

Industrial Ecology and Risk Analysis¹

Paul R. Kleindorfer

Risk Management and Decision Processes Center

The Wharton School

University of Pennsylvania

November, 2000

Risk analysis in industrial contexts consists of four integrated processes: (i) identifying underlying sources of risk, (ii) determining the pathways by which such risks can materialize, (iii) estimating the potential consequences of these risks under various scenarios, and (iv) providing the means for mitigating and coping with these consequences. Specific risks, once identified, are usually characterized by the probability of their occurrence and the magnitude of their consequences, but many other attributes of risks may be of interest to individuals affected by these risks. Risks can have both positive and negative outcomes and can occur in any domain of a company's operations, from engineering to finance.

A great deal of work in corporate finance and insurance has gone into the design of efficient risk management instruments for risks that can be monetized (e.g., Doherty, 1999), and to the extent that the consequences of these risks are borne by the owners of an enterprise, there are strong incentives for managers to make efficient choices in balancing risks and returns. This is not usually true for industrial risks having safety, health or environmental (SHE) impacts, since these impacts are often borne by the eco-system and by uninvolved third parties including future generations. Thus, for SHE risks, market forces are not usually sufficient to motivate a profit-oriented company to operate efficiently. Achieving efficient tradeoffs here requires instead that industrial practice be tempered by

¹ Prepared for L. Ayres and R. Ayres, Handbook of Industrial Ecology. Support for this research from a Cooperative Agreement to the Wharton Center for Risk Management and Decision Processes from the U. S. Environmental

regulation and public participation. Exactly how this should occur for various types of SHE risks has been a major area of development in the literature of industrial ecology and will be the focus of this chapter. I first consider the central drivers of risk analysis in industrial contexts, since this has motivated much of the research in this area. Thereafter, I briefly review key elements of current approaches to industrial ecology (IE) for SHE risks.

1. Factors underlying industrial risk analysis

In the industrial ecology framework, each company has a special role as a steward of the environment and eco-system within which it operates. Naturally this role of product stewardship and environmental waste and risk management encompasses suppliers and customers just as “extended value-chain analysis” encompassed suppliers and customers in the traditional supply chain improvement process. Indeed, it is useful to review the factors underlying the focus and need for industrial risk analysis in parallel with the extended supply chain. Figure 1 shows the leverage points for such risk analysis beginning along the supply chain from virgin resources to suppliers, through product transformation to customers. Risk analysis has the task of identifying and quantifying risks along this extended supply chain and determining appropriate mitigation and response strategies.

The key processes of interest in the industrial risk analysis process are: product and supply chain design to minimize SHE impacts; on-going waste minimization and risk mitigation after the product has been deployed; and diagnostic feedback from supply chain participants to assess opportunities for future risk reduction activities. Resulting SHE improvements in a company’s supply chain can lead to economic benefits for companies in several areas.

Protection Agency/CEPPO is gratefully acknowledged.

Corporate Image: Mitigating SHE risks is not only socially responsible behavior; it is good business. First, due to the public concern surrounding environmental issues, promoting environmental care can enhance a company's and an industry's image. The key driver from a business perspective is the avoidance of major accidents, which can have huge consequences on a company (see Klassen and McLaughlin (1996) for empirical estimates), as shown by the Union Carbide accident in Bhopal, India in 1984. As a result of this accident, Union Carbide itself lost its ability to operate as a company.

Regulatory Compliance: Regulatory compliance requires companies to track the use of hazardous substances and emissions of pollutants. While actual compliance clearly varies widely, especially among small firms with less to lose in the event of SHE incidents, major companies in the chemical and process industries have devoted significant resources over the past two decades to improving SHE performance (e.g., Jaffe et al., 1995).

Liability and Negligence: Another factor driving companies to improve their environmental performance is the risk of being held liable, or found negligent, for accidents or environmental damage. This is true even when the company is acting prudently and using state-of-the-art technology. To limit liabilities, many companies implement strict risk reduction mechanisms, with a focus on generally lowering the lower the level of pollution, biocides and toxics (P, B and T) associated with a company's supply chain and products produced (e.g., Allenby and Richards, 1994).

Community Relations: Improved relations with local communities and with other external stakeholders are becoming increasingly important for companies, both as a matter of law and of best practice (see, e.g., McNulty, Schaller and Chinander (1998)).

Employee Health and Safety: Similar to community concerns, employee health and safety is a key focus of risk reduction and risk communication initiatives (CCPS, 1989). Employee H&S is not

limited to company workers or on-site exposures, but includes all parties in the supply chain who may be exposed to a company's product.

The above issues have been important factors in promoting a new sense of urgency about the management of major risks in industry. The strategies employed by industrial companies and regulators to improve risk management have relied on new management and regulatory systems, the outlines of which we now consider.

2. Managerial and regulatory systems to promote efficient risk management

Integrating the supply chain to identify, mitigate and manage risks requires integration with key business processes, measurement of results and commitment from top management. A number of managerial concepts, tools and systems exist that promote these steps towards sustainable risk practices. Essentially, all the tools of Industrial Ecology noted throughout this Handbook have important implications in promoting reduction of SHE risks. For example, life-cycle analysis, gated DfX screens (where Design for X includes X factors such as Environment, Safety, Disassembly, Recycling, etc.), and Reverse Logistics all promote more sustainable products and supply chains and can have significant effects on the overall SHE risks of these supply chains by reducing their P-B-T content.

Of the new management systems to promote SHE risk reduction and sustainable industrial practices, the best known is certainly the Environmental Management System (EMS) under the international standards ISO 14000 (Carter, 1999) and related systems such as those promulgated by the European Union under the Eco-Management Audit Scheme (EMAS). ISO 14000 began development in 1991, after the successful deployment of ISO 9000 standards, and the aspirations underlying ISO 14000 were motivated by the experience with ISO 9000. Recent empirical research shows that process mapping, as embodied in good IE practice and in the ISO 9000 quality standard,

can be a significant aid to discovering process defects and fixing them (Angel, 2000). By extension, this same logic of process excellence appears to apply to risks and ecological effects, and industrial practice is increasingly reflecting this belief (CCPS, 1989; Bern, 1998; Friedman, 1997). Systems such as ISO 14000, EMAS and related process safety standards have become essential vehicles across the globe in codifying a company's SHE practices, in promoting auditing standards for these, and in providing information to the public and regulators about company SHE performance (Lofstedt, Kdeda and Thompson, 2000; Kunreuther, Kang and McNulty, 2000).

A prime mover for implementing IE is government regulation and economists have been concerned since the beginning of environmental regulation to provide the logical underpinnings for such regulation. In the context of the management of risk, economic models focus on the incentives a firm faces to engage in efficient risk mitigation. Theoretical and empirical results from this literature show that if the firm does not internalize all the consequences of its decisions regarding risk, then it will tend to underinvest in risk mitigation. This in turn awakens the call for regulation of such risks (see also Allenby in this Handbook). A number of models have been developed to investigate the consequences of various forms of regulation that attempt to rectify the noted underinvestment problem (e.g., Shavell (1984), Gruenspecht and Lave (1989), Watabe (1999)).

An alternative approach to risk regulation has been suggested by Kleindorfer and Orts (1998), and this approach is increasingly evident in North America and the European Union. The approach is called "informational regulation" (IR) of risks and is based on the original ideas of Ronald Coase (Coase, 1960). The IR approach requires firms to share information on their risk management programs and their performance with the public. The idea is to make it easy for NGOs, local community groups and affected citizens to identify the risks they face, and by providing thereby leverage for such groups to put pressure on firms to improve their risk performance. Under IR, the

locus of risk regulation moves away from government bureaucracy to local bargaining between affected communities, armed with legitimate information on the risks they face, and the companies giving rise to such risks. This approach is especially compelling when the risks involved are largely local and borne by an identified group of stakeholders, such as a community hosting an industrial facility.

3. The technical process of risk analysis

General procedures and a host of tools and industrial applications of risk analysis have been developed over the past half century. A good survey of these is available in Haines (1998), and further research progress is reported in the primary journal in the field, *Risk Analysis*. The accepted conceptual structure for managing SHE risks includes the following activities (see Friedman (1997)):

1. Hazard Identification: List materials, processes and products of potential concern and qualitatively prioritize these by their relative hazard.
2. Risk Assessment: Determine the credible releases, exposure pathways and events that might result from various events and scenarios and calculate the median and worst case hazard zones associated with these.
3. Risk Analysis: Consider all safety systems, redundancies and mitigation possibilities, calculate detailed probability distributions for the hazards identified, and consider damage reduction possibilities.
4. Risk Management: Specify risk acceptance and risk reduction guidelines, specify process hazards management procedures, including emergency response procedures, structure financial and insurance provisions, and establish communication procedures with affected employees and the public.

For each of the above steps, companies can rely on a variety of tools and methodologies to assist them (Haimés, 1998). In the hazard identification phase, data and procedures from various industry sources help to determine levels of hazard of various processes, materials and products. . The tools of IE in mapping material and energy flows (e.g., Ayres (1997a,b) are essential diagnostic tools to indicate likely sources and magnitudes of emissions and wastes in key processes. In risk assessment, a variety of decision support systems are available for computing for various chemicals dispersion dynamics and their consequences. Risk Analysis is supported by general tools, such as process simulation, Decision Analysis and Event and Fault Tree methods, as well as by instantiations of these tools for specific industrial sectors. Concerning Risk Management, the literature on risk and insurance is well developed in the area of SHE risks (Freeman and Kunreuther, 1998), as are approaches to emergency response. Finally, survey methods and other empirical approaches to measuring the perceptions of community members of the industrial risks they face are now widely developed, motivated by the work of Slovic (1987), to assist decisionmakers in determining what various stakeholders are concerned about and how best to communicate with them about risk reduction possibilities.

When these processes and tools are applied to a setting, the results achieved can be remarkable. In line with the findings of the effects of quality management programs, these results are in two key areas. First, is the structuring of a strong management system for companies that links their strategy process and their operations to a legitimate, science-based framework to identify, assess and manage their SHE risks. Second, is an organic structure of shared knowledge that allows all stakeholders in a company's operations to understand the potential effects of these operations on the company's eco-system. This systemic knowledge, and the purposeful activity triggered by it to

achieve a sustainable fit between a company and its environment, is the most important characteristic of the industrial ecology approach to SHE risks.

4. Risk epidemiology

The standard process of risk analysis, as described above, may use data from a number of sites, e.g., on the failure rates of specific fittings or equipment, but the results of the overall risk analysis process are usually quite site specific. Recently, it has been suggested that standardized data from across a large number of sites could be used to provide more aggregate assessments of accident rates and severities. This approach, using data from a number of facilities, has been called accident (or risk) epidemiology, since it is similar to its medical cousin in attempting to use cohort cross-sectional or panel data to determine underlying factors of undesirable outcomes.

The most well-known example of this type of study is associated with the Risk Management Plan Rule under 112(r) of the Clean Air Act Amendments in the U.S., which is now briefly described. (In the European Union, similar actions were undertaken under the Seveso II Directive, Orts and Deketelaere, 2000.) Section 112(r) sets forth a series of requirements aimed at preventing and minimizing the consequences associated with chemical accidental releases. These requirements are the basis of U. S. EPA's rule on "Risk Management Programs for Chemical Accidental Release Prevention" (hereafter the "Rule"). The federal regulations promulgated under 112(r) apply to facilities (both public and private) that manufacture, process, use, store, or otherwise handle regulated substances at or above specified threshold quantities (which range from 500-20,000 pounds). With some exceptions, the Rule requires all regulated facilities to prepare and execute a Risk Management Program (RMP) which must describe the facility's approach to hazard assessments, worst case scenarios, and prevention programs. The Rule also specifies the requirement that regulated facilities maintain a five-year history of accidental releases and submit this history to the

EPA no later than June 21, 1999, with further five-year filings expected in the future (probably repeated in 2004). The number of facilities that filed under the Rule was 14,500, with 1,145 of these facilities (7.9%) reporting 1,913 accidents over the five-year period of interest. The database itself has been named RMP*Info and, except for sensitive data on worst case scenarios, has been available to the public since August 1999.

The initial data were first analyzed in Kleindorfer, Feldman and Lowe (2000). The basic approach followed was the epidemiologic methodology known as [retrospective] cohort study design. Epidemiology is the study of predictors and causes of illness in humans. Its use in studying industrial accidents had been proposed in a number of quarters (e.g., Saari (1986), Rosenthal (1997)). The motivating idea is to study the demographic and organizational factors of those facilities whose Accident Histories are captured in RMP*Info to determine whether any of these factors have significant statistical associations with reported accident outcomes, positive or negative, just as one might use demographic or life-style data for human populations to determine factors that might be associated with the origin and spread of specific illnesses.

To provide some sense of what accident epidemiology is, consider the basic demographics of the facilities that filed under RMP*Info. There are 14,500 facilities in RMP*Info and there are 1,913 reported accidents in RMP*Info, with 1,145 facilities reporting at least one accident. However, the sample size for various statistics will not remain constant at 14,500 and 1,913, since some sites have multiple processes and some processes use multiple listed chemicals. For example, The average facility size among facilities reporting to RMP*Info, as measured in employee FTEs, is 163 FTEs, ranging from facilities with less than 0.5 FTEs (recorded as 0 FTEs in RMP*Info) to 48,000 FTEs. Half of facilities have 11 FTEs or fewer.

Various accident rate statistics can be computed from the information in RMP*Info. For example, Table 1 reports accidents by listed chemical involved in the accident for chemicals involved in 10 or more accidents. The numbers of accidents by chemical ranged from 656 accidents for anhydrous ammonia facilities to a single accident for 22 listed chemicals. Exactly half (80) of the 160 chemicals listed under the Rule were involved in at least one accident during the reporting period.

Consequences of accidents, according to various measures, are summarized in Table 2. We note in passing that there were no off-site deaths from the chemical industry in the five-year period in the United States. There were a total of 1,897 injuries and 33 deaths to workers/employees, and there were 141 injuries and 0 deaths to non-employees, including public responders. Half of accidents (956 of 1912 reporting this data) resulted in worker injuries. Table 2 also notes the damages to property and the non-medical off-site consequence analysis resulting from accidents during the reporting period. Note that the property damages alone are in excess of \$1 Billion, and they do not include business interruption costs, including losses in shareholder value and lost business associated with accidents. These interruption costs are likely to have been significantly higher than the property losses.

In addition to the above descriptive statistics, a number of analytic studies on trends in the data, underlying risk factors and other multi-variate analyses have been undertaken (see Kleindorfer, Feldman and Lowe, 2000). This research is concerned with characterizing the statistical association, if any, between such plant characteristics as size on accident frequency and severity, controlling for other demographic and process characteristics such as Prevention Level, the inherent hazard of the chemicals involved and other factors that might affect accident outcomes. Individual sector-specific and process-specific studies (e.g., chlorine plants) could also be coupled with other IE approaches

such as material and mass balance studies. Using Accident Epidemiology to discover the organizational and process determinants of accidents seems a particularly fruitful approach given the growing availability of comparative, cross-industry data.

5. New frontiers in risk analysis and industrial ecology

The above areas represent the current state of risk analysis in respect to the industrial ecology movement. New frontiers include, foremost, the use of internet technologies to improve shared knowledge about industrial impacts on the environment, globalization of activities related to risk assessment and management, and the continuing advancement of the science of risk analysis. In all these areas, the key element of risk analysis for industrial ecology remains linking of individual actors, be they government agencies, companies or households, to a science-based assessment of the impacts of their actions on their environment. The evolving paradigm of Risk Analysis continues to serve us well in this endeavor in determining and assessing sources of risk and in motivating the adoption of effective mitigation strategies to reduce these risks.

References

Allenby, B. R. and D. J. Richards (Eds) (1994). *The Greening of Industrial Ecosystems*. National Academy Press: Washington D.C.

Angel, L. C. (2000). "Comparing the Environmental and Quality Initiatives of Baldrige Award Winners", forthcoming in *Production and Operations Management*.

Ayres, R. (1997a, b). "The Life-Cycle of Chlorine" Part I, *J. of Industrial Ecology*, Vol. 1, No. 1, pp. 81-94; Part II, *J. of Industrial Ecology*, Vol. 1, No. 2, pp. 65-90.

Bern, L. (1998). *Strategy for Sustainable Growth*, Karlof Kommunikation Publ., Stockholm.

Coase, R. H. (1960). "The Problem of Social Cost," *Journal of Law and Economics*, Vol. 3, 1-44.

Doherty, N. A. (2000). *Integrated Risk Management: Techniques and Strategies for Managing Corporate Risk*, McGraw-Hill Publishers, New York.

Carter, A. 1999. "Integrating Quality, Environment, Health and Safety Systems with Customers and Contractors", in Ruth Hillary (ed.), *ISO 14001: Case Studies and Practical Experiences*, Greenleaf Publishing Ltd, Sheffield, UK.

CCPS (Center for Chemical Process Safety) (1989). *Technical Management of Chemical Process Safety*, American Institute of Chemical Engineers, New York.

Friedman, Frank B. (1997). *Practical Guide to Environmental Management*, 7th Edition, Environmental Law Institute, Washington, DC.

Freeman, P. K. and H. C. Kunreuther (1997). *Managing Environmental Risk through Insurance*, Kluwer Academic Publishers, Boston.

Gruenspecht, Howard K. and Lester B. Lave. 1989. "The Economics of Health, Safety and Environmental Regulation." Chapter 26 in Richard Schmalensee and Robert D. Willig (eds.), *Handbook of Industrial Organization*, Vol. II, North Holland: Amsterdam.

Haimes, Y. (1998), *Risk Modeling, Assessment and Management*, John Wiley, New York.

Jaffe, A. B., S. R. Peterson, P. R. Portney and R. N. Stavins (1995) "Environmental Regulation and the Competitiveness of U.S. Manufacturing : What Does the Evidence Tell Us?," *Journal of Economic Literature*. Vol. 33 No. 1, pp. 132-163

Klassen, R. D. and C. P. McLaughlin (1996) "The Impact of Environmental Management on Firm Performance," *Management Science*, Vol. 42 No. 8, pp. 1199-1214.

Kleindorfer, P. R., H. Feldman and R. A. Lowe (2000). "Accident Epidemiology and the U.S. Chemical Industry", Working Paper 00-01-15, Center for Risk Management and Decision Processes, The Wharton School, University of Pennsylvania.

Kleindorfer, P. R. and H. C. Kunreuther. 1994. "Siting of Hazardous Facilities." In Pollack, S. and M. Rothkopf, *Handbook of Operations Research in the Public Sector*, Elsevier: New York.

Kleindorfer, P. R. and E. W. Orts (1998). "Informational Regulation of Environmental Risks," *Risk Analysis*, Vol. 18, No. 2, pp. 155-170.

Kunreuther, H. C. and E. H. Bowman (1998). "A Dynamic Model of Organizational Decision Making: Chemco Revisited Six Years after Bhopal," *Organizational Sciences*.

Kunreuther, H. C., P. J. McNulty and Y. Kang (2000) "Third Party Inspection as an Alternative to Command and Control Regulation," forthcoming in Eric W. Orts (ed.), *Environmental Contracts*, Kluwer Academic Publishers, Boston.

Lofstedt, R. E., S. Ikeda and K. M. Thompson (2000). "Risk Management across the Globe: Insights from a Comparative Look at Sweden, Japan, and the United States", *Risk Analysis*, Vol. 18, No. 2, pp. 191-198.

McNulty, P. J., L. C. Schaller and K. R. Chinander (1998). "Communicating Under Section 112(r) of the Clean Air Act Amendments," *Risk Analysis*, Vol. 18, No. 2, pp. 191-198.

Orts, E. W. and K. Deketelaere (ed.), 2000. *Environmental Contracts: Comparative Approaches to Regulatory Innovation in the United States and Europe*, Kluwer Law International, Dordrecht..

Rosenthal, I. (1997). "Investigating Organizational Factors Related to the Occurrence and Prevention of Accidental Chemical Releases", in A. Hale, B. Wilpert and M. Freitag (eds), *After the Event: From Accident to Organisational Learning*, Pergamon: Elsevier Science, New York, 41-62.

Saari, J. (1986). "Accident Epidemiology", in M. Karvonen and M. I. Mikheev (eds), *Epidemiology of Occupational Health*, European Series No. 20, World Health Organizations Regional Publications, Copenhagen, 300-320.

Shavell, S. (1984). "A Model of the Optimal Use of Liability and Safety Regulation." 15 *RAND Journal of Economics*, 271-280.

Slovic, P. 1987. "Perception of Risk", *Science*, Vol. 236, pp. 280-285.

Watabe, A. (1999). "The Effect of Liability-Sharing Rules in Delegating Hazardous Activities", *International Review of Law and Economics*, Vol. 19, No. 3, pp. 349-68.

**Table 1: Accidents Reported in RMP*Info by Chemical Involved in the Accident
for the Entire Period 1994-1999 (Results for Chemicals with 10 or More Accidents During the
Five-Year Reporting Period)**

Chemical Name	Chemical ID	Number of Accidents
Ammonia (anhydrous)	56	656
Chlorine	62	518
Hydrogen fluoride/Hydrofluoric acid	55	101
Flammable Mixture	155	99
Chlorine dioxide [Chlorine oxide (ClO ₂)]	71	55
Propane	98	54
Sulfur dioxide (anhydrous)	49	48
Ammonia (conc 20% or greater)	57	43
Hydrogen chloride (anhydrous) [Hydrochloric acid]	54	32
Hydrogen	149	32
Methane	93	30
Butane	118	26
Ethylene oxide [Oxirane]	9	19
Hydrogen sulfide	63	19
Formaldehyde (solution)	1	17
Isobutane [Propane, 2-methyl]	107	17
Pentane	125	17
Titanium tetrachloride [Titanium chloride (TiCl ₄) (T-4)-]	51	15
Phosgene [Carbonic dichloride]	10	12
Nitric acid (conc 80% or greater)	58	12
Ethane	94	12
Oleum (Fuming Sulfuric acid)	69	11
Ethylene [Ethene]	95	11
Vinyl chloride [Ethene, chloro-]	101	11
Trichlorosilane [Silane, trichloro-]	153	11
Methyl chloride [Methane, chloro-]	5	10
Toluene diisocyanate (unspecified isomer)	77	10
Propylene [1-Propene]	129	10

**Table 2: Consequences Resulting from Accidents
During Reporting Period (All 14,500 Reporting Facilities)**

	Mean or Total	Std Dev'tion	Min	Max	Number of Observations
On-Site Injuries to Workers/Contractors					
Total On-Site Injuries	1,897				1,912
Injuries per Accident	.9922	2.810	0	67	1,912
Injuries per FTE per Acc.	.0202	.0784	0	1	1,896
On-Site Deaths to Workers/Contractors					
Total On-Site Deaths	33				1,911
Deaths per Accident	.0173	.2224	0	6	1,911
Deaths per FTE per Acc.	.0003	.0071	0	0.25	1,895
On-Site Property Damage (\$ Millions)					
Total On-Site Damage	\$1,006				1,907
Damage per Accident	\$0.528	\$6.716	\$0	\$219	1,907
Off-Site Property Damage (\$ Millions)					
Total Off-Site Damage	\$11				1,907
Damage per Accident	\$0.006	\$0.109	\$0	\$3.8	1,907
Number of Accidents with Effects on the Eco- System					
Fish or Animal Kills	17				1,913
Minor Defoliation	54				1,913
Water Contamination	24				1,913
Soil Contamination	31				1,913
Any Environmental Damage	101				1,913

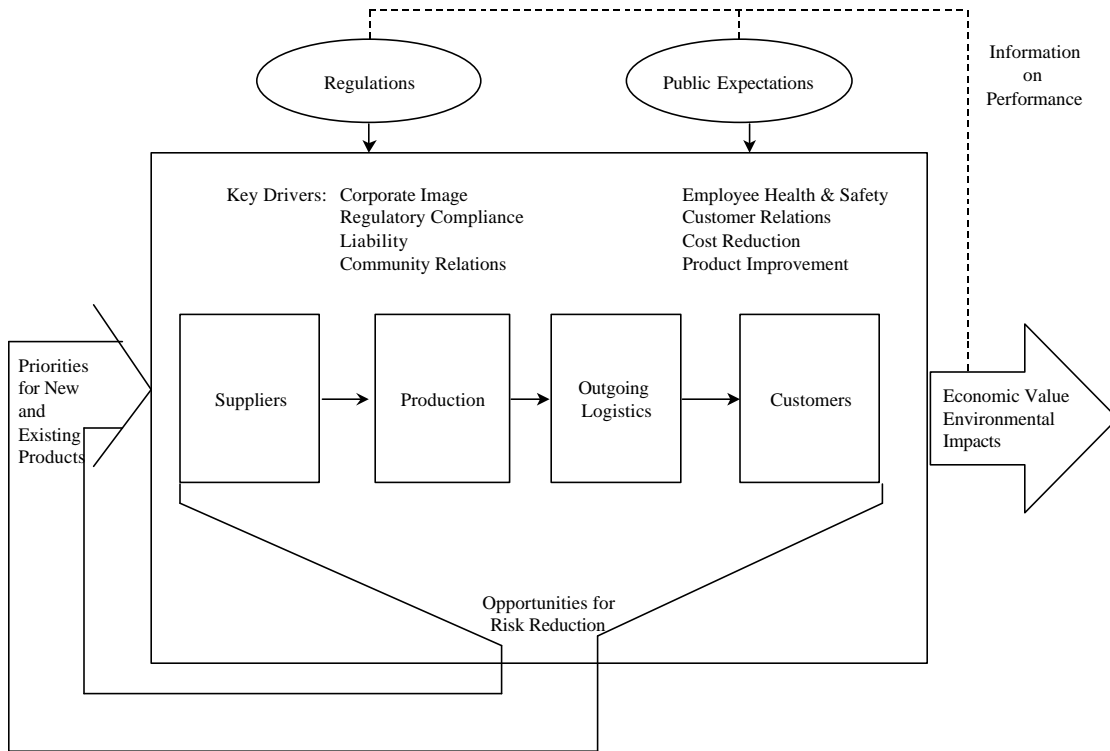


Figure 1: Risk Analysis and the Extended Supply Chain