ICDRiA

INTERNATIONAL CENTER FOR DECISION AND RISK ANALYSIS

Annual Meeting

30 November 2010

The School of Management

THE UNIVERSITY OF TEXAS AT DALLAS

UTD

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School of Management
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Advisory Board Meeting
November 30, 2010

Agenda

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  - **Alain Bensoussan**

  - **J. Chris White**

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Christophe Lamarsaude, VP Innovation, Strategy, and Alliance, Alcatel
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Divakar Rajamani, Managing Director of the Center for Intelligent Supply Networks
Sumit Sarkar, Information Systems
Suresh Sethi, Director of the Center for Intelligent Supply Networks
Bhavani Thuraisingham, Director of Cyber Security Research Center
Janos Turi, Department of Mathematics
Mathukumalli Vidyasagar, Mechanical Engineering

Alain Bensoussan
School of Management
ICDRiA Activity Report (August 1, 2008- October 31, 2009)
Date: December 1, 2009

Activity Report

1. <u>Introduction</u>

The International Center for Decision and Risk Analysis was created in September 2004, as a Research Center of the School of Management. The objective of the center is to develop education and research programs in the field of Risk Analysis and Decision Making. We report in this document the accomplishments during the period 2010.

Unfortunately, a very sad and unexpected event took place in July 2010: the decease of Dr. Hylan Lyon. Dr. Lyon had accepted the position of Director of Development last year. Besides losing a friend and a remarkable personality, with an extended knowledge, we have lost also a member of the team on whom we had great expectations to develop our network and activities.

Thanks to Hylan, we have been in contact with Chris White, whose expertise fits particularly well with the goals of the center, and we are pleased to announce Chris has accepted the position as ICDRiA's Director of Development.

2. <u>Expansion: Hong Kong and Korea Branches</u>

Among the major development aspects, the creation of two ICDRiA branches in Asia (at the Hong Kong Polytechnic University and at Ajou University in Korea)in 2009 is obviously an important landmark and a big challenge.

A tri-lateral agreement has been signed between ICDRiA, ICMS (the International Center for Maritime Studies) in Hong Kong PolyU and the WCUP-GDFE (World Class University Project and Graduate Department of Financial Engineering) in Ajou University. This agreement is endorsed by the three Deans to whom these centers report.

This initiative, which can be qualified as bottom-up, has been supported by the schools, because it fits well with the will and need of networking research and training activities as a consequence of globalization. Academic activities are fully affected by globalization because the advancement of knowledge must be recognized at a global level and also because the problems we are facing incorporate substantial global aspects. This dimension must be taken into consideration in our research as well as in our education programs.

We operate in a decentralized way. In particular, there is no exchange of funds and no consolidation of financial accounts, since there is no new legal entity. In PolyU, the University has decided to put seed

money and ICMS has also provided some support. Ajou University in Korea has won a national competition in the domain of Financial Engineering under the World Class University program. The funding comes under this program. Although the funding is local, we are eager to coordinate the programs taking the best advantage of specificities and opportunities. Naturally, we will be happy to exchange students and encourage visits of Faculty.

Although we are at an early phase, we can see already some impact. Two Korean students will spend a few months in Hong Kong. Two Faculty and one Research Assistant, working on a project hosted in UTD will also spend time in Hong Kong.

The common activities which are appearing are the following:

- Real Options and uncertainties in investment decisions
- Mutual Insurance
- Alternative Energies

Activities in real Options and uncertainties in investment decisions corresponds to a joint interest in UTD and in Ajou, in coherence with the general program in Financial Engineering that is being developed in Korea.

Mutual Insurance corresponds to a specific aspect of Hong Kong, where Maritime transport is an important activity. In maritime transport, the insurance of risks is organized in a mutual way, unlike other transport industries.

Independently, the Ajou scientists are working in the issue of incentives in insurance, and they have become naturally interested in incentives in mutual insurance.

Finally, alternative energies are expanding very fast everywhere. Very similar questions arise in the US as well as in China. It makes particular sense to coordinate the researches in this domain.
These preliminary developments show how much the vision behind the networking activity of the center corresponds to a real synergy.

Another important initiative has been planned at the beginning of the cooperation. It concerns the organization of a conference, taking place in Hong Kong December 15, 16, 17 2010. The title of the conference ("What can the Academic Community learn from the global crisis?") indicates that the objective is to encourage scientists to look at the global crisis as an opportunity as well as a necessity for evolution of models, concepts and transfer actions. This hopefully will lead to new research directions and educational activities. New York University, College de France, INRIA and Shandong University have joined PolyU, UTD and Ajou to form the group of sponsoring institutions.
The publisher, IOS Press, is also supporting this initiative. Special issues of the journal Risk and Decision Analysis will be devoted to articles coming out of the conference.

3. Education Program

Risk Analysis is now included in the education programs of the School of Management. It is also part of the new program Systems Engineering and Management, which is a joint venture of the School of Engineering and the School of Management. The class is given by Professor Mathukumalli Vidyasagar, from the School of Engineering.

The course "Introductory Mathematical Finance" has been offered as a part of the Master in Finance in fall 2008, 2009 and 2010. The class attracts motivated students and is attended by doctoral level students as well.

4. Research program

One can present the activities of the center in 5 domains: Risks and Uncertainties in Information Systems; Risks in Supply Chain Management; Risks in Financial and Economic Systems; Risks and Uncertainties in alternative energies; and Risks in Technical Systems.

4.1. Risks and Uncertainties in Information Systems

The center benefits from the activity of a group of faculty focused on security issues in information systems, a major strength of the School of Management. The center cooperates also with the Cyber-security Center of the School of Engineering, headed by Professor Bhavani Thuraisingham. In this context, we have been associated to a MURI project obtained by this center on Assured Information Systems sharing. Alain Bensoussan is also co-PI in a grant from ONR, of which Professor Murat Kantarcioglu is P.I. Under this grant, we are sub-contractors of Purdue University. The topic is "A Systematic Defense Framework for Combating Botnets"

Concerning the Information Systems project, we have proposed a model of access to information based on a scoring procedure which has analogies with that of a credit score. There are some common issues in both situations; one of which is the idea of building trust. Based on a good or bad score (using the score as an indicator of trust) the access to information (as the access to credit) is more or less difficult.

In the botnet project, the interesting aspect is that there is a market of malignant actions. An entity interested in being harmful to another entity buys the services of a botnet herder. A botnet herder has contaminated a network of computer systems, without the owner's knowledge. He can drive these systems to perform damages on targeted systems. The problem that we have treated is the calibration of the defense effort.

With Professors Vijay and Radha Mookerjee, from the School of Management Information Systems group, we have considered the defense against hackers. We use a cost benefit point of view. There is an optimal dynamic policy to be put in place optimizing a payoff combining expenses to improve security with benefits in lowering the damages caused by intrusions. The methodology is Control Theory. The state of the system is an indicator of resistance to intrusion. Without active defense this indicator will deteriorate according to some deterministic or stochastic law (there may be shocks).

In the botnet model, one can define a criterion for the botnet herder. This criterion is itself the result of an equilibrium on the market. There is a price for the malignant actions and the herder optimizes an objective based on his profit and costs (including risks). The defense can then formulate a game based on its' own criterion and that of the botnet herder. We have considered and solved completely a dynamic game, based on these considerations.

4.2. Risks in Supply Chain Management

In the "supply chain "area, the center relies mainly on the expertise of the Operations Management department. Risk arises from uncertainties at all stages of the supply chain. In particular, there are uncertainties on key variables needed to make decisions. For instance, one does not know the inventory and one must decide on the level of replenishment. Uncertainties on inventories have been at the core of

our research since 2005, when we were awarded an NSF grant to support the research in this topic over a period of three years

This grant supported four post-doc and doctoral students. We developed a general methodology which provides the optimal policy for managing inventories in the context of uncertainties. This is an original result, which was not known before. We have shown numerically that this optimal policy provides a real improvement in lowering cost compared to a policy based on the best estimate of the inventory. We have also introduced efficient and easy-to-implement approximate policies based on the mean and the variance of the inventory. This research was also funded by a two-year grant awarded by the ARP-ATP program of the state of Texas.

We now would like to explore other sources of uncertainties around demand in addition to the inventory. Demand is of course an essential source of risk for companies and also provides a wide diversity of modeling possibilities. We have had successful cooperation in this area with Blueline-Rediform using statistical methods to deal with seasonality factors. As a major outcome, the student supported on this grant has been hired by the company. His work is at the origin of a new approach to forecast the demand that is now operational.

We have been working on more complex situations, where additional uncertainties arise from pilferage or deterioration, which cannot be observed before decisions are taken. Although more complex, our general methodology applies.

It remains that optimal policies are not easy to implement. This probably explains why we have been unable so far to go to an application phase.

4.3. Risks in Financial and Economic Systems

In the third direction, we have considered several questions. Financial Engineering is a particularly challenging domain, and the present crisis will transform the needs. We expect many opportunities in the mid- and long-term. More research is needed that would make stronger connections between financial decisions and risk management and between the financial world and the 'real world'. This objective is at the core of the future activities in common between the three universities as partners of ICDRiA. This objective is also at the core of the reflection underpinning the 2010 conference.

In the context of coupling the financial world to the real world, we are particularly interested in the use of "Real options," which aims at adapting techniques from financial engineering in project risk management. We have seen in particular that the pharmaceutical industry and the aeronautical industry are making use of these methods for R&D projects. We want to apply this theory to investments in energy and water resources problems.
Thanks to support from the University of Texas at Dallas, we have financed a post-doc to study desalination projects, applying concepts and methods from real options theory. We are pursuing this direction in coupling desalination and wind energy, which is an attractive combination, that we see occurring in many countries.

Unfortunately, we cannot move fast in the direction of water resources management, since there has been no appropriation of the authorization included in the Water Resource Development legislation to support ICDRiA. The Institute of Water Resources (IWR) has clearly indicated that they could not support any specific study without additional funding.

On the more theoretical side, we have been working on problems of real options when there is competition. This is an extremely interesting but challenging problem. In real options, the number of

competitors is generally limited whereas in financial options the multiplicity of players allows to assume that a single player cannot alone modify significantly the market (this is of course not always true). Therefore, integrating competition in the model is important.

We have obtained significant results, in cooperation with Professor David Diltz, from the University of Texas at Arlington, and a post-doc, Celine Hoe. Among the interesting results, we have proven that some strategy commonly considered in the economic literature is not optimal.

4.4. Risks and Uncertainties in Alternative Energies

Fortunately, our preliminary work on wind resource forecasting raised interest with Electricité de France, which has accepted to support research in that direction.

There are many forecasting situations in this context. In particular, one must differentiate the investment phase from the operational phase. In the investment phase, the situation is to decide whether or not to install a wind farm in a specific region. This is typically a situation where the methodology of real options applies. However, we are not at this phase yet. Besides, it will involve confidential information, which is not accessible. We are at the forecasting phase. There are government and industry data that can easily be made anonymous so that confidentiality of data is not a real problem. We have obtained data from EDF and CPL (China Power Limited) in Hong Kong, so we are in a comfortable situation to progress.

The problem at the investment phase is to forecast accurately the annual production. It is important not only to forecast its mean but also quantities to assess the risk. We have developed a methodology for that purpose which has to be discussed with our sponsors.

At the operational level the problem is to make an accurate short-term forecast. Indeed, wind energy is most commonly coupled with another energy source, and it is important to assess how much is needed. Besides, there may be a surplus of wind energy, which is also a problem since a storage facility has to be available. We are not yet working on this problem.

4.5. Risks on Technical Systems

In the fifth domain, we work on technical risk management. This research was initiated by a contract with the French Atomic Energy Agency (CEA) to study the effect of vibrations on mechanical structures. This potentially leads to assessing the risk of collapse of buildings subject to seismic vibrations. We have developed new methods and new mathematical tools which were sufficiently promising to justify a proposal to NSF which was awarded in July 2007. The CEA has also increased its support to our group. We have partly supported two PhD students. One has obtained his PhD in the Mathematics department. The other will get his PhD in 2011 from the University Pierre et Marie Curie. This research is done in cooperation with Professor Janos Turi from the Mathematics Department. In relation with the NSF contract, we have obtained an extension to cooperate with the Hungarian Academy of Sciences. The NSF grant will end in 2011.

5. Present Activities

5.1. Activities in the Security in Information Systems Domain

5.1.1 Information Security in Networked Supply Chains: Impact of Network Vulnerability and Supply Chain Integration on Incentives to Invest

Participants: Tridib Bandhopadhyay, Varghese Jacob, Srinivasan Raghunathan

Recent supply chain reengineering efforts have focused on integrating firms' production, inventory and replenishment activities with the help of communication networks. While communication networks and supply chain integration facilitate optimization of traditional supply chain functions, they also exacerbate the information security risk: communication networks propagate security breaches from one firm to another, and supply chain integration causes breach on one firm to affect other firms in the supply chain. We study the impact of network security vulnerability and supply chain integration on firms' incentives to invest in information security. We find that even though an increase in either the degree of network vulnerability or the degree of supply chain integration increases the security risk, they have different impacts on firms' incentives to invest in security. If the degree of supply chain integration is low, then an increase in network vulnerability induces firms to reduce, rather than increase, their security investments. A sufficiently high degree of supply chain integration alters the impact of network vulnerability into one in which firms have an incentive to increase their investments when the network vulnerability is higher. Though an increase in the degree of supply integration enhances firms' incentives to invest in security, private provisioning for security always results in a less than socially optimal security level. A liability mechanism that makes the responsible party partially compensate for the other party's loss induces each firm to invest at the socially optimal level. If firms choose the degree of integration, in addition to security investment, then firms may choose a higher degree of integration when they decide individually than when they decide jointly, suggesting an even greater security risk to the supply chain.

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5.1.2 Outsourcing Information Security: Contracting Issues and Security Implications

Participants: Huseyin Cavusoglu, Asunur Cezar, Srinivasan Raghunathan

We examine the implications of a firm outsourcing both (i) security device management which attempts to prevent security breaches and (ii) security monitoring which attempts to detect security breaches to managed security service providers (MSSPs). In the context of security outsourcing, the firm not only faces the traditional moral hazard problem as it cannot observe an MSSP's prevention or detection effort, but also observes the security breach outcome only imperfectly. Furthermore, outsourced prevention and detection services are separate but interrelated security functions, and thereby cannot be considered independently. Hence, the firm needs to carefully design a contract or contracts to induce the desired efforts from the service providers to effectively manage the cost of information security. We first show that the current practice of outsourcing both device management and monitoring functions to the same MSSP using a contract that imposes a penalty on MSSP when the MSSP is deemed responsible for a breach results in a higher than the first-best prevention effort and zero (and less than the first-best) detection effort. This is due to the conflict of interest faced by the MSSP and the substitutable nature of prevention and detection services. We then propose two new contracts, both of which achieve the first-best outcomes. The first contract imposes a penalty for a breach and offers a reward for detecting and revealing breaches to the firm and the second contract calls for the firm to use two different MSSPs - one for prevention and the other for detection. The required penalty and reward are smaller when the firm uses two MSSPs than when it uses a single MSSP. It is possible for all three types of contracts to fail to satisfy the fairness criterion – the penalty does not exceed the firm's loss from a security breach -, and also fail to achieve the first-best efforts when there are limits on penalty and/or reward. However, the two-MSSP contract meets the fairness criterion whenever the other two contracts do. An increase in the prevention cost relative to the detection cost increases the likelihood that the two-MSSP contract meets the fairness criterion, making the two-MSSP contract even more attractive relative to the single MSSP contract with

penalty and reward. Despite these advantages of the two-MSSP contract over single MSSP contracts, the firm may be better off outsourcing both prevention and detection functions to the same MSSP with a penalty-and-reward-based contract if a strong cost complement exists between the two functions.

Paper presented at The Ninth Workshop on the Economics of Information Security (WEIS 2010)

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5.1.3 An Analysis of the Impact of Passenger Profiling for Transportation Security

Participants: Huseyin Cavusoglu, Byungwan Koh, Srinivasan Raghunathan

The proponents of airline passenger profiling claim that profiling will reduce the cost of security, improve the detection of attackers, increase the reliability of signals from screening devices, and reduce the inconvenience to normal passengers. In this paper we show that if the Transportation Security Administration (TSA) manually inspects all those passengers classified as likely attackers and sends others through a screening system, as it did when it deployed the Computer Assisted Passenger Prescreening System (CAPPS), then it is superior to no profiling on all four performance measures if and only if the quality of the profiler vis-à-vis that of the screening system is sufficiently high. If the quality of the screening device is sufficiently high, profiling could be detrimental on all four performance measures. On the other hand, if the TSA deploys two screening devices along with the profiler—each screening device optimally configured for each of the two groups of passengers—then profiling improves the reliability of screening device signals, reduces the inconvenience caused to normal passengers, and improves the social welfare even when quality of the screening device is high. One of the implications of our findings is that the security architecture used by the TSA when it deployed CAPPS could provide a strong support to the arguments by some against the use of profiling; however, if the TSA deploys a two-screening device architecture, it might not only blunt the criticism that profiling is discriminatory but also benefit normal passengers and overall society economically.

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5.1.4 Economics of User Segmentation, Profiling, and Screening in Security

Participants: Srinivasan Raghunathan, Huseyin Cavusoglu, Bin Mai

User profiling is touted as an effective and efficient tool to detect security breaches because it allows firms to target their inspection efforts at likely attackers and reduce inspection of likely normal users. However, because profiling uses superficial individual-specific criteria, it is susceptible to gaming by attackers who may be able to fake their attributes to trick the profiler into classifying them as normal users. We first analyze the impact of gaming by attackers on the firm for two types of profiling commonly used in practice – the profiler separates out attackers and the profiler separates out normal users. For both of these cases, we show that profiling hurts the firm if the profiling accuracy is sufficiently low. Surprisingly, we find that profiling may hurt the firm also when the profiling accuracy is sufficiently high. The latter result occurs because an increase in the profiling accuracy makes faking more attractive to attackers. Therefore, even when profiling is better than not profiling, the optimal profiling accuracy, which depends on the faking cost, could be less than 100%. A lower faking cost expands the region in which the firm realizes a lower payoff when it uses profiling than when it does not. We also find that, contrary to the conventional wisdom, as the firm becomes better at discriminating attackers and normal users, the inspection rates for the two groups become more similar when faking is an issue. We show that the negative effects of profiling can be mitigated if the firm uses two screening devices, one for each user group. However, the additional cost of operating a second screening device may offset the gain.

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5.1.5 Cyber Security Risk Management: Public Policy Implications of Correlated Risk and Imperfect Ability to Prove Loss

Participants: Hulisi Ogut, Nirup M. Menon, Srinivasan Raghunathan

The correlated nature of security breach risks, the imperfect ability to prove loss from a breach to an insurer, and the inability of insurers and external agents to observe firms' self-protection efforts have posed significant challenges to cyber security risk management. Our analysis finds that a firm invests less than the social optimal levels in self-protection and in insurance when risks are correlated and the ability to prove loss is imperfect. We find that the appropriate social intervention policy to induce a firm to invest at socially optimal levels depends on whether insurers can verify a firm's self-protection levels. If self-protection of a firm is observable to an insurer so that it can design a contract that is contingent on the self-protection level, then self-protection and insurance behave as complements. In this case, a social planner can induce a firm to choose the socially optimal self-protection and insurance levels by offering a subsidy on self-protection. We also find that providing a subsidy on insurance does not provide a similar inducement to a firm. If self-protection of a firm is not observable to an insurer, then self-protection and insurance behave as substitutes. In this case, a social planner should tax the insurance premium to achieve socially optimal results. The results of our analysis hold regardless of whether the insurance market is perfectly competitive or not, implying that solely reforming the currently imperfect insurance market is insufficient to achieve the efficient outcome in cyber security risk management.

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5.1.6 Intrusion-Detection Policies for IT Security Breaches

Participants: Hulisi Ogut, Huseyin Cavusoglu, Srinivasan Raghunathan

Intrusion-detection systems (IDSs) form an important component of IT security architectures, but the low proportion of hackers in the user population severely limits the usefulness of IDSs. Thus, even when the IDS is good, an intrusion signal may not imply that the user is more likely to be a hacker than a normal user. Ignoring the low base rate for the proportion of hackers results in acting on every intrusion signal, which is costly because of high rate of false alarms. This problem is known as the base-rate fallacy in IDSs. On the other hand, ignoring intrusion signals renders them useless. We propose and analyze waiting-time policies, which specify a response to signals from IDSs. We formulate the problem as a stochastic dynamic programming model and derive the optimal waiting time before acting upon an intrusion signal. Because the optimal policy is difficult to implement in many situations, we also derive and theoretically analyze a myopic policy. Our simulations suggest that the behavior of the myopic policy is qualitatively similar to that of the optimal policy. Further, the myopic policy performs better than other policies often used in practice, such as the Bayes policy and m-strike policies. The myopic policy can be implemented easily in a decision support system that supplements an IDS to mitigate the base-rate fallacy, and improve the value of the IDS.

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5.1.7 Evaluation of Intrusion Detection Systems under an Inspection Constraint

Participants: Young U. Ryu, Hyun-Suk Rhee

An intrusion detection system (IDS) plays an important role in a firm's overall security protection. The IDS's main purpose is to identify potentially intrusive events and alert the security personnel to the danger. A typical intrusion detection system, however, is known to be imperfect in detection of intrusive events, resulting in high false-alarm rates. Nevertheless, current intrusion detection models unreasonably assume that upon alerts raised by a system, an information security officer responds to all alarms without

any delay and avoids damages of hostile activities. This assumption of responding to all alarms with no time lag is often impracticable. As a result, the benefit of an IDS can be overestimated by current intrusion detection models. In this article, we extend previous models by including an information security officer's alarm inspection under a constraint as a part of the process in determining the optimal intrusion detection policy. Given a potentially hostile environment for a firm in which the intrusion rates and costs associated with intrusion and security officers' inspection can be estimated, we outline a framework to establish the optimal operating points for IDSs under security officers' inspection constraint. The optimal solution to the model will provide not only a basis of better evaluation of IDSs but also useful insights into operations of IDSs. The firm can estimate expected benefits for running IDSs and establish a basis for increase in security personnel to relax security officers' inspection constraint.

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5.1.8 Optimal and Heuristic Approaches to Sanitizing Large Transactional Databases

Participants: Syam Menon, Sumit Sarkar

The need to conceal sensitive information prior to sharing databases is well recognized. Sensitive information in transactional databases is typically based on relationships derived from frequently occurring itemsets. Prior work in this area includes optimal approaches to maximize the accuracy of shared databases, while hiding all sensitive itemsets. These optimal approaches were shown to solve problems involving up to 10 million transactions. However, many transactional databases are considerably larger and, as system memory becomes a critical bottleneck preventing the large integer programs from being generated and stored, no effective solution procedure exists for such databases. This paper first identifies a common structure that exists in these problems, and then presents an optimal solution procedure based on branch-and-price that takes advantage of this structure. This procedure is observed to identify optimal solutions relatively quickly, even on problems which cannot be solved to optimality via existing approaches. However, even this approach becomes impractical as the size of the database increases beyond a point, and we introduce a heuristic variant to identify good solutions when the optimal procedure will not work. Computational experiments show that the heuristic identifies near-optimal solutions quickly in all problems where the optimal solution is known. In addition, it enables the solution of problems much larger than those considered previously.

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5.1.9 Maximizing Accuracy when Modifying Transactional Databases to Hide Sensitive Association Rules

Participants: Syam Menon, Sumit Sarkar

Many organizations share point-of-sale data with business partners, as effective analysis of this data can often lead to competitive advantage. A common technique used to glean information from these transactional databases is the mining of association rules. While the potential benefits of sharing data can be considerable, many researchers have noted that the negative consequences of revealing association rules that are confidential can also be significant. In this paper, we focus on the problem of hiding those association rules that represent sensitive information to the owner of the data. Hiding is usually achieved through a process called sanitization, by which appropriately selected transactions are altered in such a way that they no longer support the sensitive association rules. In this paper, we introduce a formulation to maximize the accuracy of the modified database, given a sanitization approach. We then identify some conditions under which the size of the formulation can be reduced. Some sanitization approaches are better than others, and a sanitization procedure that results in the most accurate modified database is desirable. We represent the sanitization problem as an integer program and present a heuristic to solve it

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efficiently. Experimental results indicate that the approach is very effective, identifying solutions which result in accuracies of about 99.9% in less than a second.

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5.1.10 Protecting Privacy against Record Linkage Disclosure: A Bounded Swapping Approach for Numeric Data

Participants: Xiao-Bai Li, Sumit Sarkar

Record linkage techniques have been widely used in areas such as anti-terrorism, crime analysis, epidemiologic research, and database marketing. On the other hand, such techniques are also being increasingly used for identity matching that leads to the disclosure of private information. Such a technique can be used to effectively re-identify records even in de-identified data. Consequently, the use of such a technique can lead to individual privacy being severely eroded. This study addresses this important issue and provides a solution to resolve the conflict between privacy protection and data utility. We propose a data masking method for protecting private information against record linkage disclosure, while preserving the statistical properties of the data for legitimate analysis. Our method recursively partitions a dataset into smaller subsets such that data records within each subset are more homogeneous after each partition. The partition is made orthogonal to the maximum variance dimension represented by the first principal component in each partitioned set. The attribute values of a record in a subset are then masked using a double-bounded swapping method. The proposed method, which we call multivariate swapping trees, is nonparametric in nature and does not require any assumptions about statistical distributions of the original data. Experiments conducted on real-world datasets demonstrate that the proposed approach significantly outperforms existing methods in terms of both preventing identity disclosure and preserving data quality.

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5.1.11 No Free Lunch: Price Premium for Privacy Seal-Bearing Vendors

Participants: Bin Mai, Nirup M Menon, and Sumit Sarkar

Privacy is a significant concern of customers in the business-to-consumer online environment. Several technical, economic, and regulatory mechanisms have been proposed to address online privacy. A current market-based mechanism is the privacy seal, under which a third-party assures adherence by a vendor to its posted privacy policy. In this paper, we present empirical evidence of the impact of displaying a privacy seal on the product prices of online vendors of electronic books, downloadable audio books, and textbooks. Using data collected on these relatively homogeneous products sold by online vendors, we find, while controlling for vendor-specific characteristics, that vendors bearing privacy seals charge a premium for such products compared to vendors not bearing a seal. The paper provides empirical evidence of the economic value of privacy assurance from the customers' perspective as measured by the price premium charged for products. The research has implications for researchers and policy makers by providing evidence that privacy is another factor that creates friction in e-commerce, and that prices on the internet for homogeneous products need not converge.

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5.1.12 Multivariate Regression Trees for Protecting Data Privacy

Participants: Xiao-Bai Li, Sumit Sarkar

Traditional data masking techniques, such as k-anonymity and microaggregation, may be ineffective when the masked data is used for predictive data analysis and data mining, because they are not designed

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specifically to preserve the relationships between confidential attributes and non-confidential but potentially identifying attributes. Existing data masking methods that apply to predictive data analysis typically deal with only one confidential attribute. We propose a regression tree-based method that can handle multiple confidential response attributes. The proposed method adopts a novel measure, which considers the tradeoff between disclosure risk and data utility, in the regression tree pruning process. A preliminary experimental study demonstrates the effectiveness of the proposed method.

Presented at Workshop on Information Technologies and Systems, 2010, St. Louis.
http://apps.business.ualberta.ca/wits/
Nominated for the Best Paper Award

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5.1.13 Data Clustering and Micro-Perturbation for Privacy-Preserving Data Sharing and Analysis

Participants: Xiao-Bai Li, Sumit Sarkar

Clustering-based data masking approaches are widely used for privacy-preserving data sharing and data mining. Existing approaches, however, cannot cope with the situation where confidential attributes are categorical. For numeric data, these approaches are also unable to preserve important statistical properties such as variance and covariance of the data. We propose a new approach that handles these problems effectively. The proposed approach adopts a minimum spanning tree technique for clustering data and a micro-perturbation method for masking data. Our approach is novel in that it (i) incorporates an entropy-based measure, which represents the disclosure risk of the categorical confidential attribute, into the traditional distance measure used for clustering in an innovative way; and (ii) introduces the notion of cluster-level micro-perturbation (as opposed to conventional micro-aggregation) for masking data, to preserve the statistical properties of the data. We provide both analytical and empirical justification for the proposed methodology.

Nominated for the Best Conference Paper Award.

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5.1.14 A Game-Theoretical Approach for Finding Optimal Strategies in a Botnet Defense Model

Participants: Alain Bensoussan, Celine Hoe , Murat Kantarcioglu

In many cases, botnet herders are motivated by economic incentives and try to significantly profit from illegal botnet activity while causing significant economic damage to society. To analyze the economic aspects of botnet activity and suggest feasible defensive strategies, we provide a comprehensive game theoretical framework that models the interaction between the botnet herder and the defender group (network/computer users). In our framework, a botnet herder's goal is to intensify his intrusion in a network of computers for pursuing economic profits whereas the defender group's goal is to defend botnet herder's intrusion. The percentage of infected computers in the network evolves according to a modified SIS (susceptible-infectious-susceptible) epidemic model. For a given level of network defense, we define the strategy of the botnet herder as the solution of a control problem and obtain the optimal strategy as a feedback on the rate of infection. In addition, using a differential game model, we obtain two possible closed-loop Nash equilibrium solutions. These results indicate that in some cases trying to defend against botnet activity may not be economically feasible, instead the goal should be to limit the damage to an acceptable level. Also when significant resources are allocated to defend against particular botnet activity, botnet herders will choose to reduce their attack effort even if the defensive strategies are not very effective. To our knowledge, none of previous works suggested these two different equilibrium strategies.

5.1.15 When Do Firms Invest in Privacy-Preserving Technologies?

Participants: Alain Bensoussan, Celine Hoe, Murat Kantarcioglu

Privacy is a central concern in the information age. In some circumstances, customers' decisions whether to use firms' services rely on the extent of privacy that firms are able to provide. On the other hand, firms make investment decisions about privacy-preserving technologies, which require the technology adoption to yield them enough compensation for making investment. We are interested in assessing privacy-preserving technologies to formulate useful guidelines for firms' investment decisions and to make inferences, if any, about the necessity of government intervention to encourage firms' investment in privacy-preserving technologies. Two unique factors affect firms' investment valuation in our model: (1) a customer's valuation of his private information and (2) a customer's profitability to a firm. We view firms' evaluation processes as a variant of Stackelberg type leader-follower game under complete information with customers taking the role of the follower. Rational utility maximizing customers optimally decide whether to use firms' services by linking to their own decision threshold which is their own fair valuation of privacy connected to their private information. We employ copula functions to allow sufficient flexibility in formulating bivariate distribution functions. We find that dependence structures and underlying univariate distributions have significant impacts on investment valuation. Our results also identify several cases where the government intervention may be required to have firms invest in privacy-preserving technologies.

5.2. Present Activities in the Supply Chain Domain

5.2.1 Partially Observed Inventory Systems

Participants: Alain Bensoussan, Metin Çakanyildirim, Suresh Sethi

In some inventory control contexts, such as Vendor Managed Inventories, inventory with spoilage, misplacement, or theft, inventory levels may not always be observable to the decision makers. However, shortages, delayed inventory/demand observations are observable and are called signals. The signals provide partial information. We study such inventory control problems, where orders must be decided on the basis of partial information to minimize costs.

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5.2.2 Computation of Approximate Optimal Policies in Partially Observed Inventory Model with Rain Checks

Participants: Alain Bensoussan, Metin Çakanyildirim, Suresh Sethi, Ruixia Shi

We study a periodic review inventory system in which the inventory manager (IM) does not know the inventory level when it is positive. But, when the inventory level becomes negative, the IM issues rain checks to customers, thus making the shortages fully observable to him. The IM's task is to determine the optimal order quantities in this partial information setting where the inventory level, when positive, is represented in terms of an infinite dimensional probability distribution. We approximate this distribution by Chebyshev polynomials to compute the optimal order quantity/cost for our system. Moreover, we use Fast Fourier Transforms along with an appropriate discretization of backorder levels to speed up the computations. We also propose a heuristic termed a base mean-stock policy. The order quantity for the heuristic policy is computed by regarding the mean of the inventory level as the inventory level in a fully observed inventory system, and then using a base stock policy. We show numerically that the optimal order quantity is very close to the base mean-stock order quantity, when the variance of the inventory distribution is small. When the mean of the inventory distribution is large, the optimal order quantity is

more than the base mean-stock quantity, it is the other way around when the mean is small or there are backorders.

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5.2.3 Optimal Policy and Value of Information in an Inventory Model with Lost Sales and Demand Updates

Participants: Alain Bensoussan, Metin Çakanyildirim, Qi Feng, Suresh Sethi

Under many circumstances, demand observations are often censored due to the lack of tracking lost sales caused by stockouts. To understand the impact of the lost sales information on the ordering decisions, a periodic-review inventory model is formulated in which only the sales information is obtained immediately upon the realization of the demand. Subsequently, the lost sales information is obtained after a delay. In the resulting model, an optimal policy, if exists, reveals a very complex structure. By decomposing the derivative of the value function, we demonstrate two different roles of inventory in our model: satisfying the demand and deducing the demand information. We show that the optimal inventory levels under the delayed observation of the lost sales are always higher than those for which the demands are fully observed. Moreover, as illustrated in numerical examples, the optimal policy possesses a counterintuitive behavior with respect to the problem parameters. To understand the key drivers of the optimal decisions, we further compare the costs under different demand observations. Two important observations are made. First, a lower cost is obtained when the realized demand is observed than when the demand is only observed to be higher than that level, and, furthermore, the cost difference represents the value of demand information. Second, if the demand observation is censored, improved demand information may not always be desirable as it may actually lead to an increased expect cost.

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5.2.4 Numerical Analysis of Partially Observable Inventory System: Economic Loss from Mean Based Policy

Participants: Alain Bensoussan, Metin Çakanyildirim, Celine Hoe, Suresh Sethi

In this paper we provide numerical solutions for a partially observed inventory system named Zero Balance Walk Model. In this model, demand is not observed, inventory level is observed only when it reaches zero, and orders are made to minimize the total discounted cost. We prove that solutions can be obtained in a Hibertian framework and propose a numerical procedure combining a Chebyshev representation of the conditional density of the inventory level and a policy iteration algorithm. Extensive numerical examples are studied to analyze the economic loss if the model is misspecified by the mean-based policy. An approximation scheme is introduced for the computation of costs. Numerical results show that the loss is significant and is positively related to the discount factor as well as the uncertainty embedded in the inventory level. Our study thus suggests inventory managers the importance of their awareness to the partially observable inventory system.

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5.2.5 Assessing the Loss due to Parsimony

Participants: Alain Bensoussan, Metin Çakanyildirim, Leunglung Chan, Celine Hoe, Suresh Sethi

In standard inventory models, the inventory level was assumed to be deterministic or fully observed. However, in reality, inventory levels are always not fully observed. In this paper a single-period inventory model with a partially observation is considered. We use a uniform distribution, an exponential distribution and a lognormal distribution for the demand and any arbitrary distribution for the inventory.

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The optimal order quantity and the value function are derived. We analyze the economic loss if the model is misspecified by the mean-based policy. The order quantity difference and the value difference between the mean-based policy and the partially observed policy are derived. Some properties of the order quantity difference and the value difference such as bounds are discussed. The sensitivity analysis of the economic loss associated with different variables is also discussed.

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5.2.6 Optimal Transshipments and Orders: A Tale of Two Competing and Cooperating Retailers

Participants: Metin Çakanyildirim, Nagihan Çömez, Kathryn Stecke

We study a centralized inventory sharing system of two retailers that are replenished periodically. Between two replenishments, a unit can be transshipped to a stocked-out retailer from the other retailer. It arrives a transshipment time later, during which the stocked-out retailer incurs back-order cost. Without transshipment, backorder cost is incurred until the next replenishment. Since the transshipment time is shorter than the time between two replenishments, transshipments can reduce the backorder cost at the stocked-out retailer, while decreasing the holding costs at the other retailer. The system is directed by a centralized inventory manager, who minimizes the long-run average cost consisting of replenishment, holding, backorder, and transshipment costs. The transshipment policy is characterized by hold-back inventory levels, which are non-increasing in the remaining time until the next replenishment. The transshipment policy differs from the literature because we allow for multiple transshipments between replenishments, positive transshipment times, and backorder costs. We also discuss the challenges associated with considering positive replenishment time and develop upper and lower bounds of the average cost in this case. These bounds are numerically shown to have an average gap of 1.1%. The heuristic solution is based on the upper bound and differs from the optimal cost by at most this gap.

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5.2.7 Optimal Transshipments and Orders with Inventory Competition in a Decentralized Retail Network

Participants: Metin Çakanyildirim, Nagihan Çömez, Kathryn Stecke

A decentralized system of two competing retailers that order and sell the same product is studied. When a customer demand occurs at a stocked-out retailer, that retailer requests a unit to be transshipped from the other retailer who charges a transshipment price. If this request is rejected, the unsatisfied customer may go to the other retailer with a demand overflow probability. Each retailer decides on the initial order quantity from a manufacturer and on the acceptance/rejection of each transshipment request. We show that retailers' optimal transshipment policies are dynamic and are characterized by chronologically non-increasing inventory holdback levels. Order quantity decisions form a non-cooperative game. This game has an equilibrium when retailers can order fractional quantities. Pre-season and in-season transshipment price negotiations also form games; the former game has a limited effect on profits while the latter has an intuitive equilibrium that does not depend on the current time or inventory levels. Through numerical exercises, it is shown that retailers substantially benefit from using optimal transshipment policies compared to no sharing. The manufacturer also benefits in all but a handful of over 3000 problem instances. We also analytically study the magnitude of holdback levels in order to derive interesting insights, such as smaller retailers and geographically distant retailers benefit more from transshipments. Building on the optimal policies obtained for a two-retailer system, we suggest a multi-retailer heuristic whose solution performs well when compared to a profit upper bound based on the centralized system.

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5.2.8 Contracting and Coordination under Asymmetric Production Cost Information

Participants: Metin Çakanyildirim, Xianghua Gan, Suresh P. Sethi

We study a supply chain consisting of a supplier and a retailer who faces a newsvendor problem. The supplier has better knowledge of his unit production cost than the retailer has. We model this problem as a game of adverse selection. In this model the retailer (principal) offers a menu of contracts, each of which consists of two parameters: the ordering quantity and the supplier's proportion of the channel profit. The supplier (agent), who has an alternative opportunity, either chooses one from the menu of contracts or rejects them all. We derive an optimal contract menu for the retailer under a general assumption about the supplier's reservation profit. Also we find that in some cases the optimal contract coordinates the supply chain even with asymmetric information.

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5.2.9 On the Selection of Supply Chain Coordinating Contracts: The Role of Capital Constraints

Participants: Yi Xu, Jun Zhang

This paper considers a supply chain with a manufacturer and a financially constrained retailer, and examines the implications of the retailer's capital constraint on the selection of supply chain coordinating contracts. We demonstrate that the well-accepted result that buy-back, quantity discount, quantity-flexibility, sales-rebate, and revenue-sharing contracts can coordinate the supply chain and arbitrarily allocate the supply chain profit needs to be reexamined. Taking the retailer's capital constraint into account, we show that arbitrary allocation of the supply chain profit is no longer possible for all the contract forms, and that these contract forms are quite different in the flexibility in coordinating the supply chain and in allocating its profit. Surprisingly, there is a set of allocations of the supply chain profit that cannot be achieved by any of the existing contract forms. We then propose and study a new coordinating contract form: manufacturer financing contract in which the manufacturer provides financing for the retailer's purchase. We find that the manufacturing financing contract complements the existing contract forms in supply chain coordination and in profit allocation. Our study indicates that the financial status of the retailer, the gross margin of the product, and the power structure of a supply chain are important factors that influence the selection of coordinating contracts.

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5.2.10 Coordination of Supply Chains with Risk-Averse Agents

Participants: Xianghua Gan, Suresh P. Sethi, Houmin Yan

The extant supply chain management literature has not addressed the issue of coordination in supply chains involving risk-averse agents. We take up this issue and begin with defining a coordinating contract as one that results in a Pareto-optimal solution acceptable to each agent. Our definition generalizes the standard one in the risk-neutral case. We then develop coordinating contracts in three specific cases: (i) the supplier is risk neutral and the retailer maximizes his expected profit subject to a downside risk constraint, (ii) the supplier and the retailer each maximizes his own mean-variance trade-off, and (iii) the supplier and the retailer each maximizes his own expected utility. Moreover, in case (iii) we show that our contract yields the Nash Bargaining solution. In each case, we show how we can find the set of Pareto-optimal solutions, and then design a contract to achieve the solutions. We also exhibit a case in which we obtain Pareto-optimal sharing rules explicitly, and outline a procedure to obtain Pareto-optimal solutions.

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5.2.11 Channel Coordination with a Risk-Neutral Supplier and a Downside-Risk-Averse Retailer

Participants: Xianghua Gan, Suresh P. Sethi, Houmin Yan

We investigate how a supply chain involving a risk-neutral supplier and a downside-risk-averse retailer can be coordinated with a supply contract. We show that the standard buy-back or revenue-sharing contracts may not coordinate such a channel. Using a definition of coordination of supply chains proposed earlier by the authors, we design a risk-sharing contract that offers the desired downside protection to the retailer, provides respective reservation profits to the agents, and accomplishes channel coordination.

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5.2.12 A Two-Stage Newsvendor Problem with a Service Constraint

Participants: Alain Bensoussan, Qi Feng, Suresh Sethi

We extend the classical newsvendor problem by introducing a service constraint and a demand forecast update. The newsvendor orders an initial amount and has the possibility to adjust the initial order after she observes a demand updating signal. She also commits to a target service level before any forecast update is available. The resulting problem does not permit a dynamic programming formulation. We use the method of Lagrange multiplier to solve the problem, and we derive an analytical expression for the optimal ordering decisions. Various properties of the optimal policy are discussed, and numerical results are presented to provide further insights into the newsvendor's behavior.

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5.2.13 Coordination Mechanism for the Supply Chain with Leadtime Consideration and Price-Dependent Demand

Participants: Haoya Chen, Youhua Chen, Tsan-Ming Choi, Suresh Sethi

We study a coordination contract for a supplier-retailer channel producing and selling a fashionable product exhibiting a stochastic price-dependent demand. The product's selling season is short, and the supply chain faces great demand uncertainty. We consider a scenario where the supplier reserves production capacity for the retailer in advance, and permits the retailer to place an order not exceeding the reserved capacity after a demand information update during the leadtime. We formulate a two-stage optimization problem in which the supplier decides the amount of capacity reservation in the first stage, and the retailer determines the order quantity and the retail price after observing the demand information in the second stage. We propose a three-parameter risk and profit sharing contract that coordinates the supply chain. The proposed contract permits any agreed-upon distribution of the supply chain profit to the channel members.

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5.2.14 Procurement Flexibility under Price Uncertainty

Participants: Qi Feng, Suresh Sethi

This chapter examines the interaction between supply price uncertainty and demand uncertainty. We consider a manufacturer who sources a key component using different procurement options: a long-term order on a price-only contract, short-term orders on an adjustment contract, and short-term purchases directly from the market. At the beginning of the planning cycle, the manufacturer places a long-term order and reserves a certain amount of supply capacity for the purpose of adjusting the long-term order, if needed. Before the selling season, the manufacturer has multiple options to place supplementary orders

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from the reserved capacity or from the market. We compare two types of capacity arrangements: dedicated capacity and overall capacity. Under a dedicated capacity arrangement, the manufacturer reserves capacities separately for different adjustment opportunities. On the other hand, under an overall capacity arrangement, she keeps the flexibility of using the reserved capacity within the given period for possibly multiple adjustments. We discuss the optimal procurement strategies and the criteria for capacity allocations, as well as the policy behavior and service performance in different situations.

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5.2.15 New Policies for the Stochastic Inventory Control Problem with Two Supply Sources

Participants: Anshul Sheopuri, Ganesh Janakiraman, Sridhar Seshadri

We study an inventory system under periodic review in the presence of two suppliers (or delivery modes). The emergency supplier has a shorter lead-time than the regular supplier, but the unit price he offers is higher. Excess demand is backlogged. We generalize the recently studied class of Dual Index policies (Veeraraghavan and Scheller-Wolf (2008)) by proposing two classes of policies. The first class consists of policies that have an order-up-to structure for the emergency supplier. We provide analytical results that are useful for determining optimal or near-optimal policies within this class. This analysis and the policies which we propose leverage our observation that the classical "Lost Sales inventory problem" is a special case of this problem. The second class consists of policies that have an order-up-to structure for the regular supplier. Here, we derive bounds on the optimal order quantity from the emergency supplier, in any period, and use these bounds for finding effective policies within this class. Finally, we undertake an elaborate computational investigation to compare the performance of the policies we propose with that of Dual Index policies. One of our policies provides an average cost-saving of 1.1 % over the Best Dual Index policy and has the same computational requirements. Another policy which we propose has a cost performance similar to the Best Dual Index policy but its computational requirements are lower.

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5.3. Present Activities in Finance and Economics

5.3.1 Real Options and Game Models

Participants: Alain Bensoussan, David Diltz, Celine Hoe

We consider optimal investment strategies for projects under uncertainty, when there is competition. We study the situation of complete and incomplete markets. Both a Leader-Follower Stackelberg game and a Nash Equilibrium game are considered. The approach of real options bears similarity with that of American options in financial engineering. A major component of the decision is when to invest (or to enter into the market). It is a random time. Each of the players has to decide when to enter. However, in the Stackelberg game the follower cannot enter before the leader whereas in the Nash game both players face the preemption risk when making investment decisions. There is in addition a regulation which clarifies how they share the market, if they decide both to compete. The assumption of complete or incomplete markets plays a fundamental role in defining the objective functions of both players. As it is customary for optimal stopping time problems, Dynamic Programming leads to Variational Inequalities. However, new structures arise with interesting mathematical questions. In most cases, we are able to solve completely the problems and to obtain optimal stopping strategies. But the results are not intuitive.

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5.3.2 Value of Population in Economic Growth Models

Participants: K.J. Arrow, Alain Bensoussan, Qi Feng, Suresh Sethi

Traditional economic growth models are based on capital as the state variable. It is clear that modern economies must take into account other state variables. Population is a very important one. Following models developed by K.J. Arrow, we have considered an economy in which the rate of change of population depends on population policy decisions. This requires population as well as capital as state variables. By showing the algebraic relationship between the shadow price of the population and the shadow price of the per capita capital stock, we are still able to depict the optimal path and its convergence to the long-run equilibrium on a two-dimensional phase diagram. Moreover, we derive explicitly the expression of genuine savings in our model to evaluate the sustainability of the system.

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5.3.3 Cash Management

Participants: Alain Bensoussan, Suresh Sethi, A. Chutani

We consider problems of consumption and investment, with transaction   costs. These transaction costs are materialized in the evolution of cash, considered as a state variable. The return on the investment is random. The decision variables are the rate of consumption, as well as the amount of cash invested in the stocks. This approach is centered on the cash management, whereas traditional approaches in Finance tend to eliminate the cash and to center on the portfolio management. The major advantage is to introduce the transactions costs as proportional to the rate of transformation of cash into stocks. Our theory is so far limited to one stock. In this case, we characterize the optimal strategy of investment, with several assumptions on the random behavior of the return on the stock.

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5.3.4 Mutual Insurance

Participants: Alain Bensoussan, J. Liu, J. Yuan

This research takes place at PolyU. We consider a mutual insurance system whose reserve evolves as a Brownian motion, as a consequence of the occurrence of hazards. The controller tries to minimize the total cost by increasing or reducing the reserve by instant jumps. Both cases of zero and positive fixed costs are investigated. We apply the theory of Quasi-variational inequalities and make the connection between singular control and impulse control. The procedures to solve these systems are also studied. Mutual insurance is widely used in maritime transport.

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5.4. Present Activities in Risks on Technical Systems

5.4.1 Critical Excitation for Elasto-Plastic Systems

Participants: Alain Bensoussan, Keerthi Chandrasekaran, Janos Turi

Elasto-plastic oscillators are used as the simplest models in the study of the nonlinear response of structures under severe loads (like earthquakes). The response of the structure to an excitation typically can be described as a sequence of alternating elastic and plastic phases and the size of the accumulated plastic deformation plays a critical role in system reliability. In this project we are interested in finding the "critical excitation", i.e., the lowest energy input excitation that drives the system between prescribed

initial and final states within a given time span. Critical excitation corresponds to identifying a particular input, out of inputs with given total energy, which creates the largest deformation in the structure. This is an optimal control problem for a state evolution for the variational inequality modeling the elasto-plastic system. We provide a complete solution of this problem by extending classical results to a class of non-smooth systems which include the elasto-plastic case. We also derive an algorithm which provides good approximations of the critical excitation.

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5.4.2 Elasto-Plastic Systems Excited by Non-White Noise

Participants: Alain Bensoussan, Laurent Mertz

Elasto-plastic oscillators represent useful models for predicting the nonlinear response of structures when pressed beyond the elastic limit due to severe loads. In this project the case when the power spectral density (PSD) of the input excitation is non constant is investigated using the stochastic variational inequality framework. This input, which is given by an Orstein-Uhlenbeck process, is more realistic than the pure white-noise excitation investigated previously. Using an extension of Khasminskii's method the ergodic properties of the process are obtained and the corresponding invariant measure is characterized.

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5.4.3 Computing the Frequency of Deformations for Elasto-Plastic Oscillators

Participants: Laurent Mertz and Cyril Feau

Statistical properties of the response of an elasto-plastic oscillatior under white noise excitation is considered by means of its invariant measure and a modification of Rice's formula for the frequency of threshold crossings The mean frequency of threshold crossings is then obtained as the solution of a partial differential equation.

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6. Publications

2007

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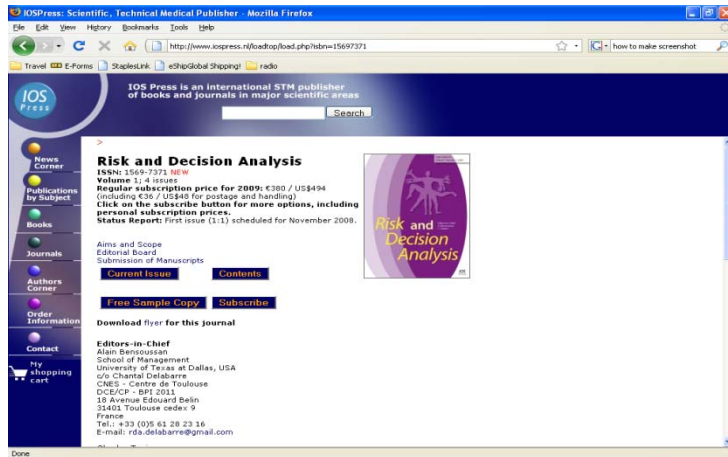
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