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Operations Risk Management: Overview of Paul Kleindorfer's Contributions

Morris A. Cohen • Howard Kunreuther
Operations and Information Management Department, Wharton School, University of Pennsylvania, 3730 Walnut St., Philadelphia, PA 19104-6340, Phone: 215 898-6431 FAX: 215 898-3664, E-Mail: Cohen@wharton.upenn.edu,
Operations and Information Management Department, Wharton School University of Pennsylvania, 3730 Walnut St., Philadelphia, PA 19104-6340, Phone: 215 898-4589, FAX: 215 573-2130, E-Mail: Kunreuther@wharton.upenn.edu

This paper reviews Paul Kleindorfer's contributions to Operations Management (OM), with a special focus on his research on risk management. An annotated bibliography of selected other contributions reviews the breadth of topics that have occupied Kleindorfer's research attention over his now 45+ years of research. These include optimal control theory, scheduling theory, decision sciences, investment planning and peak load pricing, plus a number of important applications in network industries and insurance. In the area of operations risk management, we review recent work that Kleindorfer and his colleagues in the Wharton Risk Center have undertaken on environmental management and operations, focusing on process safety and environmental risks in the chemical industry. This work is directly related to Kleindorfer's work in the broader area of "sustainable operations", which he, Kal Singhal and Luk Van Wassenhove recently surveyed as part of the new initiative at POMS to encompass sustainable management practices within the POMS community. Continuing in the area of supply chain risks, the paper reviews Kleindorfer's contributions to the development of an integrated framework for contracting and risk hedging for supply management. The emphasis on alignment of pricing, performance and risk management in this framework is presaged in the work undertaken by Kleindorfer and his co-authors in the 1980s on after-sales support services for high-technology products. This work on supply chain risk, and its successors, is reviewed here in light of its growing importance in managing the unbundled and global supply chains characteristic of the new economy.

Key words: Paul Kleindorfer; risk management; environmental management; after sales service support; supply chain risk management

1. Introduction

Paul Kleindorfer is one of the leading researchers in the Operations Management field. In the course of his career, which has spanned over 45 years, Kleindorfer has made a number of notable contributions that include the application of optimal control theory to production problems, analysis of environmental strategy, risk assessment and risk management, development of energy pricing policies and the management of postal services. In this paper we will pay tribute to Kleindorfer's contribution to the field by focusing on the challenges of managing risk in operational settings. We will do so by exploring two important concentrations of his research, i.e.:

a) Linking Risk Assessment with Risk Management for Low-Probability High-Consequence Events

b) Risk Management in the Supply Chain

We will highlight Kleindorfer's major contributions in these two areas and supplement this with a more complete bibliography in the Appendix of the full range of Kleindorfer's research contributions.

2. Linking Risk Assessment with Risk Management for Low-Probability High- Consequence Events

One of Kleindorfer's significant contributions to the risk management area has been to help link risk assessment with risk management for dealing with low probability high consequence (lp-hc) events, especially in linking Operations Management with Environmental Management. This is evident in three special issues on operations and environmental management for POMS (co-edited with Charles Corbett in 2001 and 2003) and in his recent survey with Kalyan Singhal and Luk Van Wassenhove of the emerging research area of "sustainable operations". Kleindorfer often wears two caps—-one is the system cap, which involves developing a framework for analyzing a set of problems which we label the *macro* view of the world.[1] The other parts of Kleindorfer's research activities are filling in the details required to develop meaningful strategies—the *micro view* of the world. The integration of these two views is perhaps best captured by Figure 1 taken from Corbett and Kleindorfer (2001).

The integration of the micro aspects of operations and the macro aspects of strategy and regulatory compliance are apparent in this figure. The macro aspects represent regulatory and market impacts on the company and the micro aspects represent the supply chain and operations strategies undertaken to respond to regulatory and market pressures. While there are several strands of Kleindorfer's work relevant to this matter (see the annotated bibliography at the end of this paper for details), we will focus on his most recent research on the problem of managing environmental, health and safety risks in the chemical industry. This work involved an interdisciplinary team of researchers, working in close cooperation with the U.S. Environmental Protection Agency. It was undertaken at the Wharton Risk Management and Decision Processes Center, where Kleindorfer served as co-director. The problem studied represents a wide class of lp-hc events that pose challenges for society today. Due to the uncertainties and ambiguities associated with these hazards, as well as the many interdependencies that exist in the system, there is a need for public-private partnerships to reduce future losses and a need to link operations management with both company strategies and external regulatory controls.

The next subsection proposes a conceptual framework that provides a macro view for examining chemical accidents. We then take a more micro perspective by looking at different pieces of the puzzle and examine the interdependent nature of risks, their impacts on managerial choices and strategies for managing these risks.

Macro View: Conceptual Framework

Figure 2 depicts a conceptual framework that highlights the importance of linking risk assessment and risk perception with the development of risk management strategies. *Risk assessment* means evaluating the likelihoods and consequences of prospective risks, either by the use of frequency data or on the basis of expert judgments, scenarios and subjective probabilities.[2] Risk assessment needs to be supplemented by vulnerability analyses that characterize the forms of physical, social, political, economic, cultural, and psychological harms to which individuals and modern societies are susceptible. As one moves from events where considerable historical and scientific data exist (e.g. chemical accidents, natural disasters) to those where there is greater uncertainty and ambiguity (e.g. terrorism, climate change), there is a much greater degree of discomfort in undertaking risk assessments. Constructing scenarios that may lead to the occurrence of specific events is a useful first step to take in assessing these risks. The challenge is to characterize and estimate the probabilities and resulting consequences.

In highly interdependent systems that are characteristic of modern industrial societies, failures can propagate rapidly through the system in ways that are not always obvious before a negative event occurs. For example, the consequences of a chemical accident in one plant can have impacts on other parts of the firm as well as radiate to other parts of the economy in areas quite distant from the actual disaster itself. For example, the huge explosion at the AZF (Azote de France) fertilizer factory on the outskirts of Toulouse in September 2001 had impacts on the surrounding area where 31 people were killed and over 2,400 injured. It also created problems for firms that relied on AZF to supply them with fertilizer.[3] The explosion of a Union Carbide chemical in Bhopal had a significant impact on the entire industry by leading firms to reevaluate the risk associated with chemicals that had a potential for causing catastrophic losses.[4]

Risk Perception is concerned with the psychological and emotional aspects of risks, which have been shown to have an enormous impact on individual and group behavior. While traditional risk assessment focuses on objective evaluation of risks or expert evaluation in the absence of historical data, there is a growing body of evidence that one's choices are not simply based on the likelihood and consequences of different events, as normative models of decision-making suggest. Individuals are also influenced in their choices by emotional factors such as fear, worry and love [Loewenstein et al. (2001); Slovic et al. (2002)].

[1] See Kleindorfer (2001) for a discussion of the challenges of making decisions in complex environments.

[2] See Haimes (1998) for a comprehensive summary of the risk assessment area.

[3] Details on this accident can be found at *http://www.uneptie.org/pc/apell/disasters/toulouse/home.html*.

[4] For a more detailed analysis of chemical accidents and their consequences see Rosenthal et al. (2004).

Studies by psychologists [Slovic (2000); Fischhoff et al. (2003)] have shown that hazards, which are least known, uncontrollable, have catastrophic potential and are highly dreaded, are perceived by the public as being the most risky. They are the ones most likely to attract media and public attention. Scientists, on the other hand, normally determine the risk of a hazard by weighing possible outcomes by their likelihood of occurrence. Therefore, laypeople and the experts from the scientific community are likely to see and react to risks quite differently. For technological risks there is likely to be a wide disparity between the general citizens' and the experts' views of the risk, and these need to be taken into account in developing risk management strategies.

Risk perception has important implications for the effectiveness of alternative policies, most of which are intended to alter aspects of individual and corporate behavior. For example, systematic misperception of risks affects the decisions by chemical facilities to invest in risk-reduction measures with respect to the plant's operations. More specifically, if there is a tendency to underestimate the likelihood of chemical accidents occurring, then plant managers may not want to incur the costs associated with specific mitigation measures.

Risk Management involves developing strategies for reducing the probabilities of negative events and/or their consequences should they occur. It therefore involves the full gamut of actions from preventing accidents from occurring, to reducing damage in the event of an accident, to providing funds for recovery.

Risk management strategies normally involve both the public and private sectors. Possible policy tools include risk communication strategies, economic incentives (e.g. subsidies and fines), insurance, third party inspections and audits, well-enforced regulations and standards and legal liability. In a highly interdependent system where underinvestment in protection by individual facilities is likely to occur, an important aspect of risk-management is providing incentives to assure more appropriate levels of investment. In cases where firms do not invest in cost-effective mitigation measures voluntarily, then it may be necessary to utilize regulations and/or standards that are well-enforced so that firms now see the wisdom of undertaking these actions.

The *Evaluation of Strategies,* the set of priorities for products and processes in Figure 1 and the bottom box in Figure 2, requires a definition of individual welfare and a specification of an aggregation process over people and time. The two criteria that are normally used to evaluate alternative policies are *efficiency* and *equity*. A policy is considered efficient relative to the status quo if the well being of society is improved through its adoption. The implementation of such a program may leave some individuals, groups or organizations worse off than under the status quo. These equity concerns of interested parties have become in-

Figure 1 Environmental Management and the Extended Supply Chain.

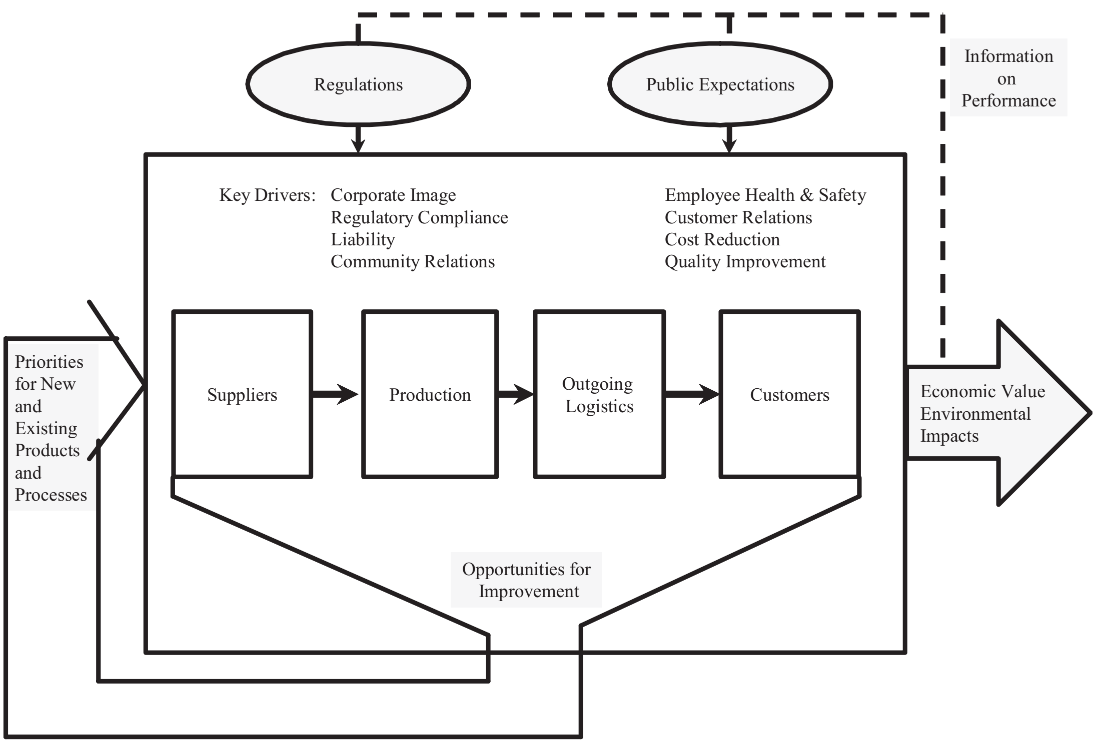
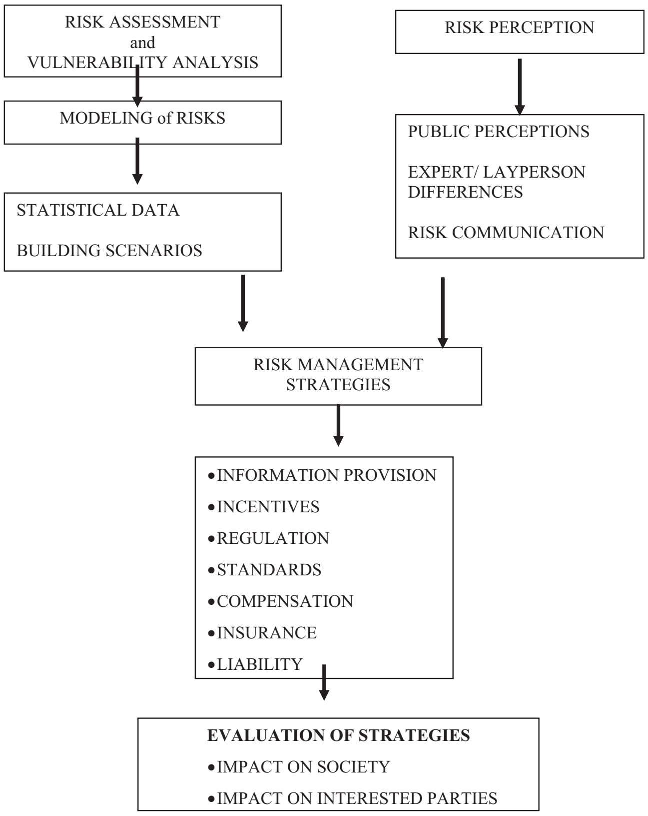


Figure 2 Conceptual Framework for Risk Analysis.



creasingly important in designing risk management programs that have a chance of being implemented.[5]

Micro View: Issues of Interdependency

A key element that needs to be considered in linking risk assessment, risk perception and risk management are issues of interdependency. Do organizations and their managers invest in security to a degree that is adequate from either a private or social perspective? More specifically, do facilities in a chemical firm have the appropriate economic incentives to undertake risk reducing measures voluntarily that improve their own operations as well as that of the entire organization? Due to issues of interdependency coupled with risk assessment and risk perception problems, the answer to this question is often "No".[6] This section explores the contributions of Kleindorfer's work on risk management in the chemical industry to map out this problem and propose risk management strategies for dealing with it.

In their path breaking studies on chemical accidents using the RMP*Info database (RMP is an abbreviation for "Risk Management Plan") provided by the Environmental Protection Agency (EPA), Kleindorfer and his colleagues provide insights into the nature of the risks associated with accidents from various chemical plants. As detailed in their recent papers [Kleindorfer et al. (2003); Elliott et al. (2003), Kleindorfer et al. (2004)], they used data collected by the U.S. EPA in 1999–2000 on more than 15,000 facilities in the United States that store or use toxic or flammable chemicals. The resulting RMP database contains the following information:

- The characteristics of the facility itself, including facility location, size and the type of hazard present (as characterized by the chemicals and process used and other facility-specific characteristics)
- The nature of regulations in force that are applicable to this facility and the nature of enforcement activities
- The complete 5-year accident history for each chemical facility reporting under the RMP Rule.

These data are key inputs to assessing the risk of chemical accidents and understanding their direct impacts in the form of damage to the plant and the surrounding area as well as the indirect impacts in the form of business interruption losses to the firm and other parts of the economy.

To illustrate the power of the analysis developed in the RMP research, consider the conceptual model for predictors of frequency and severity of chemical accidents shown in Figure 3. Let us just note a few of the findings from the extensive research of Kleindorfer and his colleagues that examined the several relationships apparent in this figure.

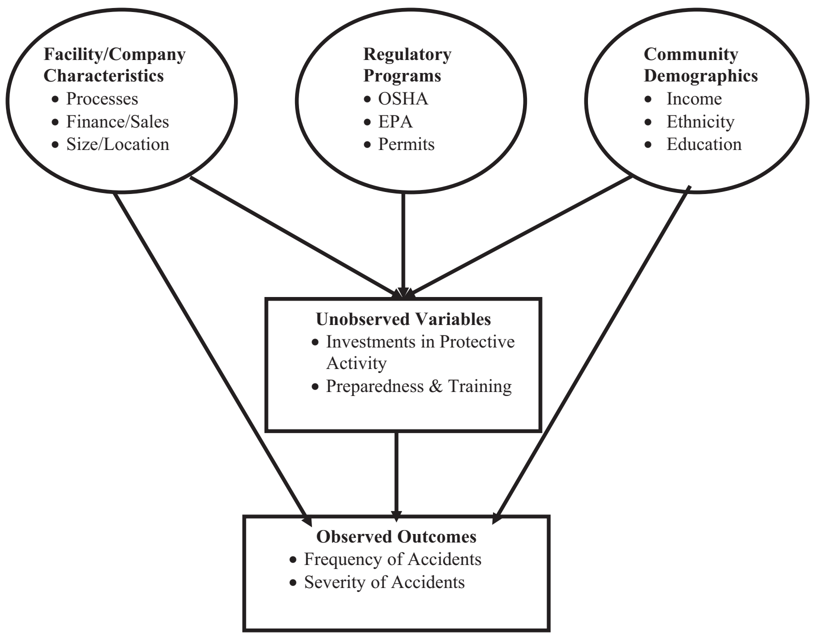
Facility Characteristics and Regulatory Impacts

The first hypothesis one might examine, motivated by Figure 3, is the extent to which facility characteristics (including the hazardousness of its processes) and regulatory programs are associated with a facility's accident history. Elliott et al. (2003) examined the interaction between accident rates and the following variables: geographic region; size of facility; and chemicals used at facility. The information contained in the RMP*Info database includes details about onsite chemicals and processes; regulatory program coverage; geographic location; and number of full-time employees (FTE). Regulated substances were grouped into hazard levels, with thresholds set to values of 500, 1,000, 2,500, 5,000, 10,000, 15,000, and 20,000 pounds. (Threshold levels are inversely proportional to the per-weight hazardousness of the chemical.) The quantity and nature of chemicals used at each facility were then summarized for statistical analyses by a single "total hazard measure," defined roughly as a measure

[5] For more details on the criteria for evaluating alternative risk management programs see Kleindorfer, Kunreuther and Schoemaker (1993).

[6] An extended discussion of interdependency for various categories of risk is provided in Kunreuther and Heal (2005).

Figure 3 **Framework of Analysis for RMP Research on Chemical Accidents.**



of the hazard of the chemicals on site and the number of covered processes at the facility.[7]

The results of Elliott et al. (2003) on facility characteristics and regulatory factors provided the first national statistical analysis of how regulation and facility characteristics were associated with size of facility and with the inherent hazards of the chemicals at the facility. As one example, Elliott et al. found that toxic chemicals were more strongly associated with worker injury, whereas flammables were more strongly associated with property damage, which makes sense because fire is obviously capable of causing a much greater degree of damage to property than release of acids or poisonous gases, which are either more contained or less damaging to property. The statistical details of risks to workers, to property and to businesses provided by these findings are of great interest to insurers, managers and regulators.

Association of Capital Structure and Sales on Accident Rates

With an eye on Figure 3, a further question of interest is the influence of capital structure and financial variables, such as total sales, on the incentives that companies might perceive to take protective action against major accidents and, thereby, to influence the accident and injury rates observed in RMP. This analysis was reported in Kleindorfer et al. (2004). Their analysis was restricted to the 2,023 facilities owned by 306 parent companies for which complete financial parent company data from 1994–2000 was publicly available. The accident-related information in the RMP database includes date and time of accident; number of associated injuries or deaths among workers, public responders, and the public at large; and other consequences such as property damage (on-site, offsite), evacuations, confinement indoors of nearby residents, and environmental damage. This could therefore be readily associated with parent company characteristics to see if the latter had any statistically significant association with accident rates at facilities they owned.

Kleindorfer et al. consider four main predictor variables of parent company financial structure and performance: previous year debt/equity (D/E) ratio, total (net) sales, return on assets (ROA), and return on equity (ROE). To account for the fact that more "intrinsically" hazardous processes tend to involve capital-intensive infrastructure that might confound relationships between attention to safety and financial performance, two control variables were used as proxies for facility hazardousness: number of full-time-equivalent employees (FTEs), and a "total hazard" measure (as defined above).

What Kleindorfer et al. found on the effects of financial variables is that companies with larger debt burdens are likely to be more accident prone, and

[7] More precisely, the "total hazard" measure used by Elliott et al. was defined as the sum over all chemicals of $\log_2$(maximum quantity of inventory on site/threshold), or, alternatively, as the number of chemicals times $\log_2$ of the geometric mean of the maximum-to-threshold quantity ratio. Hence a total hazard measure of 0 indicates that only threshold levels of chemicals are kept in inventory, a measure of 1 means 1 chemical is kept at up to twice threshold level, 2 means 2 chemicals kept at up to twice threshold level or 1 chemical at up to 4 times threshold level, and so forth; unit changes in this measure can thus be interpreted as either an doubling of volume inventoried of a single chemical or an addition of another twice-threshold chemical on-site.

companies with larger sales less so. These findings are consistent with intuition. First, companies that are more debt-ridden are likely to be less concerned with long-term cash flows, as most of the risk is borne by creditors who are not represented in the company's decision making about risk mitigating investments. Similarly, companies with large sales have a great deal at risk from disruptive accidents and this leads to greater care and lower accident and injury rates. The RMP results are therefore consistent with normal economic expectations. However, it must be noted that many "folk tales" in the industry ran counter to this prior to this research—for example, many believed that smaller firms were the most critical part of the overall risk to health and property from the U.S. chemical industry. The results from this research make plain that a considerably more detailed explanation is required in which all of the interdependent features of Figure 3 have a role to play in predicting frequency and severity of accidents, and the appropriate focus therefore of regulatory oversight.

Community and Demographic Effects

Finally, let us briefly note the findings of Elliott et al. (2004) on the statistical association between characteristics of the communities in which facilities are located and the frequency and severity of accidents of these facilities. This topic is generally addressed under the heading of "environmental justice". An extensive body of research in political economics, public policy, and public health has noted associations between environmental and health risks arising from industrial facilities and the socio-economic status (SES) of host communities. These associations could be caused by firms' preferring to locate hazardous facilities in lower-SES communities in which they anticipate lower levels of collective action and monitoring. These could also result from migration of groups of lower SES to sites where such facilities have located, since property values may be lower there.

Using the RMP data for 1999–2000 filings together with the 1990 census data, Elliott et al. (2004) looked for two potential impacts of community characteristics that reflect two essential sources of risk to surrounding populations: (1) risks associated with the decision about where to locate hazardous facilities, which we term "location risk"; and (2) risks associated with the methods of operation and standards of care that are used in existing facilities, which they term "operations risk." Their analysis proceeds by first considering the association between community characteristics and "location risk" – the risk of an intrinsically hazardous facility, as reflected by the quantity of chemicals stored there and their potential for harm, being located in a community. The enumeration unit for the demographic studies is the county in which the facility is located. To measure "location risk," Elliott et al. analyzed whether there is a statistical association between the hazardousness of a facility and the characteristics of the surrounding county. A significant statistical relationship was found, indicating that more hazardous facilities tend to be located in counties with particular demographic characteristics, including larger income disparity.

The research team then considered "operations risk," which is the risk at a facility of an accident and resulting bad outcomes, including injuries and property damage. Two questions can be asked about operations risk: (1) whether the demographics of the communities surrounding facilities are associated with risk of an accident/injury; and (2) whether these community demographics are associated with accident/injury risk *after adjusting for location risk*. The test for the effects of demographics on operations risk is simple. Elliott et al. analyzed whether there was a statistical association between facility accident and injury rates and the demographics of the surrounding county, while controlling for the size of the facility and inherent hazardousness of it (see above for their definition of hazardousness). If it were hazardousness or size of the facility alone that determined accident/injury rates, and demographics were not a factor, then there would be no additional explanatory power associated with the inclusion of county demographics. However, if such demographic factors are themselves statistically significant, in addition to facility factors, this would support the hypothesis that operations risk is associated with demographic factors. In particular, they addressed the issue of whether facilities in low-Socio-Economic Status (SES) and/or higher proportions of African-American population may exhibit higher accident rates than average, even if they have the same amount of hazardous chemicals on site.

The findings of Elliott et al. (2004) regarding the relationship between accident propensity and community characteristics may be summarized as follows. The RMP data is consistent with a finding that heavily African-American counties experience greater location risk and greater operations risk than the average for the country. Greater location risk here means greater inventories and more hazardous chemicals in use at facilities in these counties. Greater operations risk means that facilities in these counties had greater risks of an accidental chemical release, and of having injuries associated with the chemical release. The operations risk for the most heavily African-American counties persists even after accounting for location risk. These results by Kleindorfer and his colleagues were the first to control for both operations risk and location risk and they provide important new insights on these risks for both company managers and regulators.

Summary
The research of Kleindorfer and his colleagues at the Wharton Risk Center continues on the data provided by the RMP Rule as the second set of data on the five-year anniversary of the first filing, namely in 2004–2005, is now being studied. The studies undertaken thus far suggest a complex set of interactions determining facility performance in terms of accident frequency and severity, as is shown in Figure 3. The results obtained from the RMP and accident history data are rich in findings. First and foremost, they provide the most complete benchmark statistics to date on deaths, injuries and direct property damage at U.S. chemical facilities resulting from process accidents and accidental releases. They underline the expected interactions between regulatory oversight and level of hazard at facility. However, contrary to popular theorizing, it is not the small facilities per se that are the primary sources of accidents. Rather, it is the interaction of the underlying hazard at the facility with size, capital structure and sales of parent companies and location that provides the explanatory power for accident and injury rates. In many ways, these results will appear intuitive to the environmental, health and safety (EH&S) policy and management community, but it is important to note that this is the first time in the history of the U.S. Chemical Industry that we have had the data to back up our intuition and to provide benchmark results for regulators, the insurance industry and the chemical industry as they attempt to assess the magnitude of the risks arising from chemical facilities.

A question that might be posed relative to the above work of Kleindorfer on environmental risk in the chemical sector, and his other work on lp-hc events, might be: where does this fit into Operations Management? With his co-authors, Singhal and Van Wassenhove, Kleindorfer has given a partial answer in Kleindorfer et al. (2005) in defining "Sustainable OM as *the set of skills and concepts that allow a company to structure and manage its business processes to obtain competitive returns on its capital assets without sacrificing the legitimate needs of internal and external stakeholders and with due regard for the impact of its operations on the environment*." Kleindorfer et al. argue that OM has a crucial role to play in making lp-hc risks explicit and tangible, understanding action-outcome links and providing line of sight between them through performance management (i.e. the industrial and methods engineering heritage of OM). They argue further that, in the spirt of Triple A supply chains (Lee, 2004), sustainable operations are about helping firms to become Agile, Adaptive and Aligned when it comes to balancing the People and Planet part of the now well-known 3P equation with Profits. The work reviewed here on environmental, health and safety risks is very much in this spirit of providing the basis for better profitability for companies that understand and manage their risks properly, while also reinforcing the commitment of the OM profession to promote responsible operations that respect all of the 3Ps (Profits, People and Planet) as we go on about our economic activities.

3. Risk Management in the Supply Chain

Kleindorfer's work on risk management strategies facing a company where there are interdependencies naturally led him to undertake research on supply chains. The fundamental purpose of a supply chain is to match supply with demand. In a world where the factors that drive both supply and demand are highly uncertain, it is recognized that the management of risk is of fundamental importance. Indeed supply chains provide a primary mechanism for the mitigation of risk. The goal of all supply chain management policies is to achieve global efficiency, i.e. meet customer demands at the lowest total cost and with the highest level of quality. Supply chain management attempts to meet this goal through a variety of resource management decisions that affect the design of the supply chain facility network, policies for the control of resource flows, and the scheduling and allocation of capacity. The impact of these decisions will depend, to a large degree, on how effective they are in realizing the benefits of risk pooling as well as those of scale economies and inter-organizational learning.

Supply chains also provide an important coordinating function that accounts for the fact that the decisions noted above are typically made by different players, corresponding to the owners of different subsets of the extended supply chain (e.g. producers, material suppliers, distributors, end customers, support providers). The goal of supply chain coordination is to ensure that the decisions made by the various sub-system players lead to minimum overall cost and maximum quality/service performance for the extended supply chain. Such coordination requires both optimization of specific risk-reward tradeoffs associated with each player's environment as well appropriate design of the customer-supplier relationships that link each player in the supply chain. These relationships are defined by factors that include processes for information sharing, the allocation of decision rights, the setting of appropriate incentives that include contracting and through appropriate utilization of market mechanisms.

Kleindorfer's research has provided important examples of how model based theory can be used to address these challenges. As we shall see, his research captures the interaction of resource allocation decisions across complex hierarchies that span time, space and product definition dimensions. It also specifically deals with the impact of de-centralized decision making and markets. In this section we will focus on how Kleindorfer's research has contributed to the area of supply chain risk management through the adoption of a real options perspective. Figure 4 illustrates how the various components of supply chain optimization and coordination are linked together through a real option framework.

In Figure 4 we note three factors that define the context of the supply chain risk management problem, i.e. hierarchies, incentives and markets. The first factor, *Hierarchies*, refers to the relationships that define a supply chain in terms of product structure, geography and customer priorities. The geography hierarchy specifies the locations where resources are deployed to meet customer demands, and the demand supply connections between these locations. The product hierarchy is based on the connections among a product's component parts as defined by its design and associated bill of material. The product hierarchy determines the parent-child linkages between the end product and the major sub-assemblies, raw materials and piece parts. The third hierarchy is based on customer classifications which recognize that each market segment has unique service requirements for speed, accuracy, etc. along with a willingness to pay for differentiated performance.

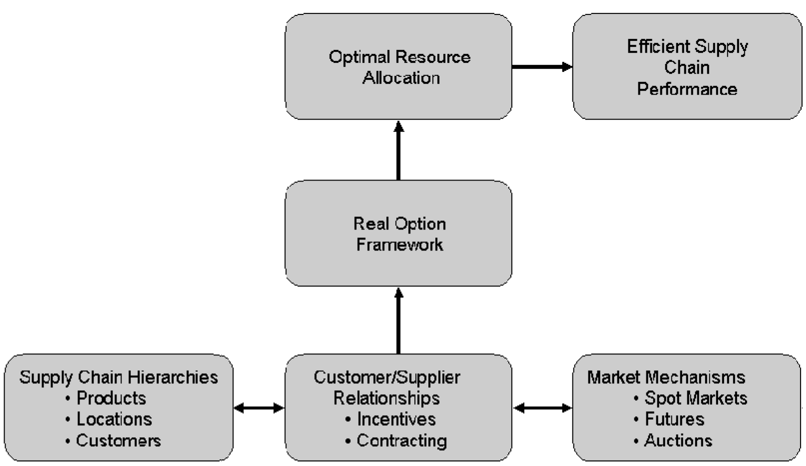
The second major factor deals with Customer/Supplier Relationships and captures the fact that most supply chains are not owned and operated by a single entity, but rather operate with multiple owners and decision makers. The relationship between these actors determines the incentive/reward structure associated with material procurement and service support. In many cases these incentives are embodied in formal contracts that explicitly deal with contingencies and risk mitigation. Examples of contract mechanisms that are used in supply chains include consignment, revenue sharing, material buy-backs and performance based logistics. The long term interaction between customers and suppliers is also relevant. In many cases, however, such long term relationships are not determined solely by contracts, but rather are also influenced by factors such as trust and reputation. As we shall see, Kleindorfer has contributed to the body of research that models the gaming behavior that is induced by supply chain customer/supplier relationships.

The third input factor to the real option framework deals with the role of *Market Mechanisms*. Supply chain risk can be mitigated by using an appropriate mix of sourcing and purchasing strategies, including spot and long term contracts. Recently other market mechanisms such as auctions, collaborative forecasting and trading groups have appeared as a part of e-commerce.

These three factors are inputs to the real option framework which is characterized by a two-stage decision process that deals with uncertain contingencies. In the first stage the firm acquires ownership of assets and capabilities that can be used to meet future customer demands. These assets could include plant capacity, production technology, inventory of parts, work force skills, etc. The assets are deployed or used in the second period ("in the day"), upon realization of the random contingency outcomes, e.g. prices, demand levels, supply availability, etc. Optimal use of the acquired assets in response to the contingency realizations corresponds to exercising the real option.

The outputs of applying the real option framework include a nested set of resource allocation and control decisions that define the firm's supply chain management policy. The extent to which this policy acts to mitigate risk in a manner that maximizes value is determined by the nature of the real option and its

Figure 4 Supply Chain Risk Management Framework.



associated resource deployment decisions.[8] The flexibility of an option that allows for decisions to be made in reaction to random contingencies can lead to an increase in the expected value and a reduction in the variability of supply chain performance. Such performance can be measured by the overall value produced by supply chain as well as by total cost and overall quality. The goal of supply chain management is to achieve a level of performance that is equal to the performance associated with first best, efficient (centralized control) solution.

We will limit our discussion of supply chain risk management to two particular sub-areas of Kleindorfer's research that deal with electronic markets and service support systems. Specifically we will review his research in the areas of:

- contracting and bidding for procurement of capital intensive goods in electronic markets, and,
- spare parts inventory management for after-sales service delivery

In our discussion of these research problems we will consider the following questions:

- What is the nature of the problem?
- How has Kleindorfer contributed to these questions in his research?
- What lessons can we learn?

In our discussion we will refer the reader to a selective set of papers that provide the details. As we shall see, in many cases, Kleindorfer's research was path-breaking and has led to extensive follow-on research as well as successful managerial applications.

Contracting and Bidding for the Procurement of Capital Intensive Goods in Electronic Markets

This research is based on an inquiry on the use of real options to coordinate supply and demand in certain industries, including those strongly affected by e-commerce and the new trading platforms that have emerged there. This work was joint with Stefan Spinler, Arnd Huchzermeier, Moti Levi and most importantly Dongjun Wu. The basic problem of interest here is one faced by procurement managers concerning the use of long term (forward) contracts vs. spot purchases. In this environment, where both demand and prices are uncertain, forward long term contracts may be of interest when there is significant price volatility or if industry capacity is limited. In a series of papers, Kleindorfer and his co-authors ask the following questions:

- Why should contracts/forwards be used?
- How should they be used optimally?
- What impact will their use have on performance and structure of the supply chain?
- How has the introduction of electronic markets affected their use and impact?

The motivation for this research is based on the fact that electronic markets have changed the way procurement managers match the supply of capacity for material inputs with demand. Integration of spot and contract markets, in particular, is key since it is now possible to access spot markets on a real time basis. The fundamental risk management problem remains however, i.e. how should contract duration and design be selected to balance the risk reduction value of a forward contract against the contingency that a spot purchase may be more profitable. There are numerous examples of this problem in industries that include agriculture, beverages, chemicals, electronics, energy trading, ocean cargo, and semiconductors.

Kleindorfer and his colleagues formulated the problem as one of supplier capacity sourcing where both contract and spot markets are available to a single (or multiple) buyer(s) with a choice set of multiple sellers with diverse technologies. The analysis has implications for the emerging structure of the electronic marketplace that include technology choice for the seller and contract vs. spot market allocations by the buyer. The modeling approach is summarized in a review paper by D. J. Wu (2005), written in honor of Kleindorfer's retirement from the Wharton School, and also in the Wu and Kleindorfer (2005) *Management Science* paper. The approach introduces a model framework that includes heterogeneous seller technologies and multi period timing. The model uses game theory (Bertrand-Nash) to develop results that include determination of the sellers' bidding strategy, the buyer's contracting strategy and characteristics of the resulting competitive equilibrium. A number of related papers that build on this framework were written by Kleindorfer and his colleagues, including Wu et al. (2002), Kleindorfer and Wu (2003), Spinler et al. (2003) and Wu et al. (2005).

The contribution of Kleindorfer's research in this area includes a characterization of how procurement strategies should respond to spot and option contract opportunities. They show in particular that a "Greedy Contracting" rule should be used for the case of substitutable capacity, to rank order seller bids, based on an index determined by seller prices and capacities. The sellers' bids on the other hand make all capacity available and are symmetric across all sellers (one price). The resulting equilibrium is also efficient in the sense that it maximizes the total surplus for the buyer and the sellers. The analysis is extended to show how suppliers allocate their bids across spot and forward markets. The research illustrates how an option modeling framework can be used to analyze electronic

[8] For example, optimal pre-positioning of spare parts in a semiconductor fab facility help to minimize down time due to unscheduled process equipment failures.

market procurement. It also illustrates how supply chain coordination can be achieved in an environment with supplier competition to yield the overall first-best optimal solution for all of the players.

After-Sales Service Supply Chains

The second research area that we consider in this section focuses on the after sales service supply chain. Kleindorfer was an early contributor to a major stream of research that concerns spare parts planning for after sales product support. This research, which builds on the classical theory of multi-echelon logistic systems, was motivated by a multi-year cooperative effort, funded in part by NSF, and the IBM Corporation.

The model paradigm developed by Kleindorfer in collaboration with Morris Cohen, Hau Lee, Dave Pyke and others, is based on the notion that the value created by customers through ownership and use of complex products is enabled by a set of resources that comprise the service supply chain, e.g. spare parts inventory, repair capacity, logistics network facilities, transportation system, information technology, etc. The role of these resources is to provide maintenance, repair and overall support to the customer in the event that the product fails or otherwise requires service. Since the timing, location and severity of such service resource demands is highly intermittent and difficult to forecast, the concepts of supply chain risk management become especially relevant in this context.

The motivation for this research includes the fact that service support is a major source of revenue, profit and competitive advantage in many industries. The resources that are required to deliver such support, however, are typically highly under utilized and often are allocated in an inefficient manner, [see Cohen et al. (2006a)]. This follows because of the high level of complexity and uncertainty associated with this problem. Typically there are tens or even hundreds of thousands of parts that need to be stocked in multiple stocking locations that support an installed base of customers. The underlying network is characterized by multiple echelons or levels that are designed to provide timely support by positioning resources close to where they are needed.

Given the intermittent and random nature of demand for support resources, the extended lead times for repair and procurement and the heterogeneity of customer service requirements, a solution to the resource deployment problem must be made in a manner that exploits risk pooling and scale economies. The challenges that faced leading companies at the time that Kleindorfer and his colleagues addressed this problem were exacerbated by the phenomenon that customers were demanding higher levels of service quality and lower costs in order to maximize the value of product acquisition through extended and efficient use. In addition, major technology changes were taking place. These included a shift to more modular product designs that led to lower costs for service and maintenance but higher costs to replace more expensive parts. Modularity also led to a decrease in product life cycles, resulting in more product variety which in turn increased the proliferation of parts needed to support the expanding installed base of end products. Finally better designs and improved technology led to increasing product reliability that made demand forecasting even more difficult.

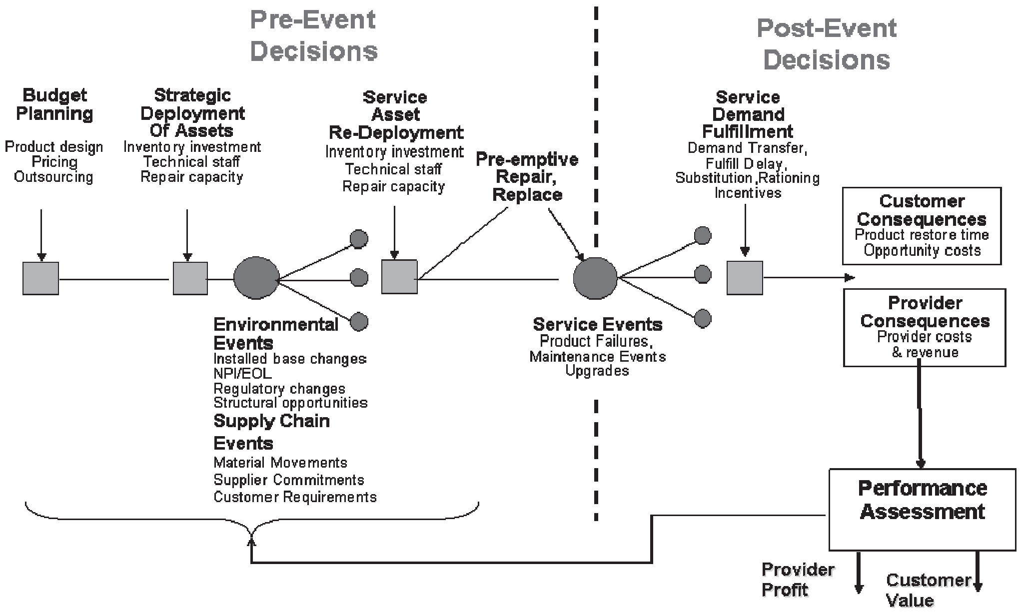
A stochastic optimization model framework introduced by Kleindorfer and his colleagues, [see Cohen et al. (1986)], was designed to address these issues and to consider a set of key questions that were especially important when the product is mission critical, i.e. when product downtime can lead to very expensive or even catastrophic losses. Industries that fit this scenario include aerospace and defense, semiconductor manufacturing, telecommunications and medical equipment. The questions they analyzed in a series of related papers included:

- How can resources (e.g. spare parts), be managed (positioned in advance of need) to maximize customer value by maximizing product up time with the lowest cost investment in resources?
- How can customers and suppliers (service providers) coordinate, to generate maximum service value at the lowest cost, thereby reducing the ultimate cost of ownership?
- How can model based optimization algorithms and decision support systems connected to real time transaction based data be used to solve this problem?

The real option perspective is appropriate here because the decisions made prior to the random occurrence of a service event require investment and deployment of expensive resources. This investment is analogous to purchasing the option. The exercise of the option is associated with utilizing the deployed resources, in real time to meet the service needs. Thus the random contingencies of product failure and maintenance resource requirements lead to the exercise of that option. Figure 5 illustrates how the real option framework applies to the service parts management context.

The early research by Kleindorfer and others was motivated by a project with IBM's field service function which was responsible for the support of an extensive installed base of computers, peripherals and associated IT hardware. At the time that this project was initiated (early 1980's) IBM was facing a crisis. Their investment in service parts inventory, which was used to enable rapid repair and maintenance of their installed base of mission critical equipment, was

Figure 5 Service Supply Chain Management as a Real Option.



rising at a rate that exceeded the growth rate in sales. At the same time, customer service, which was measured by part fill rate and which was always at a high level, was not increasing. As a result, IBM was investing more and more in parts inventory without realizing any discernable benefit to either the customer or to the company. Senior management at IBM felt that the situation was a symptom that the overall service parts supply chain was not under effective control and that, in particular, resource deployment decisions were not optimized.

In Cohen et al. (1990), the resulting project and successful implementation are described in detail. The result of the implementation included a 25% reduction in IBM's billion dollar spare parts inventory investment that was coupled with a 10% reduction in annual operating costs and an improvement in customer service (fill rate) levels. The papers by Cohen, et al. (1985, 1986, 1988, 1989, and 1992), describe a set of analytical and algorithmic results which were inspired by the project.

It is important to note that the modeling research, driven by the requirements for successful implementation, led Kleindorfer and his colleagues to introduce a new model paradigm for service parts inventory planning. Past research in the multi-echelon after market supply chain area was dominated by models that were developed for military applications. The model that the IBM project inspired was formulated to meet the needs of a non-military, commercial environment. Specifically this meant capturing the impact of emergency demand transfers within the network by using a lost sales rather than a backordering model of the impact of shortages. Essentially any demand generated by a customer's end product being down was fulfilled by locating a part at some location in the network.

In the case of IBM this could lead to the cannibalization of the part from a computer being assembled in a factory if necessary. It was also necessary to deal with the fact that there were multiple customer priority and demand classes that affected how resources are shared and rationed. Their model specifically distinguished between emergency and replenishment demands. The need to scale a solution to accommodate IBM's enormous problem size (hundred's of thousands of part numbers, thousands of stocking locations, seven echelons, etc.) led to the development of an effective heuristic algorithm (fast and near-optimal) that ultimately was implemented in IBM's decision support environment.

Multiple generations of students and faculty have developed a wide range of stochastic, multi-echelon, after market inventory models that extended Kleindorfer's early work in this area. These extensions include consideration of resource rationing in differentiated demand environments [see Deshpande et al. (2003)]. The real option framework has provided the inspiration for a successful commercial software system that has been successfully adopted by a wide range of companies in the Aerospace and Defense and High tech industries, [see Cohen et al. (2006b)]. Finally, recent research by Kim et al. (2006 and 2007), has focused on the role of incentives and support contracts in an environment where customers (product users) pay the service provider on the basis of the actual performance realized.

Summary and Conclusions

We have considered Kleindorfer's research in two areas of supply chain risk management, i.e., contracting for procurement in electronic markets and after sales service parts management, in the context of a real option framework. In each case, highly uncertain contingencies must be dealt with. In addition, the decisions available to supply chain managers can be broken down into two phases or periods. The first corresponds to option acquisition and includes structural and resource allocation decisions. The second corresponds to exercising the option after the relevant contingencies have been realized. Finally, in both cases incentives that are derived from the customer – supplier relationships and contracts must be considered. Table 1 compares the two model areas with respect to these factors.

4. Suggestions for Future Research

Risk Assessment

One area where Kleindorfer has undertaken some path-breaking research with his colleagues at the Wharton Risk Center is in collecting data on risks of catastrophic accidents using the EPA data base on chemical accidents. Currently the Wharton Risk Management and Decision Processes Center is engaging in two types of data collection efforts in this regard with the U.S. Environmental Protection Agency. The first of these uses accident history data from the U.S. Chemical industry that has already been noted. The second is concerned with the performance of management systems designed to improve the environmental, health and safety (EH&S) performance of companies.

Accident history data can be linked to financial information so one can analyze the association, if any, between the financial characteristics of the parent company of a facility and the frequency or severity of accidents. Similarly, the property damage estimates, and associated indirect costs from these, can be used to assess the consequences of environmental health and safety incidents on overall company performance and provide valuable insights for insurance underwriting for such accidents. Finally, the same data can be used to assess worst-case consequences from such incidents, including those that might arise from site security risks associated with terrorism.

The second data collection project is a study of "near misses" in organizations and the systems that have been put into place to report and analyze these data. (Phimister et al. 2003). Near misses are defined as incidents that, under different circumstances, could have resulted in major accidents. Linking these data on accident precursors to the Accident History database in RMP*Info, may enable one to identify categories of precursors that give early warnings of the potential for major accidents. Audit tools and other aspects of near-miss management can than focus not just on emergency response but on the range of prevention and mitigation activities before the fact that can help avert major disasters. Even with these data, there will still be considerable uncertainty regarding the estimates of risks associated with these low probability events (National Academy of Engineering 2004).

Risk Perception Issues

There is a need for more detailed information on how risk interdependencies affects firms' decision processes. Interviews with managers from chemical firms and those in other industries indicate that this feature is normally not taken into account in developing risk management strategies. The recent interest by firms on enterprise risk management suggests that this would be an area that should be incorporated in future analyses.

It would also be useful to know how managers process information on risk when there is considerable uncertainty on the likelihood and consequences of an accident. We know that individuals have a difficult time dealing with ambiguous risks particularly those of the low probability variety. One telling example is the way the chemical industry behaved prior and after the Bhopal disaster. Prior to the accident there was a tendency to treat an accident such as the one that occurred in the Union Carbide plant in India as one that will not happen to our firm. Following the disaster all chemical companies undertook a detailed study of chemicals with catastrophic risk potential and took special measures to deal with them. (Bowman and Kunreuther 1988).

Risk Management Issues

With respect to managing environmental, health and safety risk, an area that needs to be examined more

Table 1: Comparison of Real Option Framework for Procurement and After-Sales Problems

	Procurement in electronic markets	After-sales service parts management
Contingencies	Spot and contract prices, buyer demand, supplier capacity	Failure or maintenance based demand for parts at specific locations to support a particular customer machine
Period 1 decisions	Contracts for forward capacity	Target inventory stocking levels for every part location combination
Period 2 decisions	Spot market purchase quantity	Fulfillment of part demand from best available source
Incentives	Cost of procurement and revenue to supplier	Performance contract payments based on equipment uptime

carefully is the role that certifications, such as ISO14000, can play in encouraging firms and divisions to operate more safely. In a recent analysis of ISO data and firm performance, Kang (2005) has shown that facilities that have had serious environmental problems are more likely to arrange to be ISO14000 certified than the lower risk facilities and that their performance has improved over the other facilities in the industry after they were certified. There is a tendency for many facilities in a firm to undertake ISO14000 certification procedures at approximately the same time, suggesting that organizations are using this standard as a way of forcing many of their facilities to undergo an inspection that they might otherwise not consider.

In a related vein, there may be an important role that trade associations can play in providing guidelines for firms to follow with respect to their operations. The Applied Chemistry Council (ACC) [formerly the Chemical Manufacturers Association (CMA)] has undertaken this role through its Responsible Care initiative. Since 1988, members of the American Chemistry Council (ACC) have significantly improved their environmental, health, safety and, in recent years, security performance through the Responsible Care initiative. Participation in Responsible Care is mandatory for ACC member companies, all of which have made CEO-level commitments to uphold these requirements that includes a management system to drive environmental, health, safety and security performance, sharing progress and activities with the public and having mandatory certification by independent, accredited auditing firms.[9]

Interdependencies in Supply Chains[10]

As Kleindorfer has noted in several recent papers (Kleindorfer and Van Wassenhove, 2004; Heal et al. 2006; Kleindorfer and Saad, 2005), interdependencies exist across supply chains in every industry, and the complexity of these has been growing by leaps and bounds as industry has become more globalized through outsourcing and off-shoring activities. The increased complexity of such global supply chains has added levels of risk and interdependence that are sometimes not evident until disaster strikes, exposing hidden vulnerabilities and leading to large economic losses. For example, hurricanes Katrina and Rita in 2005 have led to huge disruptions in economic and business activity in the affected states, which are likely to far outstrip the already significant property losses of these events.

Further empirical research is needed on the effects of supply chain disruptions (whether from natural disasters, terrorists or other unexpected events) on the profitability of supply chain participants. Coping with the management challenges of such disruptions is a very difficult matter, as the interdependencies involved require cooperative activity and monitoring across the supply chain in ways that are not captured in the traditional intra-supply-chain metrics of price, cycle time, and product quality.

There are many sources of potential disruption to global supply chains, some of them just from pure congestion in ports and other (de-)consolidation centers. Today security and concerns with global terrorism have become central drivers of senior management concerns for disruption management of global supply chains, partly because of the sinister and unpredictable character of terrorism that makes traditional financial and operational response strategies less effective against it. These underlying reasons, together with the increasing evidence of the profit impact of good disruption risk management noted above, have made security of global supply chains and multi-modal logistics systems an important focus of supply chain disruption management.

Effective management strategies for security in global supply chains can not be specific to one company. Rather, these strategies need to encompass the entire supply chain of all the organizations participating in the supply chain. But one cannot stop there either, because much of the infrastructure, such as ports and (de-)consolidation centers, services multiple organizations, including end users and shippers, some in private hands and some under governmental control. To deal with the security problem, a broad private and public partnership is required. One public–private partnership, launched between the container traffic industry and the retail industry is effectively dealing with the interdependent security problems in global retail supply chains.

Supply Chain Contracting and Relationships

The buyer-supplier relationship in supply chains is often not fully determined by contracts associated with a single procurement transaction. In many cases there is a long term relationship that may be efficient even without contracts. This phenomenon was observed in the empirical study by Ren et al. (2005) that looked at buyer-supplier relationships in the semiconductor equipment industry. They found that a repeated game based on reputation and tit-for-tat punishment policies were prevalent in that industry. In subsequent research [Ren et al. (2006)], they modeled the problem as a repeated play game.

There is a need to study the long term relationships that arise between customers and suppliers in supply chains in other industries. The research of Ren et al.

[9] For more information on the Responsible Care program of ACC see http://www.responsiblecare-us.com/
[10] This material in this subsection appeared in Heal et al. (2006).

indicated that in some cases explicit contracts are required to enforce terms of trade that will move the supply chain towards an efficient solution. In others, the long term relationship can result in an efficient outcome without the use of contracts. Research needs to be conducted on answering the questions of when and how an efficient long term relationship will arise. In particular, are there particular industry, environmental, technology, or firm specific characteristics that are necessary for an efficient long term collaborative solution to emerge?

An important current challenge for integrating supply chain contracting with electronic markets is in the area of global commodities, from energy to sugar to basic metals. Drivers of increasing risk and volatility in commodity markets are emerging through increasing demands from India and China for certain commodities, as well as political and regulatory decisions that may constrain or favor the use of one commodity versus another in a particular region. These developments, together, are driving companies with commodity-intensive businesses to develop new strategies and competencies to cope with, and perhaps profit from, this increased complexity and uncertainty. The general approach being pursued is the development of short-term commodity risk management competencies. Such competencies involve using new models and new data sources to link market-based knowledge with sourcing and pricing strategies. For example, producers and industrial consumers of plastics have long understood that the prices of key feedstocks for plastics are correlated with basic crude oil prices. They are now seeing the benefits of mapping these interdependencies through formal modeling and taking hedging positions in crude oil and other related futures markets, linked to traditional contract-based forms of sourcing. The development of the competencies to do this promotes both better risk management and better internal company knowledge of the markets which, directly or indirectly, will determine the prices of plastics they face going forward. These same trends and integration of hedging and operational sourcing decisions are becoming increasingly visible in many other areas, and commodity indices and electronic market places for hedge instruments have blossomed in their wake. Thus, extensions of the work of Kleindorfer and others in this domain, as reviewed above, provide an important foundation for these continuing developments.

Performance Based Logistics

The buyer-supplier relationship is especially important in service supply chains where compensation for support is tied explicitly to the output derived from the product(s) in the hands of the customer. This approach, which is referred to as Performance Based Logistics, (i.e. PBL), has been mandated by the U.S. defense department for all of its weapon system suppliers. Commercial variants of PBL have been used for some time, e.g. aircraft engine manufacturers sell a support contract called "Power by the Hour", in which the airline customer pays the service provider for every hour of successful product usage.

Recent research by Sang et al. (2006 and 2007) has explored this issue by developing normative models that combine features of multi-echelon repairable inventory modeling with principal-agent economic theory. Their results indicate that optimal support contract design should be based on blend of performance based and non-performance base mechanisms. The positive impact of PBL contracting has been predicted for some time. The extent of that impact and its drivers, however, are not clear. Research on models that capture, more fully, the interplay between incentives and service supply chain management are needed. There is also a need to establish an empirical basis for predicting the impact of a proposed PBL support contracts. Such empirical analysis must be based on data drawn from the existing set of PBL programs that have been conducted in both government and commercial sectors. Such research is ongoing but is still at an early stage.

Appendix

An Annotated Bibliography of Paul Kleindorfer's Research

In this Appendix we have organized some of the multiple areas of Kleindorfer's extensive research contributions that have not been discussed in the paper. The breadth and depth of this body of work establishes Paul Kleindorfer as a true "Renaissance" man of Operations Management.

Optimal Control Theory

The application of control theory to operational problems represents the intersection between the key methodological construct of control theory to an important application problem area. Kleindorfer is one of the pioneers in this field, starting with his early work with his brother George Kleindorfer and Gerry Thompson, beginning in 1969. The culmination of Paul's contribution to this area can be found in the following paper and two edited books

Kleindorfer, George B., Kleindorfer, Paul R., Kriebel, Charles H., Thompson, Gerald. Discrete Optimal Control of Production Plans, *Management Science*, Vol. 22, No. 3, November 1975, pp. 261–273.

Bensoussan, A., Kleindorfer, Paul R., Tapiero, Charles S. (eds.). *Applications of Optimal Control in Management Sciences*, North Holland, Amsterdam, 1978.

Bensoussan, A., Kleindorfer, Paul R., Tapiero, Charles S. (eds.). *Applied Stochastic Control in Econometrics and Management Science*, North Holland, Amsterdam, 1980.

Planning Horizons for Production Problems

There is a linkage between control theory and production planning problems and Kleindorfer used this to address a set of problems that tied in with planning horizons as illustrated by the following papers:

Kunreuther, Howard, Kleindorfer, Paul R. Stochastic Horizons for the Aggregate Planning Problem. *Management Science*, January 1978.

Kleindorfer, Paul R. Lieber, Zvi. Algorithms and Planning Horizon Results for Production Planning Problems with Separable Costs. *Operations Research*, Vol. 27, Sept-Oct. 1979, pp. 875–887.

Production Scheduling

Kleindorfer, along with his students, Gelders and Newson and a colleague Zvi Lieber, authored several papers on the subject of production planning and scheduling in the 1970s. The problem was primarily one of integrating aggregate and detailed planning with shop scheduling and is illustrated by the following papers:

Gelders, Ludo, Kleindorfer, Paul R. Coordinating Aggregate and Detailed Scheduling Decisions in the One Machine Job-Shop: I-Theory. *Operations Research*, Vol. 2, No. 1, 1974, pp. 46–60.

Gelders, Ludo, Kleindorfer, Paul R. Coordinating Aggregate and Detailed Scheduling in the One-Machine Job-Shop: II-Computation and Structure. *Operations Research*, Vol. 23, No. 2, (March-April, 1975), pp. 312–324.

Kleindorfer, Paul R., Newson, E.F.P. A Lower Bounding Structure for Lot Size Scheduling Problem. *Operations Research*, March-April 1975, pp. 229–311.

Overview of Decision Sciences

Kleindorfer teamed up with Kunreuther and Paul Schoemaker to write a survey of the field of decision sciences, integrating normative, descriptive, and prescriptive analyses of decision making at the individual, group, organizational, and societal level.

Kleindorfer, Paul R., Kunreuther, Howard C., Schoemaker, P. J. *Decision Sciences: An Integrative Perspective*, Cambridge University Press, 1993.

Peak Load Pricing and Regulatory Economics

Kleindorfer and Michael Crew wrote a number of papers in the area of peak load pricing and regulatory economics. They examined, in particular, the interactions of capacity, diverse technologies, stochastic demand and reliability. Crew and Kleindorfer also began studying some of the new methods of regulation, including price cap regulation, rate-of-return regulation, and performance-based regulation from both a theoretical and practical perspective. The following two papers provided important foundations for questions that were central to the debate on peak load pricing and restructuring the energy sector in the United States:

Crew, Michael A., Kleindorfer, Paul R. Peak Load Pricing with a Diverse Technology. *The Bell Journal*, Spring 1976, pp. 207–231.

Crew, Michael A., Kleindorfer, Paul R. Reliability and Public Utility Pricing. *The American Economic Review*, Vol. 68, No. 1, March 1978, pp. 31–40.

Economics of Postal Service

This area combines Kleindorfer's interests in investment and operations (essentially technology planning, explored in detail for peak-load pricing area in many of his papers) with his interest in economics that was concerned with efficient pricing and regulation. Crew and Kleindorfer published the following path breaking book on the economics of postal services. Until this book appeared, there was essentially no respectable literature on the economics of postal and delivery services. This book was followed by an annual series of books on the topic. A key aspect of this and of Kleindorfer's other works in economics is the level of detail of the operating system that is represented in this work. For postal and logistics systems, where operations is extremely important and where labor costs make up more than 75% of the total cost, attention to operational details is a *sine qua non* for capturing relevant details for technology planning, pricing and other key economic decisions.

Crew, Michael A., Kleindorfer, Paul R. *The Economics of Postal Service*, Kluwer Academic Publishers, Boston, 1992.

Risk Management of Natural Hazards and Catastrophic Risk

Kleindorfer played a key role in providing linkages between risk assessment and risk management for catastrophic risks both in the U.S. and abroad. Here are some of the key papers and books in which he has either co-authored or co-edited material

Kleindorfer, Paul R., Sertel, Murat R. (eds.). *Mitigation and Financing of Seismic Risks: Turkish and International Perspectives*, Kluwer Academic Publishers, Boston, 2001.

Grace, Martin F., Klein, Robert W., Kleindorfer, Paul R., Murray, Michael. *Catastrophe Insurance: Supply, Demand and Regulation*, Kluwer Academic Publishers, Boston, 2003.

Kleindorfer, Paul R., Kunreuther, Howard C. Challenges Facing the Insurance Industry in Managing Catastrophic Risks; in Kenneth A. Froot (ed.). *The Financing of Catastrophe Risk*, University of Chicago Press, Chicago, 1999, 149–189.

Kleindorfer, Paul R., Kunreuther, Howard C. The Complementary Roles of Mitigation and Insurance in Managing Catastrophic Risks. *Risk Analysis*, Vol. 19, No. 4, 1999, pp. 727–738.

Grace, Martin, Klein, Robert, Kleindorfer, Paul R. The Demand for Catastrophic Insurance. *J. of Risk and Insurance*, Vol. 71, pp. 351–379, September, 2004.

Kunreuther, Howard, Kleindorfer, Paul R., Grossi, Patricia. The Impact of Risk Transfer Instruments: An Analysis of Model Cities; in P. Grossi and H. Kunreuther (eds.). *Catastrophe Modeling: A New Approach to Managing Risk*, Kluwer Academic Publishers, Boston, 2005.

Labor Managed Firms and Incentive Contracting

Kleindorfer teamed up with Murat Sertel to make important contributions to understanding the role of productivity incentives in organizational design. This included his work on the design of incentives for labor managed firms with a focus on evaluating the impact of input vs. output based incentives, labor-managed and cooperative firms and on the integration of incentives and information design for organizations. We note two of his several papers in this area of his research (the second of which contains a survey of most of his earlier work):

Kleindorfer, Paul R., Sertel, Murat R. Profit-Maximizing Design of Enterprises Through Incentives. *Journal of Economic Theory*, Vol. 20, No. 3, June 1979.

Kleindorfer, Paul R., Sertel, Murat R. The Economics of Workers' Enterprises; in D. Bös (ed.). *Economics in a Changing World,* St. Martin's Press, New York, Vol. 3, 80–99, 1993.

Economics of Insurance

Kleindorfer has written a number of papers related to equilibrium in insurance markets, including institutional considerations related to specific types of insurance (e.g. automobile, natural disasters, political risks).

Kleindorfer, Paul R., Kunreuther, Howard. Misinformation and Equilibrium in Insurance Markets; in J. Finsinger (ed.). *Issues in Pricing and Regulation*, Lexington Books, 1982.

Kleindorfer, Paul R., Kunreuther, Howard, Pauly, Mark. Insurance Regulation and Consumer Behavior in the U.S.–The P-L Industry. *Journal of Institutional and Theoretical Economics*, Vol. 139, October, 1983, pp. 452–472.

Kleindorfer, Paul R., Kunreuther, Howard. Insuring Against Country Risks, Descriptive and Prescriptive Aspects; R. Herring (ed.). *Managing International Risks*, Cambridge University Press, Cambridge, 1993.

Berger, Lawrence A., Kleindorfer, Paul R., Kunreuther, Howard. A Dynamic Model of the Transmission of Price Information in Auto Insurance Markets. *The Journal of Risk and Insurance*, March, 1989, Vol. LVI., No. 1, pp. 17–33.

Doherty, Neil, Kleindorfer, Paul R., Kunreuther, Howard. Insurance Perspectives on an Integrated Hazardous Waste Management Strategy. *Geneva Papers*, 1990.

Siting of Facilities

Kleindorfer has also undertaken research with his colleagues at the Wharton Risk Center on the siting of hazardous facilities as it relates to storing high level nuclear waste and ways of using economic incentives to encourage efficient location of hazardous facilities. The following papers focus on these issues:

Kunreuther, Howard, Kleindorfer, Paul R. A Sealed-Bid Auction Mechanism for Siting Noxious Facilities. *AEA Papers and Proceedings*, Vol. 76, No. 2, 1986, pp. 295–299.

Kunreuther, Howard, Kleindorfer, Paul R., Knez, Peter J., Yaksick, Rudi. A Compensation Mechanism for Siting Noxious Facilities: Theory and Experimental Design. *Journal of Environmental Economics and Management*, 1987, pp. 371–383.

Kleindorfer, Paul R., Kunreuther, Howard C. Siting of Hazardous Facilities; in A. Barnett, S. M. Pollock, M. Rothkopf (eds.). *Handbook of Operations Research in the Public Sector*, Elsevier Science, New York, 1994, pp. 403–440.

Kleindorfer, Paul R., Sertel, Murat R. Auctioning the Provision of an Indivisible Public Good. *Journal of Economic Theory*, 1994.

Health, Safety and Environmental Regulation

Kleindorfer has also focused on issues of environmental regulation as well as risk management strategies for health and safety including the use of international standards such as ISO14000 for promoting sustainability and eco-efficiency. In addition to the work reviewed in this paper on chemical accident prediction and prevention, this research stream is highlighted by the following papers:

Kleindorfer, Paul R., Orts, Eric. Informational Regulation of Environmental Risks. *Risk Analysis,* Vol. 18, No. 2, April 1998.

Kunreuther, Howard R., Renn, Ortwin, Kleindorfer, Paul R. (eds.). *Special Issue of Geneva Papers on Risk Management Strategies for Eco-Efficiency and Cooperation*, July 1996.

Kleindorfer, Paul R. Market-Based Environmental Audits and Environmental Risks: Implementing ISO 14,000; in *The Geneva Papers on Risk and Insurance*, 22 (No.83, April, 1997) pp 194–210.

Chinander, Karen R., Kleindorfer, Paul R., Kunreuther, Howard. Compliance Strategies and Regulatory Effectiveness of Performance-Based Regulation of Chemical Accident Risks. *Risk Analysis,* Vol.18, No.2, April 1998.

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Bowman, E. H., H. Kunreuther. 1988. Post Bhopal behavior of a chemical company. *Journal of Management Studies* **25** 387–402.

Cohen, M. A., P. R. Kleindorfer, H. L. Lee, A. Tekerian. 1985. Excess demand distributions for MEsS stocking policies in multi-echelon logistic systems; in *Inventories in Theory and Practice*, A. Chikan (ed.), Elsevier, Amsterdam.

Cohen, M. A., P. R. Kleindorfer, H. L. Lee. 1986. Optimal stocking policies for low usage items in multi-echelon inventory systems. *Naval Research Logistics Quarterly* **33** 17–38.

Cohen, M. A., P. R. Kleindorfer, H. L. Lee. 1988. Service constrained (s,S) inventory systems with priority demand classes and lost sales. *Management Science* **34**(4) 482–499.

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