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The J-value Framework for determining best use of resources to protect Humans and the environment

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Abstract

The philosophy of the ALARP principle (as low as reasonably practicable) will be discussed, which has been adopted as the basis for UK law on health and safety. It will be shown how ALARP leads naturally to a need for cost-benefit analysis but how there are particular difficulties in the valuation of human life. The problems with the VPF concept ("value of a prevented fatality") will be explained, and the advance brought about by the Life Quality Index highlighted. The J-value (J for Judgement) will be introduced as a single metric for deciding whether the money being spent to reduce a risk to human life is rational or not. Expenditure up to a J-value of unity is reasonable. Then a second Judgement Value, the J_{20}-value, will be described, which may be combined with the J-value to give the Total Judgement value or J_T-value. Spending up to a J_T-value of unity is reasonable to safeguard humans and the environment.

Keywords: J-value; JT-value; risk; safety; environmental protection.

1. Introduction

One of the most profound problems facing every human being as he or she steers a course through life is how to deal with random events. For while one's situation may alter only gradually and by small amounts over long periods, every so often an abrupt change will occur and break up the continuity of one's existence.

Some of the most significant changes are those that affect the health and welfare of an individual or damage the environment in which people live. Such events may be short term and repairable, but sometimes the ill-health or injury may persist, at worst resulting in the early death of the individual. Likewise, environmental contamination may cause people only short term disruption, but it is possible that the local environment will be rendered unsuitable for occupation for a very prolonged period.

The first challenge facing all of us is to recognise the reality that such discontinuities or events will occur. The second is to find a reasonable way of planning to prevent them or to diminish their consequences or at least to reduce their chances of happening to a lower level. Dealing with the event after it has happened constitutes a third task, mitigation. It is desirable to assemble a mitigation strategy for such eventualities in advance, while recognising that further, post-event data may affect the way the plans are implemented.

The mathematics of statistics and probability allow us to cope in a systematic way with the first challenge by providing a scientific framework in which to place events about which we have some information but which remain random and unpredictable nevertheless. The event's discontinuous and discoucerting nature cannot be got around, but its chance of happening may be modelled using an evidence-based probability density that is continuous or at least regular and predictable. It needs to be recognised, of course, that there will always be uncertainties and gaps in our knowledge, so that the statistical results should not be regarded as precise recommendations but rather as a guide to judgement.

Protection systems are in widespread use in industry to protect humans and the environment against the malfunction of machinery or process plant. In some cases it is possible to reduce the consequences of an accident; for example it may be possible to reduce the inventory of hazardous materials on an industrial site [1]. But whether or not the consequences of a potential accident can be reduced, it is normal practice in analysing the need for a protection system to estimate the base-line frequency of the damaging incident. This frequency is usually regarded as constant over a period of operation, when an equivalent probability may be found by applying Poisson's formula, as interpreted by Bortkiewicz [2], [3]. The expected harm may then be assessed by multiplying this figure by the consequence of the failure in protection.

A practical difficulty, and one likely to be of particular concern to politicians, is that it is always possible for an adverse event to occur, even if it has a low probability. This could, of course, be interpreted to mean that little or no credit should be given to many protection systems on industrial plant, where the incident is not normally rendered impossible, rather the probability of occurrence is reduced. Thus the incident may still occur, albeit at a much lower frequency. Seeking absolute safety by uprating the protection system would then lead to an infinite regression, with more action sought and more resources deployed to improve protection, and so on. In fact, complete protection against a threat is rarely attainable and attempts to achieve it would often lead to indefinite spending without ultimate success. What is needed is a way of determining when enough money has been spent to mitigate the threat to an acceptable level.

There are many situations in which harm can occur from such straightforward events as tripping or falling through to more serious incidents involving one or more persons to major events affecting many people. The consequences of many major accidents are wide ranging and affect both people and the environment. The range of such effects can be seen by considering events such Seveso, Bhopal, Chernobyl, Piper Alpha, BP Macondo and Fukushima. A very important issue for safety assessment is how to protect people and the environment against these types of events and, in particular, how to decide what it is reasonable to spend to prevent them and to mitigate them, should they occur. The fundamental question in safety decision-making is "How safe is safe enough?"

Here we consider how to determine what outlay is appropriate and propose the wider use in safety decision making a method that attempts to derive a rational approach to the question.

2. Reasonable Practicability

The UK law that sets out how to determine when "safe is safe enough" for most work situations is the Health and Safety At Work Act 1974, which puts duties on employers to safeguard the health, safety and welfare of their workers and to control risks to the health and safety of those not their employ *so far as is reasonably practicable* (SFAIRP). The precedent for this requirement was set in the Court of Appeal by Lord Justice Asquith in the case of *Edwards v. National Coal Board* (1949) [4]. The judge mandated that risks should always be reduced unless the employer could demonstrate that there was "gross disproportion" between the sacrifice (money, time, trouble) of implementation and the benefits, in terms of greater safety or reduced risks, the sacrifice being greater. Note that in determining the sacrifice, both the initial implementation costs and ongoing maintenance costs for the remainder of the plant’s lifetime must be assessed [5].

The requirement of "gross disproportion" creates an imbalance in favour of safety. The concept has been criticized in recent years [6], although it is not unique to the UK. In the USA, despite the landmark judgment of Judge Learned Hand in *United States v Carroll Towing Co.* (1947) [7], in which he deemed strict proportionality to be acceptable for protection schemes, the concept of disproportion appears to be reflected in other verdicts in U.S. courts. For example, the jury in the civil case *Grimshaw v Ford Motor Company* rejected the company's case that the disproportion factor needed to sanction the safety expenditure would be too great at 2.8, and found against the Ford Motor Company [8]. In the UK, inspectors of the Health and

Safety Executive (HSE) may insist on a sacrifice, in regard to a safety measures against a high risk, that is between twice and ten times the benefit in terms of risk averted (these figures have never been tested in a court but were accepted at the inquires held in the 1980s and early 1990s into the PWRs that were built at Sizewell B and contemplated for Hinkley C [5]).

In many cases there is sufficient good practice to determine the necessary safety measures but this is not always the case, particularly for complex facilities. In these cases it is necessary to carry out a direct comparison of the sacrifice with the risk averted [9]. Such a comparison requires a common measure and in general that is money, with the comparison being a form of cost-benefit analysis (CBA). The concept of risk is fundamental to UK health and safety law and methods are needed for assessing the risk in terms of accident frequency and consequent damage. However in this paper we take such methods as read, being covered in many publications elsewhere: our concern here is in considering how to measure the benefits (i.e. change in consequences) in monetary form [10].

The UK HSE expects consideration of the necessary actions after an accident that are needed to protect people, such as relocation, food bans and so on [5]. One of the significant difficulties is putting a value on the direct effects on people, *viz*. injury, ill-health and death. These aspects are rarely thought of in a financial form in general public discourse. Moreover, although courts may offer compensatory amounts to the injured and to the relatives of the dead, this has not been found to provide a good guide to how much such be spent *a priori.* (It is interesting to note, however, that the compensation offered by the courts to those injured through work is being informed increasingly by actuarial estimates of the work expectancy lost [11], [12], [13], an approach that has a number of commonalities with the J-value method that will be discussed later.) Since CBA may be used to determine if new health and safety regulations are reasonable as well in deciding what safety measures should be used in a range of different industries, getting a sound, well-established figure for the values people put on their health and life is important.

3. What is life worth?

Studies done in support of the UK Department for Transport (DfT) [14] attempt to determine people’s preferences through direct questioning. These methods go under the general name of "Willingness to Pay" (WTP), where the intention is to find the maximum sum of money that a person would be prepared to pay for some good or service. The WTP approach can be based on revealed preferences or stated preferences. The stated preference method attempts to derive the "value of preventing a fatality" (VPF) by more or less direct questioning about the consequences of accidents and what would be viewed as the price people would pay to avoid them.

The stated preference method requires surveys of a suitable group of people, which is considered representative of the public at large. This approach is, of course, subjective, and may be distorted by events, social factors or personal preferences unique to the respondent. Even if the group is large and apparently well-chosen, the results may not be truly representative of what society should spend. Comparisons with other countries using similar approaches show that, after correction for the different wealths of the various societies, there is some degree of agreement between the figures (+/- a factor of 2 or 3). But questions remain about the inherent uncertainty in the methods, due to difficulties in collecting and dealing with the data. For example, the DfT VPF uses opinion survey data collected 17 years ago, which were, in any case, subjected to single-sided censoring [15].

This paper describes a different form of objective, revealed preference approach and proposes it should be used more widely. The method derives an amount for the spend that ought to be incurred to prevent health and safety harm to people and the environment, based on economic utility considerations involving the concept of the quality of life, as encapsulated in the Life Quality Index (LQI) [16], [17]. The method is called the J-value (Judgement-value) when safeguarding humans [18], [19], [20], and it has been extended to become the J_T-value

(Total Judgement-value) when both humans and the environment are safeguarded [21], [22], [23], [24].

4. Protecting human lives: the J-value

It is necessary to be exact in our thinking about life and death when we consider how much ought to be spent on systems that protect people against being killed. The time a person is going to die is generally not known, whether tomorrow in a road accident, or from a terminal disease in the next year, or after a prosperous and contented life many years hence. But past evidence suggests that each one of us will die at some point, and everyone knows it in his heart of hearts. More detail is provided by life tables published by, for example, the UK's Office of National Statistics, from which (as well our own general experience) we know that the chances of person alive today living to the age of 120 are very small indeed, while the chance of anyone reaching the age of 150 is so close to zero as to make no difference.

When thinking about such issues, it does not help that the terminology used in assessing protection systems is sometimes confused. A prime example is the "value of a prevented fatality" (VPF) discussed in the previous section. As we have just noted, it is impossible for anyone's death to be prevented: the best that can be achieved is for the threat in question to be averted, so that the person's life expectancy is restored to what it would have been in the absence of that threat. Hence "value of preventing a fatality due to a specified cause" (VPFSC) or "value of a temporarily prevented fatality" (VTPF) would be better. But even this revised terminology is not completely satisfactory, since it diverts people's attention away from the valuable thing that is being lost, namely life.

In fact the English term, "death", is itself somewhat unhelpful, since it can mean both the act of dying, which is a discontinuous event ("His death occurred on the first day of spring"), and the continuous state of being dead as the opposite of life or being alive ("Death lasts for ever"). Since a person on the brink of expiring is alive at one moment but dead the next, we may regard the discontinuity of dying as an irreversible event of zero duration.

"Living in the past" is a phrase sometimes applied to someone who seeks too much pleasure and solace from the memory of previous activities or achievements, a course of action generally regarded as giving insufficient attention to the present and the future. Living actually occurs in the present, with a wary eye on the future to identify both opportunities and dangers. The instinct for self preservation requires this focus on the future, and the same instinct means that people will normally wish to live for longer, so that suicides are rare. In fact, the arrow of time means that what has happened in our past life cannot be influenced by any thing, person or event. For good or ill, we cannot be deprived of our past life and our life to come is all that is at stake. It follows that it is our life to come that we need to value when considering a safety system.

So it is life to come that a person loses when he dies, but what is that worth to him? Perhaps noting that death in one meaning is a switching between states, and viewing life as the opposite of death, one might suggest that life should be seen as "the vital spark" [25], [26], possessed equally by all living people. This would imply that each person's total life to come should be valued equally, whether he has only a day to live or whether he is destined to live for many years. This is the approach favoured by those who advocate a single-valued VPF. But in such a case, only two possibilities present themselves, neither conforming to rational thought, although for different reasons.

In the first possibility, it is assumed that the average value of each future day is inversely proportional to the time the individual is destined to live. This makes the average value of a future day for an old person many times more valuable than for a young person. This does not conform to the experience of humans. Moreover, it highly dubious from an ethical point of view, with older people (such as those in charge of the regulatory process) liable to be perceived as employing special pleading for themselves. Furthermore, under this scenario, the value per day of future days will tend towards a Dirac delta function for someone who has just minutes before death, with the last moment having an infinite value. This is surely an absurdity.

The other possibility is to regard the vital spark as having a significance that is not related to its duration. By this argument, the vital spark transcends its duration. The transcendental assertion has the effect of moving the argument into the realms of metaphysics, thus removing the possibility of scientific discussion or rational challenge.

But the vital spark must be a continuing feature of all living people, so that tests for the vital spark or "vital signs" would come out positive all the time that a person is alive, and negative when the person is dead. Coding the results in binary notation, the test reading would emerge as a step function when graphed against the person's length of life, starting and remaining at 1 until it switches to 0 at the point when the person dies. An analogy might be the working of the petrol internal combustion engine, where no spark means a dead engine and continued motoring depends on a spark being generated between the terminals of the spark plug on a continuing basis.

But it is not necessary to refer to the technology of the last 150 years to illustrate the case for the vital spark being continuous. 2000 years ago, for example, the Romans considered each person possessed of his own personal genius, a guiding spirit that attended him from birth to death. The Roman term "genius" would appear to pick up much of the meaning implied in the term, "vital spark", and it is instructive that the Romans considered that the individual's genius shared the same period of existence as the individual. It is suggested that the concept of the vital spark as a marker for the person continuing to live is surely more convincing than a vital spark of undetermined duration, independent of length of life.

In fact, if we want to value human lives in a scientific rather than a metaphysical way, and if we want to avoid the problem of valuing an old person's day more than a young person's, with the attendant difficulties of counter-intuitive notions, dubious ethics and logical absurdity, it is clear from the arguments above that a single "value of a prevented fatality" cannot be universally valid. It is necessary to find a securer platform on which to base our safety arguments.

The arrow of time means that we need to face forward, but, as discussed previously, there is the problem that none of us can know how much life he has left. This makes it difficult to assign a value directly to a person's future life, which may be regarded logically and mathematically as a random variable. Fortunately it is possible to make a good estimate of the *average* life to come for someone of a given age. It is this variable, namely life expectancy, that can be valued. Such is the background to the increasing use of life expectancy, or, equivalently, the expected number of life years to come, in assessing the worth of a safety system [27], [28], [29], [16], [17], [6].

Our enjoyment of life does not, however, depend simply on our being in the living state. Since we would like to spend our time doing the things we choose to do, we put a premium on our free time, as opposed to work time. We need also to consider other factors, of which income is arguably the most important, since its level will inevitably constrain the extent to which we can satisfy our desires during our free time. We may deduce that the individual's quality of life, Q_1, may be modelled generally as some function of both income, G, and expected free time from now on, F. A technique may now be employed similar to the dimensional analysis used in characterising the performance of pumps and compressors (e.g. [30]), so that Q_1 is assumed to be related to G and F by

$$Q_1 = \alpha_1 G^{\beta} F^{\gamma} \qquad (1)$$

where α_1, β and γ are positive constants to be determined. The equation has the form of a Cobb-Douglas utility function, a standard function used in welfare economics [31].

Equation (1) is the starting point for the derivation of the Judgement- or J-value, the ratio of what is actually spent to the maximum that ought to be spent on a scheme to safeguard humans. It is shown in [20] how eq. (1) may be developed to give the final form of the life quality index, Q, first derived by Nathwani, Lind and Pandey [16], [17]:

$$Q = G^{1-\varepsilon} X_d \qquad (2)$$

where $G^{1-\varepsilon}$ is the utility of income, dependent on the risk-aversion parameter, ε. Meanwhile X_d is the discounted life expectancy. [*It is future utility of income that is actually being discounted, but this can be shown to be equivalent to discounting life expectancy in this formulation. Discounted life expectancy reduces simply to life expectancy when the discount rate is zero. In this case eq. (2) returns the expected value of total future utility of income for the average person in the population.*] Average values for the population to be protected are used for X_d and ε, while G is taken to be the gross domestic product (GDP) per head.

Risk-aversion is an economic parameter with wide implications. In its simplest form, it describes the behaviour of an economic agent facing a choice. A risk-neutral agent, who has a risk-aversion of zero, will find the following alternatives equally attractive: (i) a monetary outcome that is certain and (ii) an outcome that is uncertain but has the same expected monetary value. However an agent who is risk averse will possess a positive risk-aversion, meaning he will prefer the certain outcome. More generally, a higher value of risk-aversion is associated with:

- wanting more protection against random mishaps and so being willing to pay more to insure against them [34]
- being less entrepreneurial in investment [35], [36]
- being prepared to pay more for safety [20]
- wanting a more redistributive tax regime [37]
- being more willing to pay more now to manage climate change in the future [38].

Equation (2) may be represented schematically as a balance between income on one hand and life expectancy on the other. It is sensible to give up some income to increase one's life expectancy as long as the life quality index does not fall. The limiting requirement that the life quality does not decrease as G and X_d vary may be expressed as

$$\frac{\delta Q}{Q} = (1-\varepsilon)\frac{\delta G}{G} + \frac{\delta X_d}{X_d} = 0 \qquad (3)$$

which relates the small increment in income, δG, that an average person would be prepared to give up to gain an extra period, δX_d, of discounted life expectancy. A cohort of N people should then be prepared to give up $\delta G_N = N\delta G$ each year for the rest of their discounted life expectancy. It is possible to find an up-front lump sum, δV_N ("V" for "value"), that is equivalent to this series of payments by discounting over this period using the social discount rate [39]. The J-value is the ratio of the amount actually spent on protection, $\delta \hat{V}_N$ to the maximum that is reasonable:

$$J = \frac{\delta \hat{V}_N}{\delta V_N} \qquad (4)$$

Hence $J = 1.0$ corresponds to the limiting condition where the actual expenditure on protection is justified by the gain in discounted life expectancy.

The J-value's valuation of differential effects just illustrated fits neatly into the framework of the safety optimisation of a new plant design, such as new nuclear reactor. Even if the plant as designed has a very low level of risk, it is still desirable to install an additional safety measure if its J-value is less than or equal to unity. This approach is compatible with the UK's legal requirement of ensuring safety "so far as is reasonably practicable", SFAIRP, which is usually restated in HSE guidance in the form that risks should be made "as low as reasonably practicable" (ALARP), and could encompass the concept of "gross disproportion" by increasing the value of J. In addition, it is possible in principle to adjust for injuries rather than deaths by using fractional multipliers.

5. Features of the J-value

The J-value takes the ethical position that the next hour of life for every member of the public in the same jurisidiction should be valued the same whether the individual is rich or poor, young or old. One result is that the J-value method incorporates the default assumption that an equal share of the nation's gross domestic product (£year^{-1}) will be distributed to each individual in the nation.

Actuarial data provided by the World Health Organisation that enable accurate life tables to be produced for all 193 nations that are members of the United Nations. Data for GDP per head are available from the World Bank for these countries and for the handful of countries not recognised by the UN. The GDP data are denominated in "international dollars", the appropriate units for measuring purchasing power parity across both developed and developing countries. Thus the J-value technique may be applied to analyse and judge safety expenditure that will affect any country in the world, taking account of the local conditions affecting that country.

6. Including environmental consequences: the J_T-value

As noted previously, accidents on high-hazard plants may involve, in addition to human casualties, very significant environmental and other costs. Chernobyl (in 1986), BP Macondo (2010) and Fukushima (2011) all illustrate this. Harking back to the first sentence of this paper, these were events *par excellence*.

In the case of Chernobyl, 30 men lost their lives at the time of the accident or shortly afterwards, while 209 emergency workers received high radiation doses that would increase their chances of contracting cancer. A further 530,000 emergency workers will have lost about 3 months of life expectancy, while the life expectancy of the worst affected members of the public, the 115,000 early evacuees, dropped by 9.3 days. The life expectancy of a further 6.4 million inhabitants of contaminated areas in Belarus, Russia and Ukraine were reduced by about 4 days. (The statistics for loss of life expectancy come from an analysis of UNSCEAR data [40] using the CLEARE program (Change of Life Expectancy from Averting a Radiation Exposure).) But in addition to the harm to human health summarised in these statistics, there were also significant environmental costs associated with the declaration of an exclusion zone of 30 km nominal radius [41]. Furthermore, there was a significant economic loss from writing off Chernobyl Unit 4.

11 men lost their lives in the explosion and fire at BP's Macondo oil platform and 17 were injured. The environmental cost to BP was so large as to threaten the shareholders' control of the company, with the share price dropping 35% in a month [42] and descending temporarily to about 50% of its previous value. Final costs to BP for the environmental losses have been assessed as high as $40 bn [43].

Meanwhile the tsunami that hit the Fukushima nuclear power plants in 2011 led to no deaths, but there may be delayed health effects. Certainly there are very large environmental costs associated with the declaration of a semi-circular exclusion zone of 20 km nominal radius and also very large economic costs from writing off four boiling-water reactors (BWRs) [44]. The economic consequences are likely to outweigh the directly attributable health detriments by a significant margin.

It is clear generally that a shut-down system on a chemical plant or a nuclear reactor may be called upon to protect not only against human harm but also against damage to nearby plant and the spread of contamination to the environment. A new metric is needed in the assessment when protection is provided against both human and environmental harm, and this is provided by the Total Judgement value or J_T-value. The J_T-value preserves the objectivity of the J-value and may be interpreted in a similar way. Hence $J_T = 1$ indicates the maximum reasonable expenditure; $J_T = 2$ indicates an overspend by a factor of 2, and so on.

For brevity, we shall refer to the costs associated with environmental clean-up, evacuation and/or relocation of people, food bans, loss to offsite businesses, and damage to reputation as "environmental costs", with the understanding that other costs may be brought under this umbrella in some cases. Note that the higher the assessed cost of the accident, the greater the incentive will be to provide better protection.

As with the J-value, we may use utility theory to judge where the trade-off should be made between extra spending on the protection system and these environmental costs [45], [21], [22], [23], [24], [46], [47], [48], [49]. The application of utility theory in this case may be achieved through using the ABCD model, which is described in detail elsewhere [23], [50]. The basis of the ABCD model is that an organisation with assets, A (£), faces environmental accident costs, C (£), with probability, π_1. We suppose that it is considering spending a sum, B (£), on an environmental protection system that will reduce the probability of incurring those costs from π_1 to π_2, where commonly π_1 is already small. The last, eponymous part of the ABCD model, D, denotes the difference in the expected utilities of the organisation's wealth with and without the protection system.

Decision makers are assumed to wish to maximise their organisation's expected utility. Thus they will want to implement the environmental protection scheme if the scheme's cost is outweighed by the increase in expected utility it brings about, which will happen when the expected before-and-after utility difference is negative.

If the decision on protective expenditure is taken on a purely monetary basis, the amount of money to be spent will be set equal to the loss the scheme is expected to avoid, bearing in mind its probability of occurrence. This is the risk-neutral point, where risk-aversion is zero. However, the possibility of very high loss may lead to the organisation sanctioning more money being spent on the protection system. The decision maker is becoming more risk averse, but only up to the point at which he finds it difficult to decide on whether or not to implement the protection system as the gains and losses of utility are so similar in size that he cannot distinguish one from the other. The decision maker's risk-aversion will now have risen to the "point of indiscriminate decision".

Restricting the highest level of risk-aversion to the point of indiscriminate decision provides a mathematically precise criterion for determining the maximum amount of money that should rationally be spent on protecting against environmental consequences. This amount can then be divided by the expected loss averted to provide a "disproportion factor" for the accident. The J-value framework can thus provide a mathematical justification for the principle of gross disproportion discussed previously, although here applied to environmental costs rather than human life.

7. Assessing protection expenditure to guard against both human harm and environmental damage

The J-value method may be applied to determine the maximum reasonable expenditure, δV_N (£), on the protection system to avert harm to the cohort of N people under threat. Next, we may find the maximum sensible spend, δZ_0 (£), to avert environmental costs, appropriate for the risk-neutral case where the risk-aversion is zero. This will depend on the environmental cost of the accident, the before-and-after frequencies, the period that the protection system will operate (which could be as long as 60 years in the case of a nuclear power station), and the growth rate of the organisation. This sum is then multiplied by the disproportion factor found using the

ABCD model to give the total contribution to the cost of the protection system, δZ_R (£), that is reasonable to safeguard against environmental costs.

Assuming that the protection system has an actual up-front capital cost, $\delta\hat{W}$ (£), the Total Judgement Value, J_T, will be given by the ratio:

$$J_T = \frac{\delta\hat{W}}{\delta Z_R + \delta V_N} \qquad (5)$$

8. Closing remarks

Events will always be difficult to deal with, and this will be particularly true for accidents, hopefully of low frequency, that lead to loss of life and millions or billions of pounds worth of damage. The J-value and the J_T-value, for schemes to protect humans and to protect both humans and the environment respectively, provide objective metrics that can be used as a consistent guide for decision makers. Their use does not preclude the decision maker from spending more money than would be implied by these measures. He might be inclined to do so when he has additional concerns in the socio-political area, for example. However, the availability of the J-value and/or J_T-value will provide a consistent platform on which to base the ultimate decision and to explain it if called upon to do so.

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