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The New Science of Safety

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Safety lies at the interface between technology and economics

- You need **engineering** to design the shutdown system to protect the oil refinery or the nuclear reactor, for example.
- You also need **economics** to decide how much you should spend on the shutdown system.
- Today I am going to concentrate more on **economics** than engineering, adding a little **psychology** for good measure.

Multi-buy promotions in supermarkets


Zoolander 2
What's the verdict from Planet Fashion?
Book Offer
The Buried Giant by Kazuo Ishiguro
Daisy Lowe
'I'm not ready to settle down yet'
The Daily Telegraph
Multi-buy deals may be banned
Police to review handling of rape complaints, but still no apology
'Arrogant' BBC must reveal how much it pays stars, warn MPs

The Daily Telegraph

Thursday,
11 February 2016

Quantity discounts – BOGOF (buy one get one free), 3 for the price of 2

- How do you explain:
  - why **18 'value' eggs** in Sainsbury's cost only about **twice** as much as 6 eggs, **not** three times?
  - why a **16 GB** USB stick costs £4 on Amazon, **hardly any more** than the price of an **8 GB** USB stick?
- A further question:
  - should smart retailers increase their pack sizes as the **square of the Golden Ratio** (2.62), but increase their prices by only the **Golden Ratio** (1.62)?

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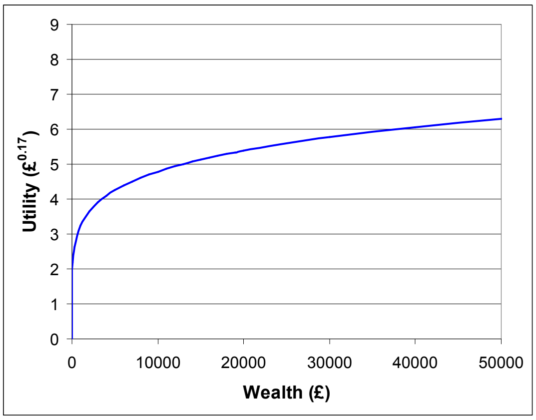
Utility: the 3rd Ferrari matters less



Utility function with

risk-aversion = 0.83

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The history of "utility"

- **1738:** utility was invented by **Gabriel Cramer** and **Daniel Bernoulli** in their similar solutions to the **St Petersburg Paradox**.
- Uncle **Nicolaus Bernoulli** had devised this **puzzle** to show how it was **not always wise** for gamblers to be guided by how much they expected to gain.
- The "**expected value**" of the bet, how much **on average** people would win, was **huge**, in fact infinite, but no sane person would risk more than a **few ducats**.

- Amongst other things, nephew **Daniel's 1738** paper explains how the insurance industry can operate and make money.
- **1954** translation Latin to English by Louise Sommer, with technical support from **Karl Menger**.
- **1871**: utility was invented by **Jevons** (UK), **Carl Menger** (Austria) and **Walras** (France) to explain why diamonds are expensive but water is cheap, even though it is essential – the "**paradox of value**".
- **1944: von Neumann** put **utility theory** on an axiomatic basis

You can explain multi-buy promotions in terms of utility

- Extending **utility theory** to cover packs of different sizes shows that **BOGOF** and **3 for the price of 2** offers are providing **what the shoppers want,** and retailers are getting as close as they can to **satisfying their customers**.
- What's the link to safety?
- **Utility** and its parameter, **risk-aversion**, have a fundamental role to play in the science of safety.

Risk-aversion

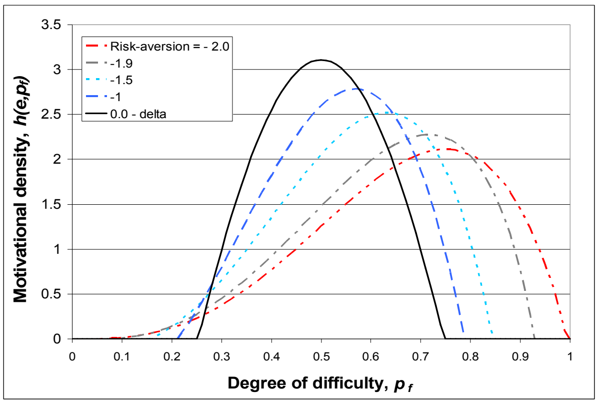
- **1964**: **John Pratt** showed that the shape of **utility curves** could be defined in terms of **risk-aversion**.
- **Risk-aversion** is a dimensionless parameter that is what it says it is. It is a **real psychological parameter** that can be defined mathematically.
- Its **value will change** depending on the decision**.**
- But while a person may vary his risk-aversion between decisions, he **will keep it constant** while comparing options.
- This reduces the number of possible utility functions to **just one** family, the "**power**" utility functions.

General applicability of **risk-aversion**: Children playing "hoop the peg"

1957: John W. Atkinson's Hoop the Peg psychology experiment with 5 year-olds

- The children had to decide how close to the peg to stand
- They had been **pre-classified** as either **highly achievement-motivated** or else with a **low achievement motivation**.
- **High achievement motivated,** confident children were prepared to take a **reasonable risk** of failing because of the extra kudos of executing a harder task.
- Hence they took up a throwing position that was a challenging but **realistic distance** from the peg.

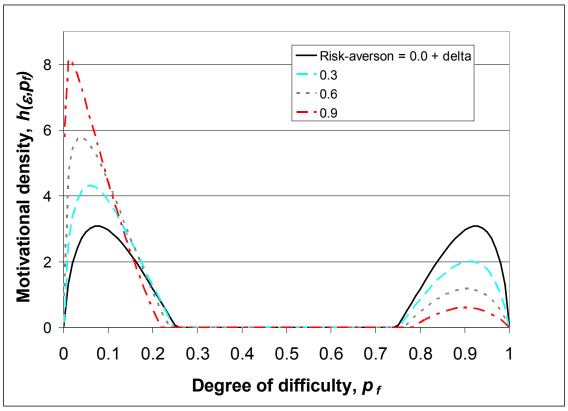
Confident children have **negative** risk-aversions for this task: they are **risk-confident**



Diffident children

- Diffident children, those with **low achievement motivation**
  - i. either stood almost on top of the peg, or
  - **ii. so far back that failure was almost certain.**
- How can (ii) be explained?
- Answer: by the **risk-aversion** the less confident children apply when deciding where to stand.

Diffident children have a positive risk-aversion: they are **properly risk-averse**



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Important conclusion: **very risk averse** people can do some **odd and inconsistent things**

- Ex-banker turned best-selling author of business books, **Robert Kelsey**:
- "**Fear of failure** explains all those **rogue trader scandals** ...
- "It wasn't that I was unable to **take the risks** that are part and parcel of an **investment banker's** role ...
- "I could take **ludicrous risks** in some of the most **volatile trading environments** on the planet ...
- "It was my **judgement of risk** that was **undermined** by my fears [as was] my ability to sort good fear from **bad fear** [which] can lead to **either paralysis ... or nonsensical leaps.**"

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How is the **Golden Ratio** (1.62) involved in shopping?

- **Super-cautious** shoppers have a risk-aversion above 1 and cannot be tempted by quantity promotions.
- But quantity promotions can **appeal** to shoppers who are merely "**cautious**", with a risk-aversion **between 0 and 1**.
- On average, the **cautious shopper** will have a **risk-aversion of 0.5**.
- The **average cautious shopper** will respond best to a **pack-size ratio of 2.62** and be prepared to **pay 1.62 times** the price of the small pack to get the bigger pack.
- (For interest, **Gabriel Cramer** set risk-aversion to **0.5**, **Daniel Bernoulli** set it to **1.0**).

Putting a value on **environmental harm**: the objective J_{20} value (J = judgement)

- **Utility functions** can be applied to find out how much an organisation that could cause environmental harm ought to be spending to reduce or eliminate the possibility.
- The **J_{20}-value**, which is fully objective, is the ratio of the amount an organisation is considering spending to reduce environmental harm to the maximum it ought to be spending.

The reluctance to invest

- The **reluctance to invest.** We assume the decision-maker in an organisation is initially sceptical and does not want to spend money on environmental protection.
- The **reluctance to invest** for an organisation is then the ratio of the expected **before and after** utility difference, to the **starting utility** (relative to the utility of £1).
- A **100% reluctance to invest** means the protection system is so expensive that it will reduce the **expected utility** of the organisation's assets to **zero**.

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You can be too risk-averse (c.f. Hoop the Peg)

- The magnitude of the **reluctance to invest** will fall as risk-aversion increases to high values.
- But so will the **motivation** to decide on any course of action.
- **Next slide** will show:
  - £10 bn organisation
  - accident costing £5 bn, with a probability of occurrence of 1 in a thousand.
  - protection system cost, £1 M, reduces the accident probability to 1 in a million.

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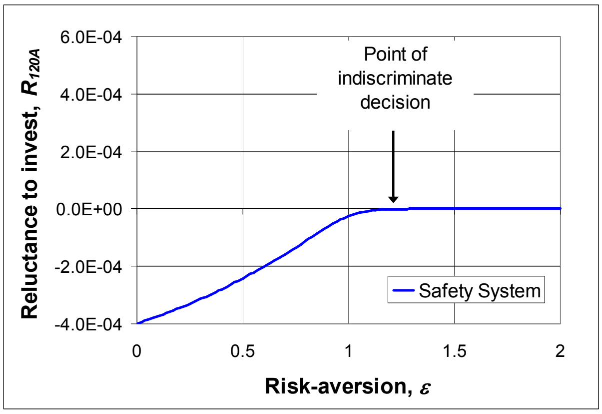
The effect of increasing risk-aversion when the investment is justified at a risk-aversion of zero.

Expected monetary saving is £5M, much more than the £1M cost.

So if when risk-aversion is zero: **go for it!**

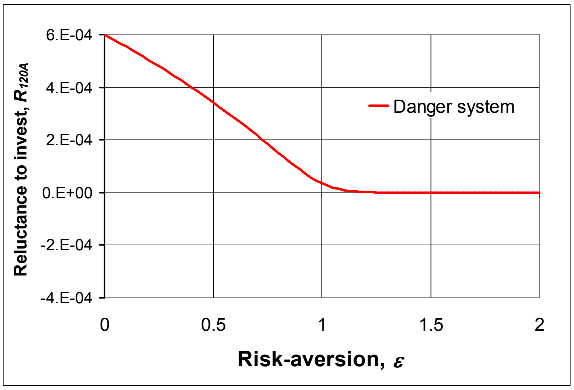


- As risk-aversion **increases**, so the desire to invest **decreases** in a protection that would be seen as good value at a neutral risk-aversion value (zero).
- The **desire to invest** will remain positive, but the **incentive** will **decrease** as risk-aversion **increases.**
- At some **high value of risk-aversion**, it will be **impossible to discriminate** between the advantages of the safety system and those of doing nothing. This is the **point of indiscriminate decision**.
- Effectively the decision maker has become **so risk-averse** that he does not want to take **any** decision.

The effect of increasing risk-aversion when the investment is **not** justified at zero risk-aversion.

Here the **danger system** is assumed to **reverse** the effect of the safety system**.**

The **more risk-averse** the person becomes, the **less reluctant** he will be to install a **danger system**.



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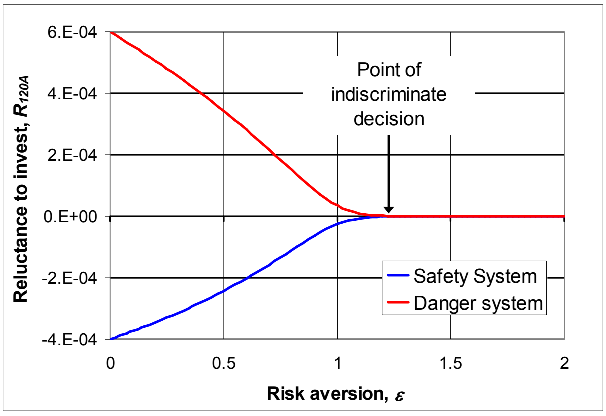
Safety system and danger system

Kelsey's financial panic: **"either paralysis ... or nonsensical leaps".**
The utility model with varying risk-aversion has simulated **panic**, when the individual's risk-aversion has reached the **point of indiscriminate decision.**



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Human safety and the J-value

- How much should we spend on human safety? The J-value (**J for judgement**) gives an **objective** answer.
- The J-value uses a **utility function** to weigh the **gain in life expectancy** brought about by a safety scheme against its cost, with **risk-aversion** mediating the balance.
- The J-value provides a rational framework for assessing how much we should spend on safety and **when we should stop spending.**

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To judge how much to spend on safety, we need to value **human life**. But how?

Q. What benefit is conferred when a safety measure **"saves"** a person's life?

A. The benefit is the **restoration of that person's life to come**.

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- **Problem**: we cannot predict how long anyone is going to live.
- **BUT** actuarial tables give us the **expected life to come** for a person of a **given age** and a **given gender**.
- We can value **life expectancy** – the average life to come for someone of a given age and gender.

Historic Interim Life Tables, United Kingdom

Period expectation of life
Based on data for the years 2005-2007

Age	Males				
x	m_x	q_x	l_x	d_x	e_x
0	0.005504	0.005489	100000.0	548.9	77.16
1	0.000402	0.000402	99451.1	40.0	76.59
2	0.000259	0.000259	99411.1	25.7	75.62
3	0.000180	0.000180	99385.4	17.9	74.64
4	0.000131	0.000131	99367.5	13.0	73.65
5	0.000120	0.000120	99354.5	11.9	72.66
6	0.000121	0.000121	99342.6	12.1	71.67
7	0.000093	0.000093	99330.5	9.3	70.68
8	0.000115	0.000115	99321.2	11.4	69.69
9	0.000118	0.000118	99309.8	11.7	68.69
10	0.000104	0.000104	99298.1	10.3	67.70
11	0.000135	0.000135	99287.8	13.4	66.71
12	0.000143	0.000143	99274.4	14.2	65.72
13	0.000179	0.000179	99260.2	17.8	64.73
14	0.000196	0.000196	99242.4	19.5	63.74
15	0.000254	0.000254	99222.9	25.2	62.75

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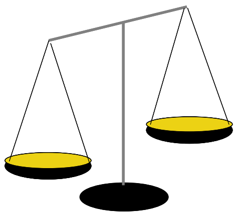
J-value: a fully objective method for valuing human life

- The J-value balances:

gain in life expectancy vs. **cost**

of the safety measure.



You are spending too much if J is bigger than 1.0

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The J-value

- The Judgement- or J-value is simply the ratio of the **amount actually spent** on protection to the **maximum that is reasonable**.
- Hence ***J* = 1.0** is the **limiting condition** where the actual expenditure on protection is justified by the gain in life expectancy.

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Case study 1: J-values for the discharge reduction plants at British Nuclear Fuels Ltd at Sellafield

Technetium-99 Removal Plant Critical group	130
Krypton-85 Removal Plant Critical group	39,700 – 178,000

Tc-99 plant implemented,

Kr-85 plant not implemented

Case study 2: J-values for NICE decisions on breast cancer

Vinorelbine for metastatic breast cancer	0.014
Paclitaxel for advanced breast cancer	0.046
Docetaxel for advanced breast cancer	0.045

All eventually recommended by NICE, but, given the **tiny J-values**, was the delay necessary?

The new science of safety ought to have **objectivity** at its heart

- The **J-value** and the **J_{20}-value** can be combined into a single, objective measure, the **J_T-value** (Total Judgement Value).
- But what has gone before?
- What is the **benchmark** for **health spending in the NHS** and **safety in UK industry** being used now**?**

The "value of a prevented fatality" (VPF) approach to valuing human life

- The **UK Health and Safety Executive** relies on studies carried out by the Department for Transport in **1997** and published in **1999**.
- These make the assumption that there is a **single-valued "value of a prevented fatality" (VPF)**, the value of which may be found from the stated preferences of a relatively small number, **167**, of people in a survey, updated for increases in GDP over the past 17 years.
- The same VPF is assumed to apply to an **80-year old** as to a **5 year old** (cf. recent debate on **meningitis B vaccination**)**.**

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There are real problems with the UK VPF

- The UK VPF is based on the "2-injury chained method".
- Common sense suggests that two measurements of the same quantity, the "value of a prevented injury" *for the same injury* should be the same.
- Using the 2-injury chained method, they turn out to be **very different** and **barely correlated**.

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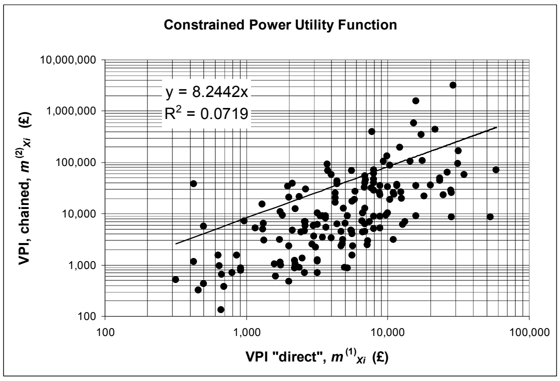
The 2-injury chained method: measurements for the same injury



For the method to be valid, the two measurements of the same thing should be giving the same value. Hence both ***m*** and the **R^2** value should be **1.0**. In fact ***m* =8.24, R^2 = 0.07**

See papers and correspondence in *Process Safety & Environmental Protection*.

2-injury chained method: typical differences in the personal VPF calculated for the same respondent

Respondent	VPF from 2-part chaining (£)	VPF from 3-part chaining (£)
30	618,569	7,713,783
31	104,726	892,040
32	707,034	9,487,290
33	131,948	29,093
34	79,387	68,020

The prior, rejected VPF study

- The 2-injury chained method was invented by the VPF team after the **team and its HSE and Government sponsors** had **rejected** the results from the team's first study (1995 – 1996) in their entirety.
- They labelled their first, rejected study, "**Caveat investigator**" – "let the investigator beware".

- The Caveat Investigator team asked the 81 original respondents to state their maximum acceptable prices for systems that would cut their "annual risk of death" in a road accident
  (i) by 1 in 100,000
  (ii) by 3 in 100,000
- Concerned at the relative valuations (**significantly less than 3 to 1**), the Caveat Investigator team then asked 52 new respondents to state their maximum acceptable prices for systems that would cut their fatal accident frequencies
  (iii) by 0.5 in 100,000
  (iv) by 1.5 in 100,000

- The 52 new respondents were even **"prompted"**
  - "In the past, we've found that some people say that preventing 15 deaths on the roads is **worth three times as much to them** as preventing 5 deaths on the roads: but other people don't give this answer. Can you say a bit about why you gave the answers you did?"
- But even so the team found that the valuations of both frequency reductions remained stubbornly **below** 3 to 1.
- Thus the Caveat Investigator team decided to reject all their results, which they considered to be based on "**aberrant response patterns**", and place their faith in their new **2-injury chained method**, just shown to be invalid.

But were the responses really **"aberrant"**?

- The reductions in fatal accident frequency were described in a **bare and factual way** – so as **commodities** in two packs, the 2nd pack being **three** times bigger than the starter pack.
- And we now know that the consumer will tend to think that **Pack 2** of a commodity that is **three times** the size of the starter pack, **Pack 1**, should cost **twice** as much **NOT** three times.

Re-analysing the Caveat Investigator results

- About **45%** of the respondents were unable to see the advantage of deploying one or more of the "**safety packs**" or were unable to discriminate between the two safety packs.
- Stripping out the responses where **discrimination** is breaking down reduces the original group by 37 and the new group by 22.
- The **average price ratio**, Safety Pack 2 to Safety Pack 1, for the remaining 44 from original group is then **1.98**, (90% confidence interval: **1.77 – 2.18**)
- The average price ratio for the remaining 30 from the new group is then **1.93**, (90% confidence interval: **1.73 – 2.14**)
- **Very close to the multi-buy figure: 3 for the price of 2.**

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Effect on the value of the UK VPF

- So the results are not "aberrant" but **economically consistent**.
- They cannot be dismissed by **believers in subjective opinion surveys**.
- The VPF comes out between £7.4M and £19.3M (2014 £s)
- The upper value, £19.3M, coming from the Safety Pack 1 price is **12 times more** than the 2014 VPF (£1.6M).

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Which value should the UK VPF have?

- The highest value is more general since it is the **asymptotic** value, say when Pack 2 is 100 times larger than Pack 1, as well as the value coming from the valuation of Pack 1.
- Unless Safety Pack 2 is much bigger and better than Safety Pack 1, it is **impossible** to get a **unique figure for VPF** when two safety packs are offered.
- **If** it was decided to base the VPF on the valuation of a Safety Pack 2 that gave **twice** the performance of Safety Pack 1, the **VPF would be known in advance** to be **biased low** – just **half** the asymptotic value
- There are echoes of quantum theory when non-equal, quantized pack sizes are introduced into opinion surveys, with the method of measurement changing the value!

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Believability of opinion surveys

- Opinion surveys are prone to **bias problems** (remember the opinion polls leading up to the **2015 General Election**?)
- They are generally used only when **there is no alternative** – no **market** for the good and no **revealed preference** method.
- But they will be particularly unrepresentative if the **bias is built into the method** of analysing the result.
- Such an analysis method, the "**Valuation Index**", was used to justify reducing the UK's expenditure against **multiple-fatality railway accidents** by a **factor of 3 in 2003**.
- The Valuation Index **violates** the criterion of **structural view independence** and will always be **biased low**.

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Validation of the J-value against pan-national data: the "Bristol curve"

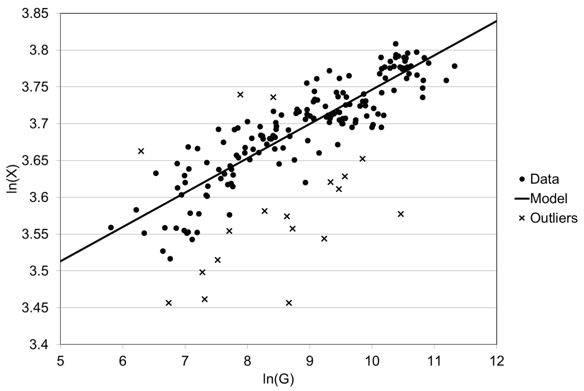
Log (ave. life expectancy) vs. log (GDP per head)

for 180 nations in 2009

R2 = 0.6 for 180 nations

18 outliers (marked with crosses) were excluded from the final fit.

R^2 = 0.8 for 162 nations



Outliers

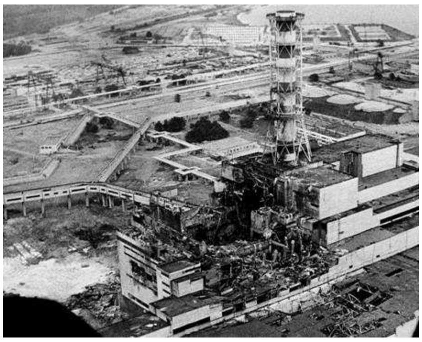
- Afghanistan
- Angola
- Botswana
- Cameroon
- Chad
- Congo
- Cote d'Ivoire
- Equatorial Guinea
- Eritrea
- Gabon
- Guinea-Bissau
- Lesotho
- Malawi
- Namibia
- Nicaragua
- South Africa
- Swaziland
- Zambia

Assumptions made in the J-value model

- The **annual budget** available to prolong citizens' life expectancy is a **fixed fraction of GDP per head**
- The budget is **spent in full** each year at **J = 1**
- **Risk-aversion** stays **constant** as wealth and life expectancy increase in tandem and is thus the same for all nations in the world
- The **net discount rate** applied to life expectancy stays **constant** as wealth and life expectancy increase in tandem.

The **J-value** emerges as a **formalisation** of an approach being used **intuitively** to assess most health and safety spending decisions **all over the world**.

Life expectancy after Chernobyl 1986, the **world's worst nuclear accident**



- Life expectancy in Ukraine and Belarus in 1986:
  - 67 years at birth.
  - **37** years is the population-average life expectancy
- 116,000 relocated 1986. If left in place:
  - **85,500** would have lost **8.7 months** or less (**3 months** on average)
  - worst affected **6,800** would have lost **3 years** or more; their average dose would induce a loss of **5.6 yr**

Initial comparison

- UK:
  - **3¼ yr** lost by moving from Harrow, North London to Manchester (**6½** yr at birth)
  - **8.6 yr** difference in life expectancy between baby boys born in Kensington & Chelsea and Blackpool.
  - **4½** months lost by Londoners to air pollution

J-value comparison for the 1986 relocation of **116,000** from Ukraine, Belarus + Russia

- The J-value would suggest relocating
  - **31,000** - those who would lose more than 8.7 months if left in place.
  - **72,500** based on the 95th percentile heuristic. It is assumed here that the 31,000 **cannot be identified**, and **precautions that exceed what is needed by 19 out of 20 people** in towns and villages **are applied to all**.

1990 relocation of **220,000** from Ukraine, Belarus + Russia

- J-value: **relocate no-one**.
- 1990 – 1992 EU study (at USSR's request): **relocate no-one**. (*Conclusions not taken up by USSR and did not come to general public notice.*)
- J-value conclusion on **335,000** total numbers moved from their homes in the 1986 and 1990 mass relocations: only between **9%** and **22%** justifiable.

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2011 relocation of **160,000** from around Fukushima Daiichi

"The future existence of Japan as a whole was at stake. Something on that scale, an evacuation of 50 million, it would have been like a losing a huge war."

Former PM Naoto Kan, *The Daily Telegraph*, 5 March 2016

- J-value: **no-one** should have been relocated.

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Concluding remarks

- I have attempted to give a **guided tour** of things that have struck me as **interesting** in my team's continuing development of the **new science of safety**.
- We have needed to explore along the way why the 3rd Ferrari matters less, BOGOF promotions in supermarkets, children playing hoop the peg, rogue traders, and big nuclear accidents, as well as concepts such as utility, risk-aversion, reluctance to invest, the point of indiscriminate decision and the J-value.
- We have also seen that there are **major problems** with the UK's treatment of and spending on safety.
- I hope that I have been able to convince you that the **new science of safety** is not only important but **needed urgently** by the world.
- I hope, too, that I managed to convince you that the subject is also **interesting**!

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