Catastrophes, Protections and the Social Welfare

Ernie Kee, Martin Wortman, and Pranav Kannan

Friday 12th June, 2020

Abstract

Although a critical activity of decision-makers as industrialists, ordinary citizens, politicians, and regulators is to ensure a proper balance is realized in protection between the harms that inevitably stem from technological systems and the social welfare, review indicates no formal development of a framework within which such decisions are made has been attempted in the academic literature.[1] Such a framework should rationally define the process of decision-making in design of technological systems that selects, among any others, the most-preferred design alternative in consideration of relevant regulatory requirements, that would optimize the social welfare. Since the basic tenets required to develop such a framework are already at hand it seems reasonable to develop it for use by stakeholders as they engage in decision-making.

Relevant stakeholders would be profit claimants (owners and investors), beneficiaries (consumers of products and services), and involuntary stakeholders ("near–neighbors" who might be harmed by catastrophic events as well as beneficiaries). Near-neighbors are those citizens who can be harmed but do not share in the profits generated by the technological system that may be the cause of the harm. While the framework within which decision-makers arrive at an optimal allocation of risk-taking, regulation, and liability lawsuit is shown to be mathematically simple, the decision-making process itself is effectively mathematically intractable.

[1] Much of the framework development in here is also presented "Protective Systems: Margins of Safety, Regulatory Authority, and the Calculus of Negligence" at the PSA 2017 conference but does not appear to have been indexed.

Introduction

Technological systems with various levels of complexity have proven necessary for humans to survive the many hazards Nature devises against them. Winter cold requires shelter and energy, animals and insects attack crops, drought and unseasonal rain destroy crops, getting goods across mountains, valleys and rivers requires transportation infrastructures. Unfortunately such technological systems inevitably bring new hazards intended to be less frequent and less deadly than those they are meant to overcome; depending on the efficacy of protections against any hazards they pose, citizens may be exposed to harm. Control of the new hazards introduced as well as the economic viability of such systems is effected in a complex infrastructure such that, when operating properly, benefits the social welfare; citizens enjoy access to goods and services at a net benefit. Of course activities surrounding access to goods and services also benefit owners and investors engaged in profit-making.

In the following we develop a rational framework, the one that maximizes social welfare against design of protection in reasonably complex technological systems. We assume compliance with regulations in the engineering design, operation, and maintenance of the "protective systems" installed; protective systems are assumed to include the following elements in our development,

- all sensoring technology used to detect anomalous operations,
- all equipment and personnel responsible for responding to detection of operational anomalies,
- all emergency response equipment and personnel (both public and private) responsible for responding to emergencies,
- all management infrastructure (both public and private) governing elements of protective system design, deployment, operation, and regulation.

We assume a technological system will be operated until it either reaches the end of its design life or prior to that, operation ends in catastrophic failure. Here, catastrophic failure refers to a sequence of events triggered by some upset, either endogenous or exogenous, that end in significant harm to humans, other animals or plant life.

With regard to the social welfare, Shavell recommends social welfare in his article "Liability for Harm versus Regulation of Safety" be measured ...

> " ... to equal the benefits parties derive from engaging in their activities, less the sum of precautions, the harms done, and the administrative expenses associated with the means of social control."
> (Shavell, 1984)

We adopt his recommendation. In the same article, Shavell makes an important point regarding the courts and regulation where he asserts the amount of parties assets must be considered against the hazard potential. That is if the injuring party's assets can not match the level of harm posed by the hazard they cause, regulation would be preferable to the courts that would likely assign liability post ante following the guidance of Judge Learned Hand's decision.[2] We think of protective systems as those that provide prior protection from harm. Liability exposure stems from ex ante harm potential; it may appear reasonable that a maximum limit on the cost of prior protection could be based on Hand's recommendation for burden of care, B,

$$B > P\,L,$$

whereby if the burden of care is greater than the product of the probability, P, for loss, and value of loss, L, the injurer bears no further liability. Although it appears to define a limit for protective system cost, we leave this line of reasoning to future work; we share concerns like those Hansson calls the "Tuxedo Fallacy" in his article,"From the Casino to the Jungle".

Framework for decision-making

Design and operation of protective systems intended to mitigate harms from hazards posed in technological systems is an essential engineering responsibility that must be accomplished at a reasonable cost and within the regulatory guidelines set by the government. Protective systems evolve over time as experience is gained with control of harms from known hazards as well as experience with emerging hazards; the evolution itself is controlled by a complex political process that attempts to balance the magnitude of societal cost of harms and cost of protections against them. It can be said that design and operational decisions regarding protective systems must be balanced between profit margins and the social welfare. In a democracy, citizens have the responsibility of electing representatives who will ultimately create laws that produce regulations designed to protect them from harm; the regulations cause protective systems subject to inspection and enforcement to be created, operated, and maintained.

We make analytical arguments that establish the economic relationship between protective system margins of safety, regulatory authority, and the calculus of negligence. As stated previously, we leave the issue of negligence

[2] 159 F.2d 169 (2d Cir. 1947), The case of 'United States v. Carroll Towing Co.'

to future work but include the notion here as it applies to decision makers' gain and loss preferences in the composite function that appears as the utility on cost. The risk–economics of margins of safety are examined by identifying the referenced efficacy with respect to which margins of safety are measured. Engineering design and operations decisions intended to improve efficacy of protection can, thus, be gauged as the degree to which they advance a risk–based margin of safety.

Framework development

In the arguments to follow, multiple probability spaces need to be identified. In the interest of a manageable notation, the de Finetti notation is adopted. Here, for a random variable X defined on the probability space $(\Omega, \mathcal{F}, P)$, the traditional expectation integral $E[X]$ is replaced by $P(X)$.

Let all candidate technologies, available for possible selection by the enterprise, be indexed with indices belonging to the set $\mathcal{A}$ where $\alpha^* \in \mathcal{A}$ is the preferred technology. Thus, there is a collection of probability spaces $\{(\Omega_\alpha, \mathcal{F}_\alpha, P_\alpha); \alpha \in \mathcal{A}\}$. For each alternative $\alpha \in \mathcal{A}$, define on $\{(\Omega_\alpha, \mathcal{F}_\alpha, P_\alpha)$ the random variables:

$V_\alpha : \Omega_\alpha \to \mathbb{R}$, the net present value of technology alternative α,

$C_\alpha : \Omega_\alpha \to \mathbb{R}_+$, the lifecycle cost of alternative α,

$\chi_\alpha : \Omega_\alpha \to \{0, 1\}$, where $\chi_\alpha = 1$ in the event that the lifetime of alternative α terminates in catastrophe.

Inasmuch as the enterprise has rationally selected technology alternative $\alpha^* \in \mathcal{A}$, it follows from the expected utility theorem that

$$\alpha^* = \arg\max_{\alpha \in \mathcal{A}} P_\alpha(u \circ V_\alpha). \tag{1}$$

Note that, since any selected technology must follow the same demand trajectory, $V_\alpha = -C_\alpha$, $\forall \alpha \in \mathcal{A}$. Hence, it follows that (1) can be rewritten as

$$\alpha^* = \arg\min_{\alpha \in \mathcal{A}} P_\alpha(u \circ C_\alpha)$$

where, $P_\alpha(u \circ C_\alpha)$ is the *expected lifecycle social cost* of technology alternative $\alpha \in \mathcal{A}$.

It is important to recall that technology α^* is selected because regulation has imposed a value on public safety (implicitly represented by the social welfare mapping u), which reflects the high social cost associated with catastrophic failures that terminate a technology's lifecycle. Thus, it is useful to explore lifecycle social costs on catastrophic events. In this way, the margin of safety that certain non–optimal alternatives might enjoy over α^* can be investigated. To this end, note that the expected lifecycle social cost can be written as,

$$P_\alpha(u \circ C_\alpha) = P_\alpha(P_\alpha(u \circ C_\alpha|\chi_\alpha)), \forall \alpha \in \mathcal{A},$$

or

$$\begin{aligned} &P_\alpha(u \circ C_\alpha) = P_\alpha(u \circ C_\alpha|\chi_\alpha = 0)P_\alpha(\chi_\alpha = 0)+ \\ &P_\alpha(u \circ C_\alpha|\chi_\alpha = 1)P_\alpha(\chi_\alpha = 1). \end{aligned} \tag{2}$$

As a matter of convenience, the following is defined: $c^g_\alpha \triangleq P_\alpha(u \circ C_\alpha|\chi_\alpha = 0)$, the expected social cost of alternative α in the event that the lifecycle terminates *without catastrophe*, or the expected social cost of catastrophe–free lifecycle

$c^f_\alpha \triangleq P_\alpha(u \circ C_\alpha|\chi_\alpha = 1)$, the expected social cost of alternative α in the event that the lifecycle terminates with catastrophe,
and, $p_\alpha \triangleq P_\alpha(\chi_\alpha = 1)$, $\alpha \in \mathcal{A}$. Hence, (2) is rewritten as

$$P_\alpha(u \circ C_\alpha) = c^g_\alpha + (c^f_\alpha - c^g_\alpha)p_\alpha, \forall \alpha \in \mathcal{A}. \tag{3}$$

$c^p_\alpha \triangleq (c^f_\alpha - c^g_\alpha)$ will be referred to as as the *catastrophe–premium* of technology α. Thus, (3) states that:
For any technology alternative, its expected social cost is given by its expected social cost with catastrophe–free operation, plus its catastrophe–premium weighted by the probability of catastrophe.

It now follows from (1) and (3) that for all $\alpha \neq \alpha^*$

$$c^g_{\alpha^*} + (c^f_{\alpha^*} - c^g_{\alpha^*})p_{\alpha^*} \leq c^g_\alpha + (c^f_\alpha - c^g_\alpha)p_\alpha$$

or,

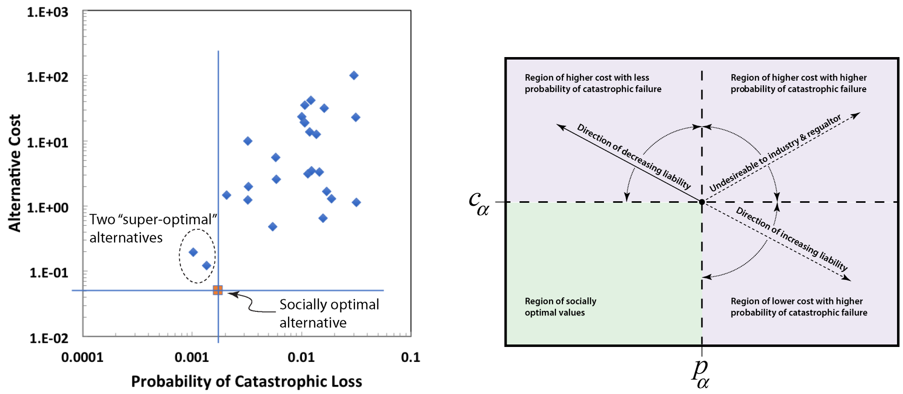
$$c^g_{\alpha^*} + c^p_{\alpha^*}p_{\alpha^*} \leq c^g_\alpha + c^p_\alpha p_\alpha. \tag{4}$$

Rearranging (4) into point–slope form gives

$$p_{\alpha^*} \leq \frac{c^p_\alpha}{c^p_{\alpha^*}}p_\alpha - \frac{(c^g_{\alpha^*} - c^g_\alpha)}{c^p_{\alpha^*}}.$$

$c^p_{(\alpha^*,\alpha)} \triangleq (c^g_{\alpha^*} - c^g_\alpha)$, the expected difference in social cost between technology alternatives α^* and α, is referred in here as the *reliability premium* of choosing α^* over $\alpha \in \mathcal{A}$. Note that it may happen that the reliability premium takes a negative value. Thus, it now follows that for all technology alternatives $\alpha \in \mathcal{A}$,

$$p_{\alpha^*} \leq \frac{c^p_\alpha}{c^p_{\alpha^*}}p_\alpha - \frac{c^p_{(\alpha^*,\alpha)}}{c^p_{\alpha^*}}. \tag{5}$$



(a) Twenty–six hypothetical socially suboptimal alternatives plotted with the socially optimal alternative selected from a total of twenty–seven alternatives hypothesized.

(b) The nature of alternative selections in relation to cost (C_α) and catastrophic failure probability (p_α) over the plant lifetime with relation to possible liability in light of failures.

Figure 1. Two views of preferences on a cost–failure probability phase plane.

To illustrate different aspects of (5) and complexity between social and regulatory optimums, Figure 1a is created based on an ad hoc correlation between the probability of catastrophic failure and social costs for 27 hypothetical alternatives. In the assumed correlation, the tendency is to relate smaller social costs with smaller probabilities of catastrophic failures which would be desirable to industry and the regulator. The figure shows that a case which is socially optimum would not necessarily be the regulatory optimum ("super–optimal"), since there are two alternative technologies plotted to the "northwest" of it. In this figure, super–optimal technologies would relate to alternatives selected under regulation (their corresponding probabilities are less than the socially optimal one). Once the socially optimal alternative is known, none of the alternatives would lie to the south of it.

Engineers typically couch technology choices in terms of system reliability and cost. (5) shows that α^* is the most preferred technology only when its life cycle unreliability p_{α^*} is at least as small as the life cycle unreliability p_α, for all $\alpha \in \mathcal{A}$, scaled by the quotient of catastrophe premiums less the quotient of the reliability premium to the unpreferred alternative's catastrophe premium. Figure 1b illustrates the behaviors described by (5). Thus, the conditions set forth by the expected utility theorem can be understood in terms that are both analytically and intuitively specific to protective system design and operation. Of course, in practice, the particular values of elements that form

(5) are difficult to obtain since information (including event probabilities and the social welfare function) is typically vague or incomplete. Nonetheless, the design decision of selecting the most preferred technology alternative cannot be avoided.

Discussion

The examination of protective systems offered establishes a decision–analytical framework capturing the relationship between margins of safety and regulatory authority. It is argued that because potential liability (as identified through the calculus of negligence and following from the well–known Coase Theorem) does not substantially influence profit maximizing decisions associated with the design and operation of safety–critical protective systems, regulatory authority necessarily arises so as to ensure mitigation of moral hazard for a certain element of the public (those having large potential for losses in the event of a catastrophe).

Regulatory authority induces a unique (up to affine transformation as corollary to the Expected Utility Theorem) social welfare function that enforces a unique socially optimal price–point for regulated protection that does not enhance revenues. Margins of safety are, thus, defined to be associated with protective system alternatives that exhibit a lower probability of catastrophe than a unique socially–optimal level of protection. The framework identifies reliability premiums and catastrophe premiums associated with safety margins in a manner that allows protective system design and operation decisions to be considered in the context of expected lifecycle costs.

References

Hansson, S. O. (2009). From the casino to the jungle: Dealing with uncertainty in technological risk management. *Synthese 168*(3), 423 – 432.

Shavell, S. (1984). Liability for harm versus regulation of safety. *The Journal of Legal Studies 13*(2), 357–374.

Bibliography

Adler, M. D. (2017, March). A better calculus for regulators: From cost-benefit analysis to the social welfare function. Working Paper EE 17-01, Duke University School of Law.

Alves, S., J. Tilghman, A. Rosenbaum, and D. C. Payne-Sturges (2012). U.S. EPA authority to use cumulative risk assessments in environmental decision-making. *International Journal Of Environmental Research And Public Health 9*(6), 1997 – 2019.

Apostolakis, G. E. (2004). How useful is quantitative risk assessment? *Risk analysis 24*(3), 515–520.

Barbour, A. D. and P. Hall (1984). On the rate of Poisson convergence. In *Mathematical Proceedings of the Cambridge Philosophical Society*, Volume 95, pp. 473–480. Cambridge University Press.

Barnard, R. C. (1990). Some regulatory definitions of risk: interaction of scientific and legal principles. *Regulatory Toxicology and Pharmacology 11*(2), 201–211.

Bierly, P., S. Gallagher, and J.-C. Spender (2014). Innovation decision making in high-risk organizations: A comparison of the US and Soviet attack submarine programs. *Industrial and Corporate Change 23*(3), 759–795.

Bjelland, H., O. Njå, A. Heskestad, and G. Braut (2015). The concepts of safety level and safety margin: Framework for fire safety design of novel buildings. *Fire Technology 51*(2), 409–441.

Bradbury, S. P., T. C. Feijtel, and C. J. V. Leeuwen (2004). Peer reviewed: meeting the scientific needs of ecological risk assessment in a regulatory context.

Clausen, J., S. O. Hansson, and F. Nilsson (2006). Generalizing the safety factor approach. *Reliability Engineering & System Safety 91*(8), 964 – 973.

Croley, S. P. (1998). Theories of regulation: Incorporating the administrative process. *Columbia Law Review 98*(1), 1–168.

Dal Bó, E. (2006). Regulatory capture: A review. *Oxford Review of Economic Policy 22*(2), 203–225.

Daley, D. and D. Vere-Jones (1987). The extended probability generating functional, with application to mixing properties of cluster point processes. *Mathematische Nachrichten 131*(1), 311–319.

Doob, J. L. (1953). *Stochastic processes.* Wiley publications in statistics. New York : Wiley, [1953].

Doorn, N. and S. O. Hansson (2011). Should probabilistic design replace safety factors? *Philosophy & Technology 24*(2), 151–168.

Fell, R. (1994). Landslide risk assessment and acceptable risk. *Canadian Geotechnical Journal 31*(2), 261–272.

Hahn, R. W. and C. R. Sunstein (2002). A new executive order for improving federal regulation? deeper and wider cost-benefit analysis. *University of Pennsylvania Law Review 150*(5), 1489–1552.

Hansson, B. (1968). Choice structures and preference relations. *Synthese 18*(4), 443–458.

Hansson, S. and T. Aven (2014). Is Risk Analysis Scientific?. *Risk Analysis 34*(7), 1173.

Hansson, S. O. (1993). The false promises of risk analysis. *Ratio 6*(1), 16–26.

Hansson, S. O. (2002). Uncertainties in the knowledge society. *International Social Science Journal 54*(171), 39–46.

Hansson, S. O. (2007). Social decisions about risk and risk-taking. *Social Choice and Welfare 29*(4), 649–663.

Hansson, S. O. (2012, August). Safety is an inherently inconsistent concept. *Safety Science 50*(7), 1522–1527.

Huber, P. (1985). Safety and the second best: The hazards of public risk management in the courts. *Columbia Law Review 85*(2), 277–337.

James, W. and H. Thayer (1975). *Pragmatism*, Volume 1. Harvard University Press.

Kaplan, S. and J. Garrick (1981, March). On The Quantitative Definition of Risk. *Risk Analysis I*(1), 11–27.

Laffont, J.-J. and J. Tirole (1991, November). The politics of government decision-making: A theory of regulatory capture. *The quarterly journal of economics 106*(4), 1089–1127.

Levine, M. E. and J. L. Forrence (1990). Regulatory capture, public interest, and the public agenda: Toward a synthesis. *Journal of Law, Economics, & Organization 6*, 167–198.

Meyer, P. et al. (1962). A decomposition theorem for supermartingales. *Illinois Journal of Mathematics 6*(2), 193–205.

Meyer, P. et al. (1963). Decomposition of supermartingales: the uniqueness theorem. *Illinois Journal of Mathematics 7*(1), 1–17.

Miller, G. J. (2005). The political evolution of principal-agent models. *Annu. Rev. Polit. Sci. 8*, 203–225.

Möller, N., S. O. Hansson, J.-E. Holmberg, and C. Rollenhagen (2018, January). *Handbook of Safety Principles* (First ed.), Volume 9 of *Wiley Essentials in Operations Research and Management Science*. 111 River Street, Hoboken, NJ, 07030, USA: John Wiley & Sons.

National Research Council and others (1996). *Understanding risk: Informing decisions in a democratic society*. National Academies Press.

Noll, R. G. (1989). Economic perspectives on the politics of regulation. *Handbook of industrial organization 2*, 1253–1287.

Peltzman, S. (1976). Toward a more general theory of regulation. *The Journal of Law and Economics 19*(2), 211–240.

Peltzman, S., M. E. Levine, and R. G. Noll (1989). The economic theory of regulation after a decade of deregulation. *Brookings papers on economic activity. Microeconomics 1989*, 1–59.

Posner, R. A. (1971, Spring). Taxation by regulation. *The Bell Journal of Economics and Management Science 2*(1), 22–50.

Posner, R. A. (1974, Autumn). Theories of economic regulation. *The Bell Journal of Economics and Management Science 5*(2), 335–358.

Roca, J. B., P. Vaishnav, M. G. Morgan, J. Mendonça, and E. Fuchs (2017). When risks cannot be seen: Regulating uncertainty in emerging technologies. *Research Policy 46*(7), 1215–1233.

Rogerson, W. P. (1982, Autumn). The social costs of monopoly and regulation: A game-theoretic analysis. *The Bell Journal of Economics 13*(2), 391–401.

Rosenberg, N. (1982). *Inside the black box: technology and economics*. Cambridge University Press.

Ruckelshaus, W. D. (1985). Risk, science, and democracy. *Issues in science and technology 1*(3), 19–38.

Shavell, S. (1984a). A model of the optimal use of liability and safety regulation. *RAND Journal of Economics (RAND Journal of Economics) 15*(2), 271 – 280.

Shavell, S. (1986). The judgment proof problem. In *Foundations of Insurance Economics*, pp. 341–354. Springer.

Shavell, S. (1987). *Economic analysis of accident law. Steven Shavell.* Cambridge, Mass.: Harvard University Press, 1987.

Shavell, S. (2013, June). A fundamental enforcement cost advantage of the negligence rule over regulation. *JOURNAL OF LEGAL STUDIES 42*(2), 275 – 302.

Stigler, G. J. and C. Friedland (1962). What can regulators regulate? the case of electricity. *The Journal of Law and Economics 5*, 1–16.

Tribus, M. (1969). *Rational descriptions, decisions, and designs.* Pergamon unified engineering series: engineering design section. New York : Pergamon Press, [1969].

United States and J. G. Kemeny (1979). *The need for change, the legacy of TMI: report of the President's Commission on the Accident at Three Mile Island, John G. Kemeny, chairman.* Washington, D.C.: s.n. : for sale by the Supt. of Docs., U.S. Govt. Print. Off.

Westcott, M. et al. (1976). Simple proof of a result on thinned point processes. *The Annals of Probability 4*(1), 89–90.