLY, QALY and VSLY indices, are discussed in detail in Harada et al. (2014), Higgins et al. (2008), Jones-Lee et al. (2007), Jones-Lee (2007), Mason, Jones-Lee, and Donaldson (2009), Wells (2011), both for a broad variety of health effects and specifically for radiation-related effects. In addition, a number of studies since Chernobyl have shown that the health effects due to stress may be commensurate with the health effects associated directly with the radiological exposure (IAEA, 2006; Karaoglou, 1996). We believe that at the current state of knowledge there is no absolutely compelling evidence in favour of any particular approach for putting monetary values on heath, including the effects of radiation, and coming up with the best possible valuation for economic consequences of receiving a dose remains of large significance (Thomas & Vaughan, 2015).

5.3. Remediation costs

According to Munro (2013), remediation costs are simply proportional to the number of clean-up exercises, N. The cost of each exercise is the same regardless of the relevant radiation levels and averted dose. Typical remediation measures include replacement of contaminated soil in populated areas, radical improvement of grassland, application of mineral fertilisers to potato fields and application of special food additives to livestock (Jacob et al., 2009).

Our earlier assumption regarding the remediation dynamics (5) implies that remediation efficiency is declining as further amounts of the radioactive substances are being removed at a given location. This matches with the evidence from Fukushima (Munro, 2013). At a current radiation level r the additional clean-up exercises $\mathrm{d}N$ will remove $\xi\, r\, \mathrm{d}N = -\mathrm{d}r$ of radiation during a short period of time $\mathrm{d}t$, where constant parameter ξ (dimensionless) stands for the relative efficiency of the remediation (radiation removed per one remediation exercise per unit of radiation remaining). Comparing this with (5) shows that the remediation rate $\varkappa = \xi\, \frac{\mathrm{d}N}{\mathrm{d}t}$.

Introducing the cost $f_\varkappa > 0$ of a single remediation exercise (pounds per exercise per unit area), the rate of spending (denoted as $\dot{C}$) on remediation exercises carried out at a rate $\frac{\mathrm{d}N}{\mathrm{d}t}$ is simply

$$\dot{C} = f_\varkappa \,\frac{\mathrm{d}N}{\mathrm{d}t} \equiv F_\varkappa\, \varkappa \quad (£ \text{ per year})\,; \tag{8}$$

here $F_\varkappa = \frac{f_\varkappa}{\xi}$ is the characteristic cost of reducing the radiation e times at a constant rate $\varkappa$. Combined with (5), this definition implies that cumulative spending on remediation is equal to $C(r) = -F_\varkappa \ln(r/r_0)$. Therefore, the marginal cost $\mathrm{d}C/|\mathrm{d}r|$ of clearing an additional unit of radiation rises according to $\frac{F_\varkappa}{r}$ when r decreases; this corresponds to the diminishing returns from further remediation, which is in line with the evidence from Fukushima (Munro, 2013). We note that $F_\varkappa$ by definition does not include restoration costs ($F_{\beta+}$) that arise when people return to the previously abandoned areas.

5.4. Costs associated with relocation, resettlement and repopulation

In the simplest case, annual costs of relocation, resettlement and repopulation are directly proportional to the rate $\mathrm{d}p/\mathrm{d}t$ at which the population is being removed from the given location (or brought back), and therefore they could be modelled as $-F_{\beta\pm}\,|\mathrm{d}p/\mathrm{d}t|$, where $F_{\beta\,\pm} > 0$ are the costs of relocating/ resettling one person ($F_{\beta-}$) and bringing one person back ($F_{\beta+}$) at time t. In the case of relocation the costs are associated with *short-term actions* such as transportation, renting new temporary accommodation and paying subsidies until a new job is found, as well as *long-term actions* such as building new infrastructure (housing, schools, hospitals, care homes) to absorb the new arrivals. Abandoning the existing infrastructure in relocated areas is accounted for by a separate depreciation term F_l introduced below.

All the costs are offset to the times when each individual move in and out of the area is taking place. It is assumed for simplicity that people get removed immediately into a location with no contamination, thus allowing to draw a distinct line between either being present at the given location or not; this assumption is justifiable on the longer timescales. Note that $\mathrm{d}p/\mathrm{d}t$ in the above formula does not include voluntary relocation which often takes place even when no measures are being taken. If the existing economic infrastructure in the destination areas of resettlement, which are presumed to be scattered around the country, is elastic enough to absorb the extra people, then most of the relocation/resettlement costs F_{β_-} would be accounted for by the short-term actions.

5.5. Economic productivity and disruption

In the simplest case, economic productivity of the area is proportional to the remaining population, p, and therefore can be written as $F_p\, p$. The constant term F_p represents the average pre-accident productivity rate per person across all the economic sectors excluding agriculture (for example, industry and services). The agricultural term is accounted for separately in our model due to its relative importance in the context of severe nuclear accidents. The applicability of the linear relation could be questioned in the cases of very small/very large population densities, and also when the economic output area is separated from residential areas (a factory outside the city, etc). There is also an indication in the literature that in relatively large urban areas F_p and F_{pp} are slowly increasing functions of the population p, which grow by approximately 6% when the population doubles (Ciccone & Hall, 1996). However, owing to the fact that the vast majority of nuclear installations are surrounded by rural or, at most, semi-urban areas (Grimston et al., 2014), we can safely assume that all the productivity figures per person defined in this section are constants and are determined by the economic make up of the given locations regardless of their population sizes.

A radioactive release is likely to lead to partial disruption of the normal economic activity at the affected area through a variety of factors including stress from perceived nuclear risk (Munro & Managi, 2014), which could be modelled by adding the negative $-F_d\, p$ term to the productivity (the disruption cost per capita, F_d, is positive by definition). The number of people who get relocated from the original to new areas is $p_0 - p$ (ignoring voluntary evacuees), and their new economic output is $F_{pp}\,(p_0 - p)$, with F_{pp} effectively replacing F_p. Even though relocation eliminates the radiation-related risks, it also leads to stresses associated with the loss of individual property and jobs at the abandoned area, uncertainties for the future, etc. This is likely to cause disruption to the economic activity at the new location, which is modelled by the negative $-F_{dd}\,(p_0 - p)$ term.

The four terms introduced above could be written as $-F_\Delta\,(p_0 - p) + (F_p - F_d)\,p_0$, where

$$F_\Delta = (F_p - F_d) - (F_{pp} - F_{dd}) \tag{9}$$

is the net productivity gain (per person) from staying at the affected area as opposed to moving. We exclude compensation payments such as special victims' pension and medical insurance from the model since they involve transfers between different groups within the society which are assumed to have no net losses or benefits. Therefore, accounting for the compensation payments is only going to distort the economic valuation of the true costs of a nuclear disaster, as was arguably the case for Chernobyl (Lochard & Schneider, 1992).

It is worth noting that there may be considerable difference between normal pre-accident productivities (GVAs), F_p and F_{pp}, at the two locations under consideration ('old' and 'new'), in particular when one of them is rural and the other one is urban. This economic 'potential difference' often results in migration between regions of a country (and between countries). However, we expect that in a balanced free market economy it is going to be partially or fully compensated by various social and economic pressures, such as restrictions in the job and property markets. At the same time the quantity F_Δ defined in (9) represents the economic difference for the people affected by the accident, and since it involves potentially significant disruption losses, it is likely to be considerably different from the pre-accident value $F_p - F_{pp}$. To avoid including the unnecessary forcing term $F_p - F_{pp}$ in the model, we are going to assume that there is an *economic equilibrium* between the two areas under consideration prior to the accident, and re-define

$$F_\Delta = -(F_d - F_{dd})\,.$$

Thus, the F_Δ represents the newly-created economic 'opportunity' (or 'disruption') in the aftermath of an accident, which arises from the possible differences in the effect of radiological exposure on various industries and businesses.

For example, it may be difficult to relocate certain industries and farming to new areas, resulting in the need to pay long-term benefits to the affected individuals plus ripple effects in the economy; in this case $F_\Delta > 0$, i.e. it is more viable to keep the people at the old place. At the same time, certain economic sectors such as retail may benefit from the extra workforce associated with relocation, and this could result in $F_\Delta < 0$, suggesting that moving the people to the new area is viable. However, moving considerable amounts of people to new areas is likely to put extra pressure on the local jobs and property markets, and could cause higher unemployment and lower overall productivity. All these factors should be taken into account when estimating F_Δ. It is also worth noting that commuters who reside within the exclusion zone but work far enough from it are likely to be affected very little by the relocation in terms of their economic output; the effect of commuters on the decision making is beyond the scope of our model.

5.6. Added value from agricultural produce

The net benefit from agricultural produce originated at the given contaminated area depends on a variety of socio-economic factors, including the perception of radiological risks associated with low levels of food contamination by consumers and regulators. In the simplest case the rate of consumption through distribution chains matches the agricultural production rate m per unit area and is fixed. If the average added value per unit mass across all the contaminated products, π_f, is also fixed, then the gross revenue rate from selling contaminated foods originating from a given area A is simply $\pi_f\, m\, A$ (pounds per year).

It is worth clarifying that π_f accounts only for the values added within farms, i.e. net income of the farmers, and it excludes all the added values across the subsequent food distribution chains. This is in line with the so-called *smallness assumption* in which the gap in supply created by the food production ban at a particular area is going to have a negligible effect on the equilibrium market prices and on the economy in general. Also, in many cases farming is subsidised by governments, which means that net revenue rates from agriculture are lower (and sometimes even negative) than the gross rates. However, banning subsidised food production in a given area means the resulting marginal deficit in the produce will have to be sourced either from other subsidised farmers in the same country or from abroad (often with trade tariffs) at the expense of the local workforce, making it difficult to draw a clear line in the comprehensive evaluation of socio-economic costs and benefits of the local farming. These issues are clearly beyond the scope of the present study, and we direct the reader to (Anderson, Martin, Valenzuela et al., 2006) for more information on the effect of agricultural subsidies on welfare. For the remainder of the paper π_f will be treated as a positive net added value to the economy per unit mass of the produce, with the estimates based on the UK data for the gross value added (GVA) from agriculture (Section 7.3).

Using the extraction rate α defined in 3.2 and introducing the term $F_\alpha = \frac{\pi_f}{a\, p_0}$, which is the characteristic agricultural added value per one person living in the contaminated rural area that could be generated on the timescale of α^{-1}, the revenue rate may be written as $\alpha\, A\, F_\alpha\, p_0$. This is based on the assumption of the full workforce in place; in the event of partial or full relocation when the remaining population p is less than p_0, and the agricultural revenue rate is adjusted to $\alpha\, A\, F_\alpha\, p$. Therefore, the accident-driven change in the revenue from agricultural production in a given area is

$$(\alpha\, p - \alpha_0\, p_0)\, A\, F_\alpha\,,$$

which is going to be negative if either α or p drop below their respective pre-accident values. The estimates for α and F_α are given in 7.3.

5.7. Depreciation of the infrastructure value

In urban areas land value is largely related to the market prices of households, real estates and other infrastructure. Relocating the area would cause the infrastructure to depreciate with time, giving rise to an additional annual cost F_l per relocated person which should be incorporated in the net economic disruption cost rate associated with the move:

$$F_\Delta = -(F_d - F_{dd}) + F_l\,. \tag{10}$$

F_l could be estimated as the cost of non-radiological restoration of the previously relocated areas spread over the period when these areas were empty. A constant F_l implies linear depreciation of the infrastructure with time.

5.8. Total cost as a combination of the individual costs

Putting all the individual costs defined in the previous sections together, we get the so-called *cost rate function* describing the total cost (per unit time) incurred at a given location as a result of radiological exposure, economic disruption and implementation of preventative/ recovery measures:

$$F(p,r,t) = -F_r\, r\, p\left[1+\frac{\alpha}{\gamma_0}\right] - F_\Delta\cdot(p_0-p) - F_d\, p_0 - F_\alpha\cdot(\alpha_0\, p_0-\alpha\, p) - F_{\beta\pm}\left|\frac{\mathrm{d}p}{\mathrm{d}t}\right|_\beta - F_\varkappa\,\varkappa\,. \tag{11}$$

Here $\alpha = m\, a\, \omega$ is the additional radiation decay rate (y^{-1}) through food production introduced in Section 3.2, and $\gamma_0 = c\, p_0/e$ (y^{-1}) provides conversion between doses from ground shine and ingestion described in Section 5.2. By definition, negative values of F imply costs (expenditure).

We also note that with all the effects combined, the equation for the radiation dynamics takes the form

$$\frac{\mathrm{d}r}{\mathrm{d}t} = -(\gamma+\varkappa+\alpha\cdot(p/p_0))\, r\,, \tag{12}$$

with the (p/p_0) term once again corresponding to the agricultural productivity drop in the event of partial/full relocation of the workforce from the region.

The combined cost rate function F is needed to find cost-minimal strategies for post-accident recovery. This is achieved by using the methodology based on Bellman's principle of optimality, which is described in the subsequent section.

6. A continuous time cost-minimisation problem for the long-term response

6.1. General cost-minimisation problem

First we introduce the notion of the expected 'remaining' costs at a given location (per unit area) between the current moment t and a given *optimisation horizon* T by integrating the instantaneous flow of costs F along hypothetical future optimal paths and discounting by constant interest rate δ (the latter is significant for the long-term problem) Dixit and Pindyck (1994):

$$V(p,r,t,T) = \int_t^T F(p(t'),r(t'),t')\,\mathrm{e}^{-\delta\,(t'-t)}\,\mathrm{d}t' + V_T\,. \tag{13}$$

This function depends on the state variables p, r evaluated at the current moment t, in accordance with the Optimal Control Theory.

Eq. (13) implies that $V|_{t=T} = V_T(p,r)$, which is the condition in the end of the optimisation period, described in Electronic Supplementary Materials III. The horizon T is an exogenous parameter usually specified by the regulators for each particular problem setting, based on the set of characteristic timescales involved and on the management options available (Dixit & Pindyck, 1994). For example, in financial markets T stands for the maturity period of a bond or an option and its value is often specified prior to the sale. There are no generic rules for choosing T apart from it being an indicator for stopping any actions and fulfilling obligations.

According to Bellman's principle of optimality, the cost function (13) satisfies a PDE often referred to as the Hamilton–Jacobi–Bellman (HJB) equation (Bellman, 1956). In the deterministic case (corresponding to our long-term problem) with dynamic constraints (3), (12) it takes the form

$$\frac{\partial V}{\partial t} + \max_{p_c,\varkappa,\alpha}\left[-\beta\,(p-p_c)\,\frac{\partial V}{\partial p} - (\gamma+\varkappa+\alpha\cdot(p/p_0))\, r\,\frac{\partial V}{\partial r} + F(p,r,t) - \delta\, V\right] = 0; \tag{14}$$

p and r are the state variables, and the control parameters p_c, $\varkappa$ and α can vary in the ranges $p_c \in [0, p_0]$, $\varkappa \in [0, \varkappa_0]$, and $\alpha \in [0, \alpha_0]$, respectively.

Eq. (14) allows one to minimise the long-term damage to both public health and the local economy under *medium* levels of radiation, for which the initial dose rate does not exceed the relevant 'emergency reference level' (ERL) required to initiate relocation, $r_0 < r_*$ (see Electronic Supplementary Materials I for typical ERLs). Generally, continuous time optimal control problem settings such as this are rare in OR literature, but there are some notable exceptions. He and Zhuang (2016), for example, use a "damage from disaster" function V similar to (13) to find a balance between investment in preparedness and potential costs of relief for a generic disaster. In the context of a nuclear disaster, however, there is practically no trade-off between spending on preparedness and recovery, which partially explains the high costs of designing and building new reactors. Therefore, our model for optimising recovery measures in the aftermath of a nuclear accident justifiably excludes preparedness costs.

6.2. Similarity criteria

The next step is to scale the PDE and introduce non-dimensional groups in order to establish the minimal number of

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independent parameters that provide unique solutions, and investigate the similarities between a wide range of possible setting. Based on the obvious mathematical and economic properties of the problem, we are going to use the relevant upper bounds p_0 and r_0 to scale p and r, and introduce characteristic time τ to scale the rates and times, leading to the following non-dimensional variables:

$$\bar{p} = \frac{p}{p_0}, \quad \bar{r} = \frac{r}{r_0}, \quad \bar{t} = \frac{t}{\tau}, \quad \bar{\beta} = \beta\,\tau, \quad \bar{\gamma} = \gamma\,\tau, \quad \text{etc}. \qquad (15)$$

The easiest way to define τ is through the maximal possible dose R_T from ground shine that would have been received per person over the optimisation period T if there were no relocation and no remediation measures in place:

$$R_T = \int_0^T r(t)|_{\varkappa=0}\,\mathrm{d}t = r_0\,\frac{1-\mathrm{e}^{-\gamma T}}{\gamma}, \quad \tau = \frac{R_T}{r_0} = \frac{1-\mathrm{e}^{-\gamma T}}{\gamma}. \qquad (16)$$

For the case $\gamma T \ll 1$ ($T \ll T_{1/2}$) the characteristic timescale of the problem is T, whereas for the case $\gamma T \gg 1$ ($T \gg T_{1/2}$) the timescale is $T_{1/2}$; the latter corresponds to the total dose $R_\infty = \lim_{T\to\infty} R_T = r_0/\gamma$ associated with the initial dose rate r_0.

We further introduce the following non-dimensional economic groups:

$$\lambda_\Delta = \frac{1}{\tau\,r_0\,F_r}\left[\frac{F_\Delta}{\delta} + \frac{F_{\beta-} - F_{\beta+}}{2}\right], \quad \lambda_\alpha = \frac{\gamma_0\,F_\alpha}{r_0\,F_r} \equiv \frac{c}{e\,a}\,\frac{\pi_f}{r_0\,F_r},$$
$$\lambda_\beta = \frac{1}{\tau\,r_0\,F_r}\,\frac{F_{\beta-} + F_{\beta+}}{2}, \quad \lambda_\varkappa = \frac{F_\varkappa}{\tau\,p_0\,r_0\,F_r}. \qquad (17)$$

λ_Δ is a general measure of the accident-driven difference in economic disruption between the old and new locations, including infrastructure losses, λ_β represents the average cost of relocating people in both directions, while $\lambda_\varkappa$ and λ_α correspond to remediation costs and revenue from agricultural production, respectively; all the λ's are scaled by the characteristic health cost.

The scaled cost function $\bar{V}(\bar{p}, \bar{r}, \bar{t})$ is defined implicitly as

$$V = \frac{-(F_{dd} + F_l)\,p_0 - F_\alpha\,\alpha_0\,p_0 + F_\Delta\,p}{\delta} + \tau\,p_0\,r_0\,F_r\,\mathrm{e}^{-\delta\,(T-t)}\cdot\bar{V}. \qquad (18)$$

The resulting scaled PDE and the final condition are given in Electronic Supplementary Materials IV.

6.3. Radiation exposure thresholds as constraints to the cost-minimisation problem

Given the existing regulations concerning the 'emergency reference level' (ERL) of the received dose required to initiate a given response measure (Electronic Supplementary Materials I), it appears natural to introduce a certain critical level of radiation exposure as optimisation constraint to the cost-minimisation problem (14). Thanks to the similarity properties outlined in the previous section, this can be achieved by restricting the lower ends of the parameter ranges for the non-dimensional economic groups $\lambda = \{\lambda_\Delta, \lambda_\beta, \lambda_\varkappa, \lambda_\alpha\}$. The economic groups are inversely proportional to the initial radiation level r_0 (mSv/yr) following the deposition period, which is in turn linked with the specified ERL dose threshold. A more conservative ERL would imply a lower threshold value of r_0 required to initiate the specified response measure regardless of the economic considerations. If we think of all the possible values of the λ parameters as a sector within a hypersphere, the lower initial radiation level r_0 will correspond to the values of λ further away from the origin, therefore limiting the number of the acceptable cost-optimal strategies out of all possible solutions of (14) that exist in the hypersphere. We explore this effect numerically in Section 8.

7. Calibrating the model based on Chernobyl and Fukushima data

In this section a brief analysis of the historic data from Chernobyl and Fukushima disasters is performed in order to shed light on possible values of the characteristic costs and rates at the basis of our model. In doing so we recall that many of the actual costs and rates associated with relocation, remediation, repopulation and food production, as well as the preferred methods of evaluating the health costs, may vary greatly between different settings. This is particularly relevant for interpreting the Chernobyl data because of the very unique set of political and economic conditions that existed in the Soviet Union at the time when the disaster took place. Therefore, we intend to use the values obtained in this section as illustrative only, and subsequently provide results for a wide range of possible values of the input parameters that define the model.

7.1. Data from Chernobyl

The data in Lochard and Schneider (1992) is given in the RUB (1987 price levels), whereas (Jacob et al., 2009) is using EUR (2010 price levels). Based on the official Soviet exchange rate of 0.67 RUB for 1 USD in 1987, on the inflation factor of 1.92 for the values of USD between 1987 and 2010, and on the exchange rate of 0.75 EUR for 1 USD in 2010, the conversion factor between the two currencies is 2.15 EUR (2010) for 1 RUB (1987). This estimate is only approximate since the 1987 RUB to USD exchange rate corresponds to the era of limited trade between the USSR and the rest of the world, and therefore is likely to include political biases. The GDP of USSR in 1987 was estimated at 866 bRub/yr, which corresponds to the country-average productivity rate €6386 per person per yr given the population of 289 million. This figure could be used as an estimate for the relevant productivities F_p and F_{pp} in the model, although there is no explicit data for any specific locations and the differences between them; it is also difficult to determine the relevant levels of economic disruption, F_d and F_{dd}, at each pair of locations involved in moving people.

The health costs from radiation-induced effects were estimated in Lochard and Schneider (1992), who quote the value $F_r =$ € 10,750 per man Sv claimed to account for the costs associated with LLE from fatal cancers as well as the costs of medical treatment. In comparison, the WTP-based estimates in Section 5.2 resulted in the middle of the range value $F_r =$ € 50,000 per man Sv (GBP converted into EUR and rounded up). This higher value is partly due to a significantly higher GDP in the UK/Europe in 2010 compared to that of the USSR in 1987.

A detailed account of remediation costs from a number of rural areas in Ukraine, Belarus and Russia is provided in Jacob et al. (2009). Based on the total population $p_0 = 78,000$ and the collective annual exposure $D(2010) = p_0\,R(2010) = 52.2$ man Sv in year 2010, the relevant average individual dose received in this year is $R(2010) = 0.669$ millisievert, which roughly corresponds to the dose rate from ground shine $r(2010) = 0.669$ millisievert/year. As of year 2010, if no further measures were going to be implemented, individual *residual* dose would be equal to

$$R_{\text{res}}(2010) = \int_{2010}^{\infty} r(t)\,\mathrm{d}t = \frac{r(2010)}{\gamma}, \qquad (19)$$

where $\gamma = 0.023\,\text{yr}^{-1}$ is the decay rate for Cs-137. According to (Jacob et al., 2009), multiple remediation measures undertaken in year 2010 collectively averted $\Delta D_{\text{avt}} = p_0\,\Delta R_{\text{avt}} = 161.7$ man Sv, corresponding to average individual averted dose $\Delta R_{\text{avt}} = 2.073$ millisievert. Noting that the averted dose and the change in the residual dose are related as $\Delta R_{\text{avt}} = -\Delta R_{\text{res}}$, we find by differentiating (19) that the relevant change in the dose rate in year 2010 is $\Delta r(2010) = \gamma\,\Delta R_{\text{res}} = -0.048$ millisievert /year. As a

Table 3
Estimates for λ_β and $\lambda_\varkappa$ based on the data from Chernobyl (Jacob et al., 2009; Lochard & Schneider, 1992), and for three contrasting initial radiation levels. λ_Δ is approximated assuming economic disruption and infrastructure loss at a rate of 10% of GDP per capita.

...	High	Medium	Low
r_0 (millisievert/year)	30	15	5
λ_β	6.798	13.596	40.789
$\lambda_\varkappa$	0.005	0.010	0.029
λ_Δ	2.390	4.781	14.343

result, the remediation rate in year 2010 is $\varkappa_0 = \frac{1}{r(2010)}\left|\frac{\Delta r(2010)}{\Delta t}\right| = 0.072\,\mathrm{y}^{-1}$, roughly 3 times greater than γ for Cs-137.

Using the quoted remediation cost per unit collective averted dose, $F_{\text{avt}} =$ € 21,000 EUR per man Sv, and the collective averted dose $\Delta D_{\text{avt}} = 161.7$ man Sv in year 2010, we find that the total rate of spending on remediation for this year in the given area is roughly equal to $\dot{C} = 3.4 \cdot 10^6$ EUR per yr. According to (8), this translates to the characteristic remediation cost $F_\varkappa = \dot{C}/\varkappa_0 = 5.07 \cdot 10^6$ EUR for the e-folding remediation rate $\varkappa_0$ obtained above.

Lochard and Schneider (1992) also has information for the overall resettlement costs. Based on the total population affected of 705,600 and the total relocated population of 218,900 during the 5-year period after the disaster, the rough estimate for the relocation rate $\beta_- = 0.069\,\mathrm{y}^{-1}$, which is of the same order as the remediation rate $\varkappa_0$. Clearly, this figure is going to be much higher for individual settlements. The total spend of 9251 MRub on the resettlement of the 218,900 people implies the individual relocation cost $F_{\beta_-} =$ € 90,860 per person. The relevant spend rate $\beta_- F_{\beta_-} =$ € 6280 per person per annum is very close to the productivity rate F_p estimated by the relevant GDP in the USSR in 1987. As mentioned in Section 5.5, various compensation costs are excluded from the analysis.

Based on this data, and using the estimate $F_r =$ € 50 per person per millisievert, we can evaluate the non-dimensional economic groups λ defined in (17). We use the single-radionuclide expression (16) with the optimisation period set to $T = 24$ years (from the Chernobyl accident up to year 2010) and $\gamma = 0.023\,\mathrm{y}^{-1}$ for Cs-137. First, note that all the λ's depend on the initial radiation levels, r_0, according to their definition (17). Assuming $F_{\beta+} = F_{\beta-}$, with the latter estimated at €90, 860 per person, one gets the set of values of λ_β shown in Table 3. The three contrasting values of the initial dose rate r_0 are chosen for illustrative purposes.

There is not enough information in Jacob et al. (2009), Lochard and Schneider (1992) to estimate λ_Δ and λ_α. For illustrative purposes, one could assume that the overall rate of economic disruption and infrastructure losses, F_Δ, is 10% of the GDP per capita in 1987, giving $F_\Delta =$ € 639 per person per year. Setting the interest rate $\delta = 0.02\,\mathrm{y}^{-1}$, we get the estimates for λ_Δ corresponding to three contrasting values of the initial dose rate r_0 shown in Table 3. The same Table contains the estimates for $\lambda_\varkappa$ based on the characteristic remediation cost $F_\varkappa = 5.07 \cdot 10^6$ €.

It will be demonstrated in Section 8 that for these generally high relocation costs the optimal strategy is *no relocation* by a significant margin, even for relatively high initial contamination levels (as long as the guidance dose thresholds are not exceeded, see Electronic Supplementary Materials I). We note that the estimates in Table 3 are based on the aggregated data for the entire relocated population of over 200 thousand people, and individual costs for small towns and villages that are more relevant in the context of our model are likely to have varied considerably. It is also worth noting that if significantly more weight is placed on the health costs through the inclusion of morbidity and psychological effects, the above estimates for λ_β and λ_Δ could be brought down to 1 and below for higher radiation levels, potentially justifying the relocation measures in highly-contaminated areas. On the other hand, the stress of moving is likely to disrupt the lives of those involved, resulting in larger values of λ_Δ which may justify the no-relocation policy.

Table 4
Estimates for $\lambda_\varkappa$ based on the data from Fukushima (WNN, 2012), and for three contrasting initial radiation levels.

...	High	Medium	Low
r_0 (millisievert/year)	30	15	5
$\lambda_\varkappa$	0.113	0.226	0.677

7.2. Data from Fukushima

Following the emergency evacuation and relocation carried out in the aftermath of the Fukushima disaster, it was deemed that the in evacuated areas the return was possible for dose rates less than 20 millisievert/year, while decontamination was ordered for the areas with the radiation between 20 and 50 millisievert/year. The areas with the radiation levels in excess of 50 millisievert/year were designated as difficult to return (Omoto, 2012; WNN, 2013).

According to (WNN, 2012), the Fukushima City (65 kilometres from the plant) with $p_0 = 290,000$ inhabitants (110,000 households) received the contamination levels between 5 and 10 millisievert/year due to Cs-137. The total clean-up cost was estimated at 370 million USD, which is approximately £250 million for the entire city and £2, 270 per household. Furthermore, the decontamination of the first 4000 houses during the 18-month period between the disaster and autumn 2012 reduced the radiation levels from $r = 7$ millisievert/year to $r - \Delta r = 2$ millisievert/year. Thus, the remediation rate for this subset of households could be estimated as

$$\varkappa_0 = \frac{1}{r}\left|\frac{\Delta r}{\Delta t}\right| = 0.476\,\mathrm{y}^{-1}$$

which is around 20 times greater than the decay rate γ of Cs-137 (the relevant remediation rates in Chernobyl were of the same order of magnitude as γ). Given the total cost £250 million of reducing the radiation levels by the average of 5 millisievert/year in the *entire* Fukushima City (110,000 households), the relevant cost for the 4000 households incurred over the 18-month period is £9.09 million, corresponding to the rate of remediation spending $\dot{C} =$ £6.06 million per yr. This translates to the characteristic remediation cost $F_\varkappa = \dot{C}/\varkappa_0 =$ £12.75 million for the e-folding remediation rate $\varkappa_0$ obtained above (see the definition in (8)). We note that these figures neglect the natural processes such as mixing by air and washing by precipitation, and therefore they are likely to be on the higher end of the range.

Using the estimate $F_r =$ £39.9 per person per millisievert for the health costs, and employing the single-radionuclide expression (16) for the characteristic timescale $\tau = R_T/r_0$, with the optimisation period set to $T = 24$ years (same as for the Chernobyl data) and $\gamma = 0.023\,\mathrm{y}^{-1}$ for Cs-137, we get the estimates for $\lambda_\varkappa$ corresponding to different levels of the initial radiation r_0 summarised in Table 4.

It is harder to estimate the costs of relocation from the Fukushima prefecture because of the considerable economic damage to the infrastructure caused by the earthquake and the tsunami. Omoto (2012) quotes the total number of 140,000 evacuees as a result of the nuclear disaster; 58% of the evacuees had received a dose less than 1 millisievert and 99.3% – less than 10 millisievert . To estimate the rates and costs of moving the people, a clear distinction between evacuation and relocation has to be

Table 5
Estimates for λ_α based on the post-Chernobyl agricultural data from the UK, and for three contrasting initial radiation levels.

...	High	Medium	Low
r_0 (millisievert/year)	30	15	5
λ_α	0.143	0.285	0.856

made. For the purpose of our study, one could say that displacing the people for more than a month form their original residential area is referred to as *relocation* while shorter periods are referred to as *evacuation*. There are detailed accounts of moving the people at the Fukushima prefecture (see, for example, Akahane, 2013) that could be used to estimate $\beta_\pm$ and $F_{\beta\,\pm}$, but we are going to leave this for a future study.

7.3. Radiation uptake by agricultural produce based on post-Chernobyl UK data

Gillett et al. (2001) gives rough estimates for radiocaesium flux through food produce (becquerel/year/hectare) across England and Wales in the aftermath of Chernobyl, quoting figures of 18, 40 and 110 Gbecquerel/year for sheep meat, cereal crops and cow milk, respectively, from all the agricultural areas during the first year after the disaster. With the total flux $Q =$ 168 Gbecquerel/year, average "pre-accident" yield $m_0 = 5$ tonnes per hectare per annum (DEFRA, 2008), average UK contamination level of $B = 2.21$ kilobecquerel/m^2 over the total affected area $A = 2.4 \cdot 10^5$ square kilometre (see Table III.1 from De Cort et al., 1998, quoting the total UK contamination at 0.53 Pbecquerel), we can get a rough estimate for the transfer coefficient from soil to food: $a = Q/(A\, m_0\, B) = 6.33 \cdot 10^{-4}$ becquerel/kilogram per becquerel/sqaure metre. Assuming the share of the agricultural production area within a given region is $\omega = 0.5$, we estimate the relevant extraction rate $\alpha_0 = m_0\, a\, \omega = 1.58 \cdot 10^{-4}\ \mathrm{y}^{-1}$.

To estimate the characteristic revenue $F_\alpha = \pi_f/(a\, p_0)$ associated with the contaminated food produce, we note that the total added value to the economy from farming in the UK in 2010 was £ 7.2 b,[6] while the annual food biomass productivity in the UK is estimated at 90 billion kilograms (Weighell, 2011). These figures correspond to around 8 pence per kilograms of the biomass, which could be used as an estimate for π_f, the latter treated as the direct revenue from the agriculture. Food processing and supply chains add significantly higher costs to food (up to 10 times greater than raw produce). In the event of a ban on food production from a given contaminated location, the supply chains are expected to switch to alternative raw produce in free market economy without significant knock-on effects. This means that the characteristic revenue from contaminated agricultural produce that could be generated on the timescale of α^{-1} is $F_\alpha \approx$ £ 1, 579, 780 per person, based on the radioactive transition coefficient $a = 6.33 \cdot 10^{-4}$ m^2/kilogramm and the population density $p_0 = 0.8$ persons per hectare typical of the UK rural areas. We note that this large value should be seen as the agricultural revenue potential spread over a very long period of time due to the relatively small agricultural extraction rates that are of the order of $\alpha_0 \sim 10^{-4}$ per year.

The relevant non-dimensional group λ_α contains small parameter $\gamma_0 = 1.13 \cdot 10^{-4}$ per year, which negates the large value of F_α and produces the estimates presented in Table 5, based on the same health cost that has been applied to the Chernobyl and Fukushima data.

[6] http://www.ukagriculture.com/statistics/farming_statistics.cfm?strsection=Economy.

8. Case studies and results

Using the estimates from the previous section, we define hypothetical ranges of possible values of the main parameters of the problem that broadly fit within the historic data from Chernobyl and Fukushima, and then obtain numerical solutions for a set of randomly simulated combinations of costs and rates within these ranges. This Monte-Carlo-based methodology serves to explore hypothetical settings that complement the limited historic data, and allows us to identify a small number of distinct qualitatively different optimal strategies that may take place. Using the generated relative likelihoods of occurrence for the distinct types of strategies within the specified parameters' space, one is able to investigate the sensitivity of the optimal recovery measures to varying economic conditions and varying 'capacity constraints' while implementing these measures, and also explore the effect of possible regulatory differences in the economic evaluation of health.

8.1. Parameter values and numerical scheme

First, we assume that each of the main three parameters defining the dimensionless economic groups λ_z, namely F_z, F_r and r_0 (Section 6.2), can vary two-fold between its hypothetical extreme values; here $z = \Delta, \beta, \varkappa, \alpha$. For example, if the central (arithmetic average) estimate for the characteristic remediation cost is assigned the value $F_\varkappa \equiv (F_\varkappa)_{\rm cent} =$ £ 12.75 million from Fukushima (Section 7.2), then the corresponding extremes are defined as $(F_\varkappa)_{\rm min} = (2/3) \cdot (F_\varkappa)_{\rm cent} =$ £ 8.5 million and $(F_\varkappa)_{\rm max} = 2(F_\varkappa)_{\rm min} =$ £ 17 million. The multiplicative structure of λ_z means that the two-fold variations in its three underlying parameters, if independent from one another, translate into $2^3 = 8$ -fold variations in λ_z itself, giving rise to the following relationship between the minimal, central and maximal values of each λ: $\lambda_{\rm min} = \frac{3}{8}\,\lambda_{\rm cent} = \frac{1}{8}\,\lambda_{\rm max}$. We opt not to vary the initial population density, setting it to $p_0 = 0.8$ persons per Ha which is typical for rural areas in the UK; if this assumption is relaxed, $\lambda_\varkappa$ will be the only parameter to gain a greater uncertainty range.

Second, we consider the initial dose rates within the range 10 millisievert/year $< r_0 <$ 20 millisievert/year (central value of 15 millisievert/year), which is in compliance with the existing ICRP and IAEA guidance for the highest levels of radiological exposure allowed before relocation has to be carried out (Electronic Supplementary Materials I), and use the remediation data from Fukushima to define the central value of $\lambda_\varkappa$ (Tables 4), and the UK-based food production data as a central value for λ_α (5). The central value of λ_β is defined by downscaling the relevant estimate from Chernobyl (Table 3) by a factor of four, to account for the possibility that the spending on the relocation costs was sub-optimal and that the official exchange rate between RUB and USD was inflated. The resulting lower-end values, $(\lambda_\beta)_{\rm min} = 1.27$, $(\lambda_\varkappa)_{\rm min} =$ 0.085 and $(\lambda_\alpha)_{\rm min} = 0.107$, are rounded to 1, 0.1 and 0.1, respectively, which gives the hypothetical ranges for the three λ parameters listed in Table 6. The range for λ_Δ is an expert guess. We also perform a separate sensitivity analysis for considerably higher dose rates in the range 50 millisievert/year $< r_0 <$ 100 millisievert/year (Section 8.5), with the relevant ranges of the λ parameters shown in Table 9.

The values of the four characteristic rates, $\beta_\pm$, $\varkappa_0$ and α_0, are also set to vary two-fold. We use expert judgements for the characteristic relocation and repopulation half-times, $T_{\beta\mp} = \ln 2/\beta_\mp$, in the ranges between 1 and 2 weeks for relocation and between 3 and 6 months for repopulation, to define the rates $\beta_\pm$. Based on typical values of agricultural yield m_0 in the range between 5 and 10 tons per hectare, we define the relevant extraction rate $\alpha_0 = m_0\, a\, \omega$, with the share of agricultural land in the exclusion zone set to $\omega = 0.5$ and the radiation plant uptake a given in

Table 6
Input parameter ranges for Monte-Carlo simulations: characteristic scaled costs λ_Δ (accident-driven difference in economic disruption per capita between the current and new locations), λ_β (average between relocation and repopulation costs per capita), $\lambda_\varkappa$ (remediation cost) and λ_α (revenue from agriculture), characteristic times $T_{\beta-}$ (relocation) and $T_{\beta+}$ (repopulation), remediation rate $\varkappa_0$ and agricultural yield m_0. All the costs are scaled based on the health cost per unit dose per capita.

...	min	max	...	min	max
λ_Δ	$\pm$ 0.5	$\pm$ 4	$T_{\beta-}$ (weeks)	1	2
λ_β	1	8	$T_{\beta+}$ (months)	3	6
$\lambda_\varkappa$	0.1	0.8	$\varkappa_0$ (1/year)	0.25	0.5
λ_α	0.1	0.8	m_0 (ton/hectare/year)	5	10

Electronic Supplementary Materials II.[7] The values of $\varkappa_0$ are defined using the relevant estimate from Fukushima, which is assigned to the upper end of the range. We summarise the default parameter ranges in Table 6.

The computations are performed for the three main radionuclides: Cs-137 (30.17 y), Cs-134 (2.07 y) and I-131 (8.02 d). To specify their relative contributions to the dose rates, we use the total deposited quantities similar to those from the source term in Fukushima (WHO, 2013), and assume that the deposition period lasts for $t_0 = 30$ days, with constant deposition rates throughout.[8] Consequently, the amount of I-131 remaining at the end of the deposition period is around a third of the total amount released, while the remaining quantities of the Cs isotopes are roughly equal to the relevant totals due to their slow decay rates. The specified source term results in the combined initial dose rate (i.e. at the very end of the deposition period) from ground shine $r_0 \approx 33\,\text{millisievert/year}$, which falls to around $12\,\text{millisievert/year}$ after a few weeks due to the rapid decay of I-131. However, due to the properties of the optimisation problem, the source term is only needed to define dose rates from the individual radionuclides relative to one another, while the actual range of values of the initial radiation, either $10\,\text{millisievert/year} < r_0 < 20\,\text{millisievert/year}$ ("baseline") or $50\,\text{millisievert/year} < r_0 < 100\,\text{millisievert/year}$ ("high radiation"), is defined implicitly through the ranges of the λ parameters (see above).

The optimal 'paths' for the population and radiation, $p_*(t)$ and $r_*(t)$, are found by integrating the dynamic constraints (3) and (12), respectively, from the relevant initial conditions, and with the optimal policies for $p_c(p,\ r,\ t)$, $\varkappa(p,\ r,\ t)$ and $\alpha(p,\ r,\ t)$. The latter are obtained from solving the PDE (14) backwards from the final condition (III.2) numerically (Electronic Supplementary Materials IV), which is achieved by running exhaustive search enhanced by checking the binary alternatives (known as "bang-bang" solutions), combined with a standard Lagrangian scheme.

Three different time steps are used throughout the optimisation horizon, adjusted to resolve the fast processes associated with the decay of I-131 and relocation, before being set to a larger value corresponding to the next fastest process to speed up the computations for the remainder of the optimisation period. We use 10 steps each for two smallest e-folding timescales and 40 steps for the largest timescale (covering the rest of the period). The grid steps for p and r are linked with the largest of the three timesteps through the convergence criterion for numerical schemes based on the method of characteristics, which requires that each grid cell should be able to fully accommodate the steepest characteristic. The final condition is obtained by direct numerical integration between T and $3T$ with a single constant time step, combined with a simplified analytical solution beyond $3T$ (Electronic Supplementary Materials III). Finally, the interest rate is kept constant at $\delta = 0.02\,\text{y}^{-1}$, and the optimisation horizon is set to $T = 15$ years.

While our central estimates of the costs draw on the data both from Chernobyl and Fukushima, it is not possible to infer with great certainty where these two accidents would 'sit' within the range of variations considered in the present study. Their source terms had different strength and compositions, and there were differences in the underlying socio-economic conditions in their respective surrounding areas. Given the generally higher levels of radiation and lower costs of implementing protection and recovery measures in Chernobyl, it is likely that the optimal strategies for Chernobyl would be more in line with the "high radiation" case described in Section 8.5, while Fukushima would be closer to the "baseline" case.

Likewise, we do not specifically distinguish between rural and semi-urban settings, and keep the initial population p_0 constant at UK's rural levels, although it is possible to make generic conclusions as to where each of these setting would belong in the parameters' space. More urban-like settings are characterised by a higher economic output per person, which could lead to greater levels of economic disruption described by larger negative values of λ_Δ, giving a greater incentive to relocate. However, relocation would lead to losses of the land value that are going to be higher in urban areas with more infrastructure, resulting in positive values of λ_Δ and additional pressures to avoid relocation. Higher population densities would also reduce the scaled remediation cost $\lambda_\varkappa$, making earlier remediation more attractive, while the share of the agricultural land ω and with it the extraction rate α_0 would drop, reducing the weight of the agricultural terms in the overall cost function.

8.2. Three contrasting problem settings

For the rest of the paper we are going to focus on the medium-term timescales of around a decade in the combined problem setting (areas with both urban and rural elements). In this setup, three main variations of the optimisation problem emerge: no pre-relocation, no pre-relocation with an additional economic incentive to move the people to a better location, and pre-relocation in the immediate aftermath of the accident, referred to as "Full", "Full-Negative" and "Empty". These labels reflect on the underlying initial condition for the population, Full vs Empty, and on the sign of the parameter λ_Δ, Positive (default) vs Negative, which captures the difference between accident-driven economic disruption in the old and new locations, as well as the loss of infrastructure at the old location. If $\lambda_\Delta < 0$, the new location provides an additional economic incentive for the people to move. In the opposite case, $\lambda_\Delta > 0$, the expected high economic disruption at the new location (as a result of having to provide for and ultimately integrate the relocated people) and the loss of the infrastructure at the old location create an incentive to remain. It is obvious that the Empty setting only provides non-trivial solutions when there is an incentive to repopulate the originally relocated area, and therefore only the settings with $\lambda_\Delta > 0$ are applicable in this case, explaining why there is no "Empty-Negative" setting in the mix.

Both of the two Full problem variations are applicable to the areas where no *emergency relocation* is ordered in the earliest stages (during the deposition period). Even though there still might have been partial *emergency evacuation* from these areas, it is assumed that no decision has been made with regards to longer-term

[7] The corresponding parameter ranges for the rates of relocation (β_-), repopulation (β_+) and food production (α_0) are (all measured in 1/year): $\beta_- \in [18.1, 36.2]$, $\beta_+ \in [1.4, 2.8]$, $\alpha_0 \in [1.6 \cdot 10^{-4}, 3.2 \cdot 10^{-4}]$.

[8] See Electronic Supplementary Materials II, Electronic Supplementary Materials V and Electronic Supplementary Materials VI for further details.

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Table 7
Relocation, remediation and food regimes with no pre-relocation (Full).

No Relocation	Reloc = 1
Partial Relocation & Full Repopulation	Reloc = 2
Full Relocation & Full Repopulation	Reloc = 3
Full Relocation & Partial Repopulation	Reloc = 4
Full Relocation & No Repopulation	Reloc = 5
No Remediation	Remed = 1
Delayed Remediation	Remed = 2
Early Remediation	Remed = 3
No Food Ban	Food = 1
Temporary Food Ban	Food = 2
Perpetual Food Ban	Food = 3

relocation of the people, and our model could be used to make an optimal decision on whether to proceed with the relocation or not (see Section 2 for the distinction between our definitions of the evacuation and relocation). In some cases there may be no evacuation at all during the deposition period due to low perceived risk, and the model could show whether keeping the people in the area had been justified (with the doses received initially through cloud shine and inhalation taken into account, see Electronic Supplementary Materials V).

The problem setting referred to as Empty corresponds to the cases when emergency relocation takes place before any analysis of the feasible long-term protection and recovery measures is carried out, and/or when non-economic factors such as high levels of risk-aversion to radiation among the public and the possibility that some people could receive life-threatening doses are taken into account. In this regard, the initial relocation is not necessarily optimal in the economic terms, leading to the so-called *sunk costs* being incurred in some cases. This situation appears to be the most realistic of all. However, in the aftermath of the relocation the question of whether to remediate and then repopulate the given area or not is still legitimate, and one would want to make economically optimal decisions in accordance with our model, providing the corresponding health-related cost are taken into account. Mathematically, the only difference between the Empty and the Full settings is in the initial condition for the population: $p(0)=0$ for the Empty and $p=p_0$ for the Full settings.

8.3. Classification for the optimal strategies and the relevant costs

Depending on the preferences of the decision makers, the optimal regimes could be ranked according to their total cost, to the health cost only, to the ratio of the total cost to the health cost and so on. We are going to sort the regimes based on an estimated relative percentage of occurrence for the strategies within the specified ranges of the parameters in our Monte-Carlo simulations.

The individual measures for population, remediation and food ban could be distinguished from one another by setting different integer values to numerical flags that we call “Reloc”, ‘Remed” and “Food”, respectively. For the problem settings with no pre-relocation, the possible values for each of the three flags are possible are given in Table 7. For the settings with pre-relocation (Empty) there are only four alternatives for the population dynamics: Immediate Full Repopulation (Reloc = 1), Delayed Full Repopulation (Reloc = 3), Partial Repopulation (Reloc = 4) and No Repopulation (Reloc = 5). The Remed and Food flags remain the same. Our code distinguishes between these alternatives by running a sequence of binary checks for any computed optimal strategy, which allows to obtain reliable classification across a wide range of the Monte-Carlo parameter values.

The three flags considered together define the following combined rank of the relevant joint optimal strategy:

$$\mathrm{Rank}(\mathbf{x},\ldots)=\mathrm{Food}(\mathbf{x},\ldots)+3\cdot(\mathrm{Remed}(\mathbf{x},\ldots)-1)\\ +9\cdot(\mathrm{Repop}(\mathbf{x},\ldots)-1). \tag{20}$$

This function has a maximum of 45 integer values and is a scalar defined in the state space Ω of the input parameters represented by the vector $\mathbf{x}=\{\lambda_\Delta,\lambda_\beta,\lambda_\varkappa,\lambda_\alpha,\bar\beta_-,\bar\beta_+,\bar\varkappa_0,\bar\alpha_0\}$; the dots correspond to the remaining parameters which are kept constant in the simulations. In reality only a small subset from the possible 45 strategies exists for the reasonable ranges of the input parameters (usually between 2 and 5 strategies).

Once the optimal strategy is found for a given set of the input parameters, it is possible to calculate the relevant aggregate scaled costs (Net Present Values) associated with carrying out this particular strategy. These costs include accident-driven difference in economic disruption between the current and new locations and depreciation of the abandoned infrastructure (C_Δ), expenses associated with relocation and/or repopulation (C_β), remediation spending ($C_\varkappa$), accident-driven decrease in revenue from food production (C_α), health-related economic losses (C_r) and total cost associated with a given strategy (C_Σ) during the entire period of optimisation:

$$C_\Delta=-\lambda_\Delta\int_0^{\bar T}\frac{\mathrm{d}\bar p}{\mathrm{d}\bar t}\,\mathrm{e}^{-\bar\delta\bar t}\,\mathrm{d}\bar t,\quad C_\beta=\lambda_\beta\int_0^{\bar T}\left|\frac{\mathrm{d}\bar p}{\mathrm{d}\bar t}\right|\mathrm{e}^{-\bar\delta\bar t}\,\mathrm{d}\bar t,$$
$$C_\varkappa=\lambda_\varkappa\int_0^{\bar T}\bar\varkappa\,\bar\xi(\bar t)\,\mathrm{e}^{-\bar\delta\bar t}\,\mathrm{d}\bar t,\quad C_\alpha=\lambda_\alpha\int_0^{\bar T}\frac{\bar\alpha_0-\bar\alpha\,\bar p}{\bar\gamma_0}\,\mathrm{e}^{-\bar\delta\bar t}\,\mathrm{d}\bar t,$$
$$C_r=\int_0^{\bar T}\left[\bar\xi(\bar t)+\bar\eta(\bar t)\,\frac{\bar\alpha}{\bar\gamma_0}\right]\bar p\,\bar r\,\mathrm{e}^{-\bar\delta\bar t}\,\mathrm{d}\bar t,$$
$$C_\Sigma=C_\Delta+C_\beta+C_\varkappa+C_\alpha+C_r. \tag{21}$$

The integrals are taken along the relevant optimal paths and all the costs are discounted to $t=0$. For the sake of clarity, positive costs by definition imply expenditures, while negative costs imply revenues, which is possible for C_Δ.

8.4. Results for the optimal strategies: medium radiation levels

We use the parameter ranges in Table 6 to set log-uniform distributions for the four λ parameters and uniform distributions for the four rates, and perform 1000 Monte-Carlo experiments to search for distinct optimal strategies. The reason behind using log-uniform distributions for λ's is in their multiplicative nature (individual characteristic costs divided by the relevant health cost and the initial radiation rate). The choice of 1000 simulations represents a compromise between having a sufficiently high resolution in the numerical scheme for the PDE and a sufficiently large number of experiments in order to capture a plausible set of the optimal strategies. We note that the uncertainties introduced in this Section are associated only with the ability to choose from a range of values of the input parameters in each Monte-Carlo run, but these values are assumed to be time-constants in each particular simulation. Thus, each run on its own represents a deterministic problem in the OR terminology, while the statistical sample of multiple runs with the given probability distributions for the input parameters is used as a tool to search for the distinct optimal strategies. In Figs. 4 and 5 we present the computational results for the optimal ‘paths’ $p(t)$ (red), $\varkappa(t)$ (green) and $\alpha(t)$ (blue) plotted as functions of time t (in years) in the mid-term combined problem setting to show the qualitatively different types of solutions that exist. The three paths are scaled, respectively, to 1, 2/3 and 1/3 for illustrative purposes, so that $p(t)=1$ corresponds to the initial population (implying no relocation or full repopulation), $\varkappa(t)=2/3$ implies the highest possible remediation rate and

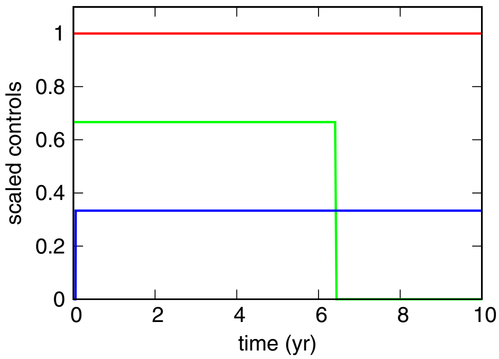

Fig. 4. Representative scaled optimal population p (red, initial population = 1), remediation rate $\varkappa$ (green, highest possible rate of remediation = 2/3) and food production rate α (blue, business as usual food production = 1/3), plotted throughout the optimisation period (in years) for the Full and Full-Negative setting and Medium radiation levels. Interpretation: No Relocation, Early Remediation (lasting around 6.5 years), Short Early Food Ban (just over a week long, until most of I-131 decays; not visible in the plot). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

$\alpha(t) = 1/3$ stands for the business as usual food production (no restrictions/ bans). For the Full and Full-Negative settings with no pre-relocation the initial condition for the population is $p(0) = p_0$ and we get the characteristic optimal scenarios in Fig. 4.

Under the chosen parameter ranges, all 100% of the runs both in the Full and Full-Negative settings represent No Relocation (Reloc = 1), Early Remediation (Remed = 3) and Short Early Food Ban (Food = 2) which allows for I-131 to decay naturally. For the particular case shown in Fig. 4, the remediation period lasts around 6.5 years, while the food ban is implemented for just over a week.

For the setting with pre-relocation (Empty), the initial condition for the population is $p(0) = 0$, resulting in the characteristic optimal scenarios in Fig. 5. Around 75% of all the runs represent Delayed Repopulation (Reloc = 3) and Lifting of the Food Ban (Food = 2) after around one year, along with Early Remediation (Remed = 3) lasting several years. We see a representative case of this in Fig. 5(a), which shows remediation ending after 5.5 years and repopulation and lifting of the food ban being implemented simultaneously after around 15 months. The next most common strategy (21% of the runs) is the one with Early Repopulation (Reloc = 1), Early Remediation and either Short Early Food Ban (Food = 2), as shown in Fig. 5(b), and *complete abandoning* of the area (around 2% of the runs, not shown). The results are summarised in Table 8.

Therefore, there is a visible tendency to repopulate the area either with a delay or immediately, and in all these cases remediation plays a crucial role. In most cases food banning tends to follow the population movements, suggesting that the availability of the workforce who are allowed to live and farm in a given contaminated area despite receiving small residual doses via ground shine is a stronger decision-making factor for food production than the resulting contamination of the food.

Table 8
Relative occurrence of distinct optimal regimes with pre-relocation (Empty) for Medium radiation levels. 1000 Monte-Carlo runs.

...	Relative occur.	C_Σ	C_r	Rank	Reloc	Remed	Food
1	75.6%	1.013	0.159	26	3	3	2
2	20.9%	0.862	0.264	8	1	3	2
3	1.9%	1.646	0	39	5	1	3
4	1.4%	2.658	0.101	23	3	2	2

8.5. Higher radiation levels

In the language of our model, higher initial radiation levels translate into proportionally lower values of the four economic dimensionless groups λ. In this section we examine the sensitivity of the optimal prevention and recovery strategies to higher radiation levels by increasing the range of the initial dose rates five-fold to $50\,\text{millisievert/year} < r_0 < 100\,\text{millisievert/year}$, which translates into the lower values of the λ parameters shown in Table 9, providing all the other parameter ranges are the same as before (Section 8.1). The radiation levels of up to 100 millisievert/year are beyond the current public safety laves provided by ICRP and IAEA, although they may still be allowed for specialist workers (WHO, 2013). Nevertheless, these levels are well below the doses that tend to trigger deterministic health effects, suggesting that the LNT hypothesis at the basis of our estimates for the health costs is still likely going to be applicable.

Increasing the radiation levels creates additional optimal strategies that did not appear before, some of which are shown in Fig. 6

Table 9
Estimated ranges for the characteristic scaled costs λ corresponding to the initial radiation levels $50\,\text{millisievert/year} < r_0 < 100\,\text{millisievert/year}$, which are five times higher than those used in Table 6.

...	min	max	...	min	max
λ_Δ	±0.1	±0.8	$\lambda_\varkappa$	0.02	0.16
λ_β	0.2	1.6	λ_α	0.02	0.16

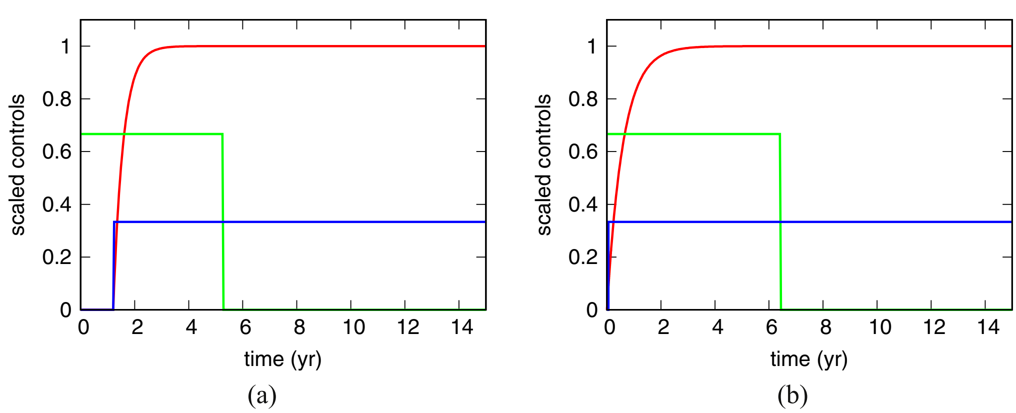

Fig. 5. Representative scaled optimal strategies plotted against the time (in years) for the Empty setting: (a) Delayed Repopulation and Lifting of the Food Ban (after around 15 months), with Early Remediation (lasting just over 5 years); (b) Early Repopulation, Early Remediation (lasting around 6.5 years), Short Early Food Ban (just over a week long, until most of I-131 decays; not visible in the plot). The variables represented by the three coloured lines and their respective scaling are described in the caption to Fig. 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

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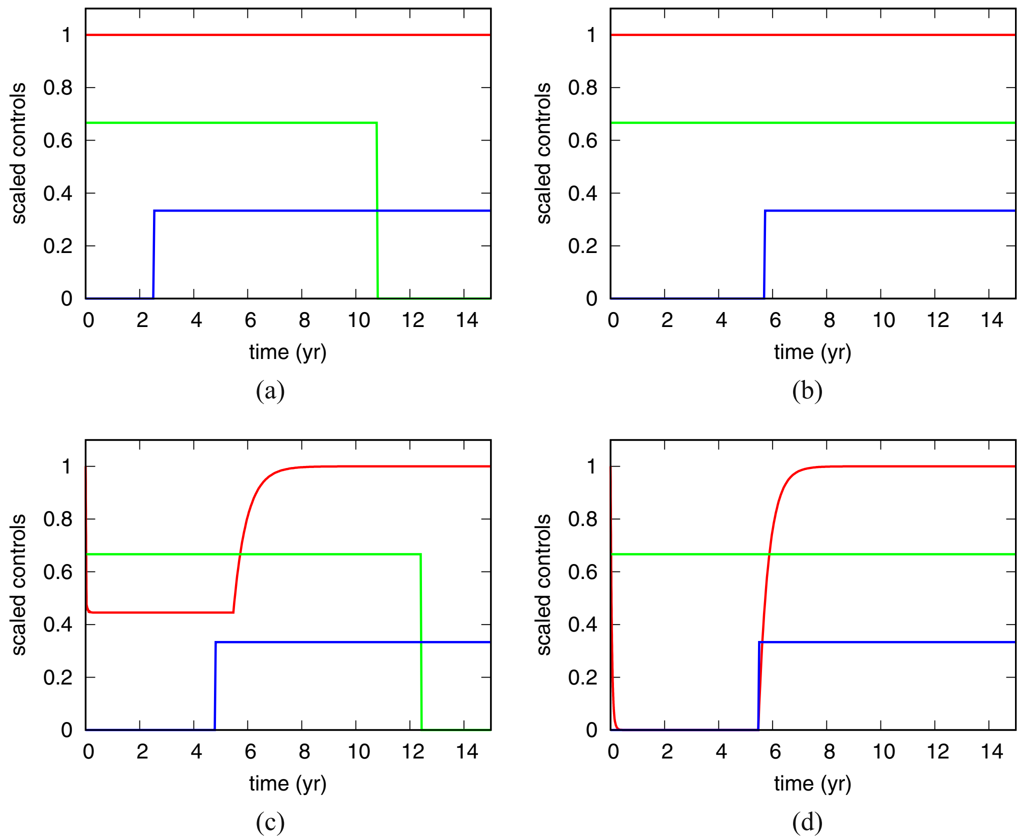

Fig. 6. Representative scaled optimal strategies plotted against the time (in years) for the Full-Negative setting and High radiation levels: (a) No Relocation, Early Remediation (lasting around 11 years), Temporary Food Ban (lasting around 2.5 years); (b) No Relocation, Early Remediation (lasting for the entire optimisation period), Temporary Food Ban (lasting around 5.5 years); (c) Partial Relocation (with around 45% of the population remaining) & Full Repopulation (starting after around 6 years), Early Remediation (lasting around 12.5 years), Temporary Food Ban (lasting around 5 years); (d) Full Relocation & Full Repopulation (starting after around 5.5 years), Early Remediation (lasting for the entire optimisation period), Temporary Food Ban (lasting around 5.5 years). The variables represented by the three coloured lines and their respective scaling are described in the caption to Fig. 4. Note the time range on the plots: $t \in [0, 15]$ years.

for Full-Negative problem setting (Section 8.2). The duration of remediation actions is significantly longer in most cases, and food ban also tends to be longer. The main new features of the selected optimal strategies are remediation throughout the whole optimisation period (plots (b), (d)), and partial (plot (c)) or full (plot (d)) relocation followed by full repopulation. The latter strategies are similar to those typical of the Empty setting, but with the key difference that the costs associated with relocation are included in the economic optimisation. *Complete abandoning* of the area also becomes an option under the Full-Negative setting. However, the most commonly found strategies still correspond to No Relocation, Early Remediation (lasting around 10 years) and Temporary Food Ban (lasting around 2 years), which is due to the comparatively high costs of relocation and repopulation relative to remediation.

In the Empty setting (emergency pre-relocation regardless of the costs) the most striking change associated with the considerably higher radiation levels is manifested by lack of the strategies with Immediate Repopulation, although the prevalent strategy (Delayed Repopulation, Early Remediation and Temporary Food Ban) becomes more common. As with the Full and Full-Negative settings, complete abandoning of the area is more likely, while in some cases remediation continues throughout the optimisation period.

8.6. Distributions of the total discounted health costs for optimal strategies

Based on the 1000-strong Monte Carlo sample of optimal strategies for the given set of *subjective* input probability distributions, we plot the output distributions of the aggregate discounted health costs C_r (NPVs) in Fig. 7 for the medium (column 1) and high (column 2) radiation levels in the Full-Negative (row 1) and Empty (row 2) settings introduced in previous sections. The relevant NPVs of the costs are defined in (21), and additional scaling is applied using the maximum possible health cost, $\max C_r$ (NPV), which would have been incurred in the given area if *no relocation*, *no remediation* and *no food banning* measures were implemented:[9]

$$\max C_r = \int_0^{\bar{T}} \left[\bar{\xi}(\bar{t}) + \bar{\eta}(\bar{t}) \, \frac{\bar{\alpha}_0}{\bar{\gamma}_0} \right] \mathrm{e}^{-(\bar{\alpha}_0+\bar{\delta})\,\bar{t}} \, \mathrm{d}\bar{t}. \tag{22}$$

As a result scaled optimal health costs are always less than 1, as expected, and in fact do not exceed 0.46 for the chosen ranges of the input parameters. The distributions have multi-modal features in line with the discrete nature of the distinct optimal regimes described in the previous section, for example with the small clusters close to zero corresponding to complete abandoning of the area, which is cost-optimal in some cases.

Comparing the rows in Fig. 7, we see that the distributions for the health costs shift considerably to the left as we move from the Full-Negative (row 1) to the Empty (row 2) setting. Indeed, in the latter setting the public does not experience any radiation until the onset of repopulation, which is delayed by several years in many cases, therefore cutting out the high initial doses that would have

[9] Recall that for the sake of convenience the cost function V was scaled based on the health cost $F_r R_T p_0$ corresponding to no relocation, no remediation but with complete food ban (Section 6.2).

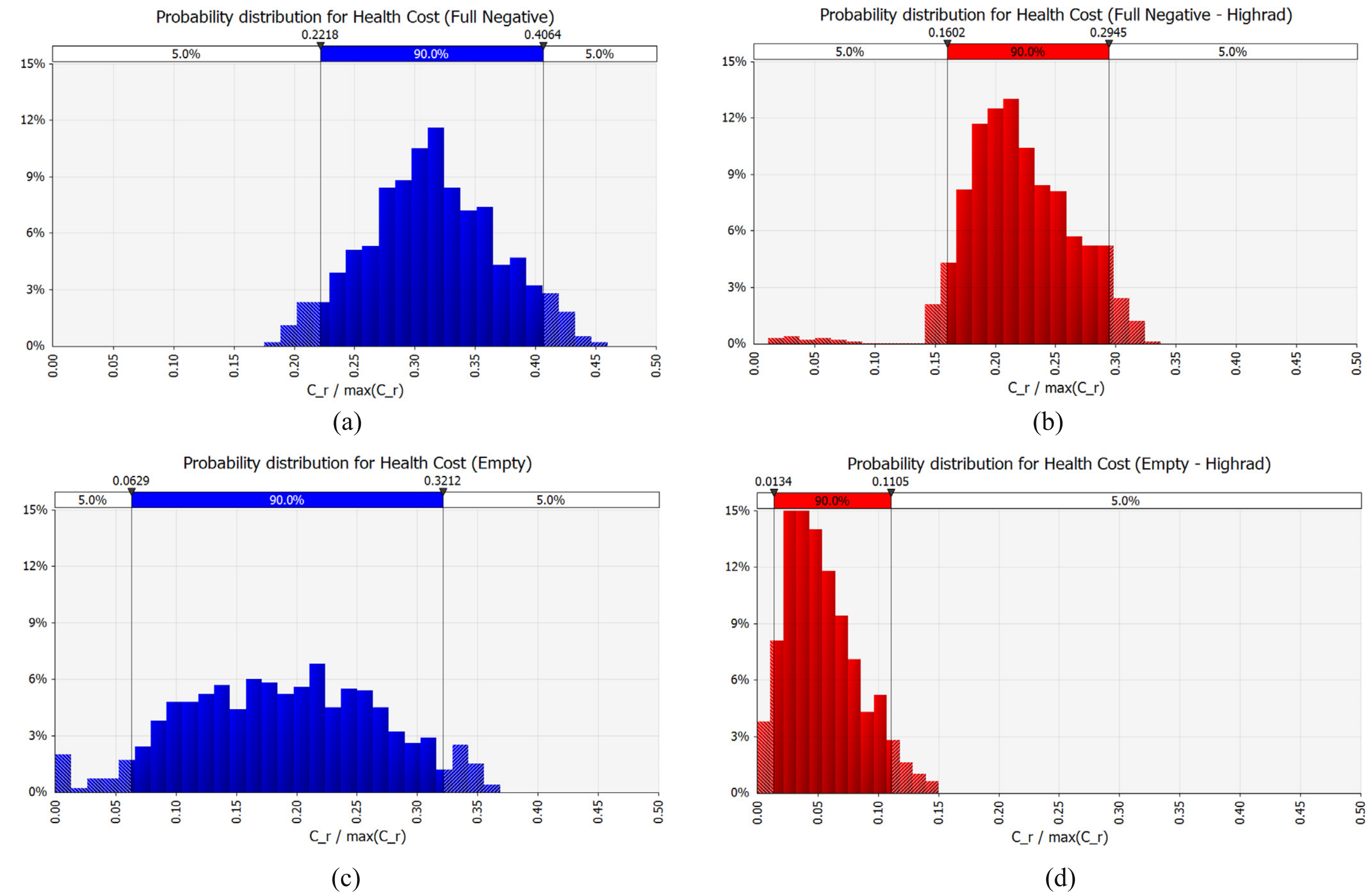

Fig. 7. Probability density functions of the aggregate discounted Health Costs (NPVs) for Medium radiation levels (left column) and High radiation levels (right column) generated from 1000 Monte-Carlo runs with subjective input probability distributions. The plots are provided for two contrasting problem settings: Full-Negative (top row) and Empty (bottom row). The costs are defined in (21) and are further scaled relative to the maximum possible health cost (22) incurred when no protection and recovery measures are implemented. The units on the *x* axis represent the scaled costs (relative to the maximum health cost), while the units on the *y* axis represent the frequencies of occurrence.

been received if the population had not been displaced. The total costs, however, are the highest in the Empty setting due to the loss of sizeable quantities of both agricultural and non-agricultural output for the extended periods before repopulation is triggered and/or while it is being carried out. One also has to bear in mind that the very setting with the pre-relocated initial state often implies economically sub-optimal decisions and sunk costs during the initial relocation, which are not part of the main optimisation problem in the Empty setting. It is, therefore, fair to say that there is a payment for reducing the health costs by pre-relocating the population in the form of higher total costs.

Comparing the columns in Fig. 7, it is clear that significantly higher radiation levels (column 2) lead to the optimal strategies with a very pronounced decrease in the health cost relative to the maximum possible health cost (NPV) which would have been incurred if no measures were implemented, marked by the shift of the probability distributions to the left relative to the corresponding medium radiation settings (column 1). This effect is particularly strong in the Empty setting where the ratio $C_r/\max C_r$ does not exceed 0.15. This is because he high relocation costs are excluded from the optimisation in the Empty setting, and therefore minimising the health costs has more weight overall. We note that the absolute value $C_r \cdot F_r R_T p_0$ of the health costs in the high radiation setting is still larger than that for the medium radiation setting, but this increase is smaller compared to the increase in the radiation level R_T itself. The reason behind this is that higher radiation levels trigger more wide-ranging protective and recovery measures, which is manifested by stronger reductions of the key ratio $C_r/\max C_r$ seen in column 2 of Fig. 7.

8.7. Applicability to other types of disasters

The methodology developed in this study could be adapted to a wider disaster management context. For instance, in the aftermath of Hurricane Katrina, the initial emergency response and restoration lasting days and weeks was followed by the full reconstruction of the area which took place over a longer time scale of months and years, with changes in the New Orleans' population over this longer period playing an important role (Fussell, 2015). Obviously, over these longer time scales the economic factors become more and more important when it comes to making decisions on whether to repopulate the affected area or not, suggesting that having spatial and temporal flexibilities in applying various recovery measures, similar to those introduced in the present study, could improve the overall cost-effectiveness.

However, a nuclear disaster involves natural decay of the contaminant and health effects that are unique to radiation, which restricts transferability of the "lessons learnt" to other types of disasters. In addition, our model has a number of general limitations (Section 9) that are likely going to be relevant in the settings such as Hurricane Katrina: lack of inter-dependencies between different regions in the affected area, no explicit distinction between different vulnerability groups, no sectoral detail in the economy and omission of macroeconomic feedback loops. These limitations call for the use of full macroeconomic models enhanced with temporal optimisation algorithms like the one applied in our work.

9. Critical review of the findings

The model presented in this paper is based on a number of simplifying assumptions. These include: (i) exclusion of the initial radioactive deposition period with high levels of uncertainty from the optimisation problem, (ii) uniform distribution of radiation, people and economic activity across the region under consideration, (iii) exclusion of the natural processes such as mixing by air and washing by precipitation, (iv) idealised models describing planned relocation, repopulation, remediation and food production processes, (v) no voluntary decisions to be made by the population on whether to take any of the actions or not, (vi) LNT hypothesis for the effect of radiation on health, (vii) no inter-dependencies between different regions in the exclusion zone (for example, no commuters and no restrictions on the available emergency response resources), (viii) no explicit distinction between different vulnerability groups including age, (ix) no sectoral detail in the economy, (x) no long-term stochastic effects associated with economic uncertainty, (xi) no macroeconomic feedback loops of the different recovery measures considered, and (xii) omission of the multiple non-economic factors relevant for the long-term decision making. We argue that these assumptions are justifiable for the purposes of the present study, but any practical implementation of our model to aid decision-making in a specific context would require further methodological advances aimed at making its multiple components more realistic. We also advocate for using a more generic methodology such as MCDA to extend the analysis to multiple non-economic factors, in addition to the purely economic valuation considered in this paper.

The calibration of the model parameters using historic data from Chernobyl and Fukushima has its own limitations due to the obvious difficulties associated with translating the real data into the simplified model, the gaps in the data itself, as well as the issue of applicability of certain historic results to present-day conditions. Therefore, the chosen ranges and probability distributions for the λ parameters and for the characteristic rates $\beta_{\pm}$, $\varkappa_0$, α_0 for which the Monte-Carlo simulations are performed can only be viewed as illustrative and subjective. Any potential application of our model for nuclear risk planning would require a detailed survey in order to obtain more precise values of all the model parameters that are specific to the given location.

However, the Monte-Carlo-based methodology combined with the similarity criteria for the costs introduced in this paper is useful for exploring a wide range of possible outcomes, including the distinct qualitatively different strategies that might be optimal depending on the specific context in which the model is being applied. The main results of this study are, therefore, in identifying the possible set of distinct qualitatively different optimal strategies for the three main problem settings (Full, Full-Negative and Empty), and obtaining quantitative estimates of the relative likelihood of occurrence for these distinct strategies under two contrasting radiation levels (medium and high). In particular, the findings that in the Full and Full-Negative settings (no pre-relocation) the relocation option should be used sparingly, and that in the Empty setting (with pre-relocation) repopulation should be delayed in 75% of the cases (medium radiation) until enough remediation and natural decay has taken place, could have the most significant implications for the policy makers.

10. Conclusions

In this paper we developed a decision-making model that describes cost-minimal medium-term and long-term strategies for relocation, remediation and food banning for a single economic location affected by radioactive release from the nearby nuclear power plant (NPP). The initial period of the release and deposition was excluded from the optimisation since it is characterised by a high degree of uncertainty, which is likely to lead to precautionary emergency measures being carried out regardless of the likely dangers to the public and the costs involved. Instead, it was assumed that the decisions on whether to implement preventative and recovery measures are going to be made on the timescales of weeks, months, years and decades after the accident. It is possible that on these longer timescales the governments may prioritise the economic factors by seeking to minimise the total cost associated with carrying out the various measures while also accounting for the resulting benefits to public health.

All the costs describing the individual preventative and recovery actions were scaled based on the health cost associated with radiation doses that would have been incurred in the case when none of the actions are taken. As a result, four main dimensionless economic parameters λ_{Δ}, λ_{β}, $\lambda_{\varkappa}$ and λ_{α} that appear to affect the structure of the optimal strategy were identified. In addition, three dynamic controls were introduced: relocation/repopulation target, remediation rate and food production rate, allowing to find the joint optimal solution according to Bellman's principle of optimality. The optimisation was performed on the timescale of several half-lives of Cs-134 (medium- to long-term horizon).

We carried out a series of Monte-Carlo simulations for the resulting Bellman-type optimisation problem with probability ranges for the four λ parameters and the four characteristic rates for relocation, repopulation, remediation and food production, revealing a small number of distinct optimal regimes that can be grouped together according to their qualitative similarities such as delays in implementing specific measures. Where possible, the probability ranges were chosen based on historic data from Chernobyl and Fukushima, together with the two hypothetical ranges for the initial radiation levels: medium (baseline, 10–20 millisievert/year) and high (50–100 millisievert/year). Computations were performed in three contrasting settings with no pre-relocation (Full), with no pre-relocation but with an economic incentive to move (Full-Negative), and with pre-relocation regardless of the costs involved (Empty). In all these settings, there is a noticeable reduction in the aggregated health costs computed for the entire optimisation period relative to the maximum possible health cost (NPV) which would have been incurred if no measures were implemented, with the bigger reductions taking place in the high radiation settings. Higher radiation levels also result in longer periods of remediation and agricultural production banning, and lead to new types of optimal strategies such as partial or complete relocation followed by repopulation after several years.

Health costs associated with radiation exposure are commonly estimated based on either the human capital (HC) or willingness to pay (WTP) approaches, and several specialised indexes such as value of statistical life (VSL) and value of life year (VOLY) are often used by regulators. For all these indexes, the underlying relation between the dose and the harm caused is the linear-no-threshold (LNT) hypothesis. We believe that at the current state of knowledge the choice between either of the approaches for putting economic values on health effects of radiation, as well as finding reliable alternatives to the LNT hypothesis, is up to the regulators and policy makers. In the language of our model, varying the health cost estimate would change the values of the key dimensionless economic groups (λ) proportionally in exactly the same manner as when varying the initial radiation levels (r_0), providing all the other costs remain the same. As a result, a switch between different optimal regimes might occur, which could lead to significant economic and even political consequences. There is no compelling evidence in favour of any particular approach, and therefore the

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decision on how best to value economic consequences of receiving a dose still hinges upon the regulators' risk aversion.

Given the pressing need to de-carbonise the world's economy to avoid dangerous climate change, and the significant role that nuclear power could play in this process, we cannot afford repeating the same mistakes as in the aftermath of the Chernobyl and Fukushima disasters. It remains to be seen whether the lessons will be learnt when it comes to planning post-accident response and recovery measures both at the existing and future NPPs. Even though large-scale nuclear accidents are extremely unlikely, safer and smarter emergency response strategies that allow higher levels of flexibility have to be put in place if nuclear energy is to become a major driver of global transition from fossil fuels.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.ejor.2017.01.054

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