



**Activity Report**

**December 1st, 2015**



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Naveen Jindal School of  
Management  
Alain Bensoussan  
Ashbel Smith Chair  
Professor  
Director

**THE UNIVERSITY OF TEXAS AT DALLAS  
INTERNATIONAL CENTER FOR DECISION AND RISK  
ANALYSIS**

P.O. BOX 830688 SM30 RICHARDSON, TEXAS 75083-0688  
(972) 883-5970 FAX (972) 883-5850



**ICDRiA Activity Report 2015**

**1. INTRODUCTION**

The International Center for Decision and Risk Analysis was created in September of 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 2015. The cooperation with the Johnson School of Engineering and Computer Science, on the domains of cyber security, systems engineering and energy management is developing in a very positive manner. The cooperation with City University Hong Kong has elicited visits of professors and PhD students. Discussions for setting a dual degree are underway, but not yet finalized.

**2. FUNDING**

**2.1 “EREN Development”**

Optimization of Wind Farms and Solar Plants Facilities: Competitive Markets  
Alain Bensoussan (PI)  
150,000€ (\$190K)  
October 20, 2014 – October 19, 2017

This activity is performed with Professor Alexandre Brouste, University du Maine, as co PI. Professor Brouste will be associated with the center in a formalized way, starting 2016.

**2.2 Mean Field Games, Mean Field Type Control and Extensions**

National Science Foundation  
Alain Bensoussan (PI)  
\$ 339,572, October 1, 2013- September 30, 2016

**2.3 RGC, General Research Fund, Hong Kong**

Mean Field Theory, Stochastic Control and Systems of Partial Differential Equations  
Alain Bensoussan (PI)  
HK\$ 423,562, October 1, 2013-September 30, 2016

We recall the objective of the contract with EREN Development. We are dealing with new markets, for which there is no precedent. So far, the power providers, relying on wind and solar energy, can benefit from a privileged status,

which is the consequence of the general political will to reduce environmental risks, occurring from classical power plants. Their profitability is protected by a system of subsidies or guaranteed markets. This is changing rapidly. The providers, exploiting a park of turbines or solar plants, will compete on markets which will be open and without backing from public sources. In this context, the profitability will highly depend on the way risks are managed. In view of the fact that things can change fast, and that many players will enter these new markets, the best preparation will be an essential asset for success.

The type of problem to be faced by the provider is to guarantee a given amount of energy, for a given duration, at a given price. The contract commitment is for some future date, which can be short term or longer. The major difficulty is that the capacity of production comes from wind turbines and solar plants. Therefore, this capacity is highly dependent on the wind speed and direction, or sun availability. Consequently the capacity is highly random. The problem is to assess the risk of bidding for a contract.

This year we have been developing short term forecasting models for wind speed.

Concerning NSF, we are applying for a new grant on mean field control theory. This is done jointly with Dr. Jameson Graber as a co PI. Recalling that Dr. Graber has been recruited on the current grant, it is certainly a positive outcome of the current grant, that the PI and the co PI have formed a solid team, able to write a completely new joint proposal.

### **3. EDUCATION PROGRAM**

Risk and Decision Analysis is included in the education programs of the Jindal School of Management. The course is taught in the fall every other year and is also part of the program “Systems Engineering and Management” which is a joint venture between the School of Engineering and the School of Management. The course is now well established, although not taught anymore by Alain Bensoussan.

The course “Introductory Mathematical Finance” has been offered as a part of the Master in Finance in fall since 2008. The class attracts motivated students and is attended by doctoral level students as well. It is however now completely taught within the Finance area, without ICDRiA involvement.

The major effort is now devoted to a new class “Stochastic Dynamic Programming and applications to Operations Management and Finance” It is taught for the 1<sup>st</sup> time in Fall 2015. Stochastic Dynamic Programming is a general methodology which plays an essential role in many areas of economics and management science. It deals with decision making under uncertainty for dynamic systems, which is the situation appearing commonly in a lot of applications. Although this fact has been known for long time, it has become even more evident in view of the new problems which are presently at the forefront of research.

This is particularly true for mathematical finance, whose developments have motivated many innovative techniques related to SDP (Stochastic Dynamic Programming). The consumer-investor problem of Merton is the most famous one, but option pricing, credit risk, corporate finance, optimal compensation and many others have originated substantial new effort and interest in SDP related techniques.

In Operations Management, the application of SDP goes back to inventory theory, with the well-known base stock and s, S policies. However, the structure of the supply chain has become very complex, and has justified new approaches, in particular the use of principal-agent methodology. For realistic situations, one has to consider dynamic systems, with moral hazard problems, asymmetric information, risk-sharing issues and incentives considerations. A lot of interest is related to linking Operations Management with other management domains, like Marketing and Finance. The issue of pricing, traditionally a marketing question, is now considered together with capacity planning and inventory control. This new and very important topic is called revenue management. Dynamic models are essential, and lead to substantial extension of SDP.

Investment theory, growth of firms and real options are now connected and elicit new questions related to SDP methodology. As soon as there are several decision makers, in competition, or contracting with each other, the issue of information comes naturally, with very delicate questions, for each intuition is of little help. A solid theory

requiring sophisticated mathematical techniques is imperative. Even if mathematics is not the objective, it is indispensable to be comfortable with some of these techniques and concepts.

The case of a very large number of decision makers leads to the question of dynamic equilibrium, topics of strong interest in economics, but also for financial markets, and social networks. “Big data” has become the new framework, and involves new statistical problems, advanced simulation techniques and stochastic optimization with dynamic structure. All these considerations have amply modified the type of background which is indispensable to perform relevant research in the current circumstances. They all have to do with stochastic dynamic programming and its evolution.

#### **4. RESEARCH PROGRAM**

The activities of the center are presented 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;
- 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. Currently, Alain Bensoussan is Co-PI of two NSF grants, with Murat Kantarcioglu as P.I. : *TC: Large: Collaborative Research: Privacy-Enhanced Secure Data Provenance*, initiated in 2011, which runs till 2016, and *TWC Medium: Collaborative Incentive Compatible Privacy Preserving Data Analytics, which runs till 2018*.

We have now obtained a set of interesting models, dealing with IDS (Intrusion Detection Systems), Hackers and Botnets. We use control theory as well as differential games. We look at defense in cybersecurity as an investment, to be dealt with the framework of cost-benefit analysis. 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.

One can define a criterion for the botnet herder. This criterion is itself the result of 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.

A new recent finding concerns connections between Mean Field Games and Cybersecurity. Indeed, let us take the situation of botnets. We have a large network of computers. Each of them is an individual agent, which has a defense strategy and a level of infection. But the more the network is infected, the more each computer will face a risk of infection, because of contamination, as in the spreading of epidemics. With a colleague from Warwick University, we have found that this aspect is amenable to Mean Field Games theory, so that we can consider the network as an entity, characterized by a state of infection. In this way, the averaging effect leads to a substantial simplification in defining the defense strategy.

We are very happy to be associated with the center for cybersecurity, which is extremely dynamic and offers the opportunity of interesting and challenging new areas of research.

## 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 many years.

We have developed a general methodology which provides the optimal policy for managing inventories in the context of uncertainties. This is an original result that was not known before. It is now commonly referred in the field. 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.

The usual approach in inventory management is to reduce the uncertainty in the inventory level by using technology which provides accurate counting, like RFID technology.

Our approach follows the idea of fault tolerant systems. We do not correct the pathology, which is the uncertainty, but we incorporate it in the decision making. In practice we combine both.

We have been addressing new sources of uncertainty, in particular shrinkage, which may imply serious risks on the inventory. The Inventory Manager observes the level of sales. Our general methodology applies.

A general situation in which the methodology works well is *learning*. This is a common situation when one tries to learn about the demand. Demand is of course an essential source of risk for companies and also provides a wide diversity of modeling possibilities. As an example, we have studied in Hong Kong the situation of dynamic inventory management of nonperishable products with a Poisson demand process. We learn on the demand rate through past sales. We have compared three scenarios, no observation of the sales, full observation and partial information.

Inventory Management in the context of global supply chain is the source of numerous research problems. In fact, it is more and more connected to the definition of contracts with suppliers. Big issues concern the setting of incentives, the issue of moral hazard, the sharing of risks and the lack of information.

In these new directions, we have initiated two actions, involving new participants at UTD as well as in Hong Kong. One concerns a “Principal-Agent approach to inventory control” We propose a contractual approach between a supplier and a retailer. The inventory manager, the supplier or principal, proposes a contract to the retailer, based on a replenishment policy of base stock type. This guarantees the availability of the product to the retailer, against the payment of a premium. There is an asymmetry of information. The retailer (Agent) knows the demand better than the supplier (Principal). He provides some information to the principal. The issue for the principal is to design the contract so that it has the revealing property; the agent has no interest in distorting the information. Besides the design of the contract, the problem of the principal is to choose the time when he proposes the contract. This leads to problems of optimal stopping in inventory control with partial information, which is new and challenging.

The second direction has been initiated in Hong Kong. It concerns simultaneous inventory and pricing optimization. This is a very natural problem, considered in the literature with primitive techniques. More advanced mathematical techniques should be used to handle it. The version in continuous time is completely open, and we have solved the case called “base stock, list price” in the literature, studied in discrete time. It is the topic of the dissertation of a PhD candidate in the mathematics department. We are currently working on the case with set up cost. Moreover, when prices are decision variables, we have a natural extension to games, when firms compete in pricing. This is an extremely challenging problem, offering a lot of possibilities.

### 4.3. RISKS IN FINANCIAL AND ECONOMIC SYSTEMS

In the third direction, we are considering several questions. Financial Engineering is a particularly challenging domain, and the current crisis has introduced new research aspects. In particular, there should be stronger connections between financial decisions and risk management and between the financial world and the 'real world'.

In the context of coupling the financial world to the real world, we are particularly active in the area 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 similar domains.

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, with Celine Hoe, who now holds a position at Texas A&M. With another post-doc, Benoit Chevalier-Roignant, we have connected the methodology of real options to that of building capital in firms. This is a very well-known problem in economics, under the name of growth of firms. Real options are linked with management science and finance.

These questions have been considered separately in the literature. They are obviously linked; a firm builds its capital through projects. We can formulate the general problem as an impulse control problem. We have obtained new results, to characterize the optimal policy. It must be emphasized that, in spite of a huge literature, only partial results existed so far. We consider a comprehensive approach. Several publications are under way. The impulse control problems which arise in this context are quite new and challenging. We have delicate free boundary problems to solve.

Also, with colleagues from Ajou University we have been considering interesting questions related to credit risk. We solved a problem of defining the relation between a loan and its reimbursement taking into account the possibility of default. We have now a general methodology to solve dynamic programming for this type of situations. With other Korean colleagues, problems related to optimal retirement policies have been also considered. These problems become more and more popular, in view of the uncertainties linked with health and active life duration. We have worked on the incomplete market case and obtain solutions when the incompleteness is sufficiently small.

A major effort of research is devoted to *Mean Field Theory*. This is a direction of research initiated a few years ago, which has become extremely popular in many countries. The general idea is to apply concepts well known in Physics, and deemed very useful, to social and economic sciences. The objective is to study the systemic risk, and more generally the influence on decisions of a large community of agents, with characteristics similar to the decision-maker. This impact is in general discarded, because of its complexity. Note that this is different from equilibrium theory in economics.

In equilibrium theory, one takes decisions based on market prices. These prices reflect the interactions between all players, but they remain external for the agent, unlike in the mean field theory, in which the effect of the large community is endogenous. This theory is becoming popular in many other domains, like traffic congestion, consumer behavior, or information technology.

Our efforts in this domain are supported by an NSF grant and RGC-GRF grant. We have studied the new concept, called "The Master Equation" It encapsulates the system of Hamilton-Jacobi-Bellman and Fokker-Planck equations which represents the core of the mathematical problems to be addressed in Mean Field Games. Jameson Graber has obtained significant results in Mean Field Games application to economic problems, related to the exploitation of exhaustible resources.

#### **4.4. RISKS AND UNCERTAINTIES IN ALTERNATIVE ENERGIES**

We continue our research in this domain, with cooperation with EREN Development. It concerns forecasting wind energy. We recall that 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.

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 been well received by EDF. We have shown that a substantial amount of risk is presently overlooked in the literature and by practitioners. This has been the work with EDF, which is now implemented by the company. Our contribution has been to identify a structural risk, previously neglected, and not negligible, arising from the correlation between periods. We have also considered the impact of seasonality. Since seasonality leads to an improvement of accuracy, we can obtain formulas which reduce the structural uncertainty.

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. In addition, the potential surplus of wind energy is a problem since a storage facility has to be available; these questions are related to smart grid management, which is a huge area of research. This domain is more and more popular. Thanks to the support of EREN Development, we have developed methods of various kinds to forecast wind energy in the short term. We have tried to connect short term and long term aspects. We have considered diffusions, whose ergodic behavior is a Weibull probability distribution. This is because the Weibull distribution is commonly used to model long term wind speed. We intend to test these models in practical cases, with data obtained from EREN.

#### **4.5. RISKS ON TECHNICAL SYSTEMS**

Unfortunately, we do not have support anymore in this domain, since CEA has decided not to renew the support. It is understandable after 10 years. Nevertheless we continue a scientific cooperation with Dr. Laurent Mertz, currently Professor at the University of Nice. He is in fact, on leave to New York University, first at Courant Institute and now at the NYU campus of Shanghai. Promising works in collaboration with Prof. George Stadler from Courant Institute and Prof. Jonathan Wylie from City University of Hong Kong are under way.

We have a good record of publications in this area, and on practical standpoint, we have obtained explicit formulas for the fatigue of a material which goes from elastic to plastic stages. These formulas are very much appreciated by practitioners, which rely mainly on simulation to obtain them. From the theoretical point of view, we have introduced new random processes and have studied their ergodic properties. This provides the mathematical framework to perform the calculations of quantities of interest to engineers, like fatigue of materials, which otherwise are accessible only through simulation.

### **5. PRESENT ACTIVITIES**

#### **5.1. ACTIVITIES IN THE INFORMATION SYSTEMS DOMAIN**

##### **5.1.1. Predictive Analytics for Readmission of Patients with Congestive Heart Failure**

Participants: Indranil Bardhan, Cath Oh, Eric Zheng, Kirk, Kirksey

Mitigating preventable readmissions, where patients are readmitted for the same primary diagnosis within thirty days, poses a significant challenge in the delivery of high quality healthcare. Toward this end, we seek to understand whether health information technologies (IT) can help lower readmission risks. We develop a novel,



predictive readmission model, termed as the beta geometric Erlang-2 (BG/EG) hurdle model, which predicts the propensity, frequency, and timing of readmissions of patients diagnosed with congestive heart failure (CHF). This unified model enables us to study the role of health IT applications, as well as patient demographics and clinical factors, in terms of their association with the risk of patient readmissions. The BG/EG Hurdle model provides superior prediction performance compared to extant models such as the logit, BG/NBD hurdle, and EG hurdle models. We test our model using a unique dataset that tracks patient demographic, clinical, and administrative data across 67 hospitals in North Texas over a four-year period. We find that health IT, patient demographics, visit characteristics, payer type, and hospital characteristics are significantly associated with readmission risk. We observe that implementation of cardiology information systems is associated with a reduction in the propensity and frequency of future re-admissions, while administrative IT is correlated with a lower frequency of future readmissions. Our results indicate that patient profiles derived from our model can serve as building blocks for a clinical decision support system to identify CHF patients with high readmission risk.

Bardhan, I., Cath Oh, Z. Zheng, K. Kirksey. "Predictive Analytics for Readmission of Patients with Congestive Heart Failure: Analysis Across Multiple Hospitals" *Information Systems Research* **26** (1), 2015, 10 - 30.

### **5.1.2. Know Yourself and Know Your Enemy: An Analysis of Firm Recommendations and Consumer Reviews in a Competitive Environment**

Participants: Jabar Wale and Eric Zheng

Reviews and product recommendations at online stores have successfully enabled customers to readily evaluate alternative products prior to any purchase. In this context, firms generate recommendations to refer customers to a wider variety of products. They also display customer-generated online reviews to facilitate evaluation of those recommended products. This study integrates these two IT artifacts in order to investigate consumer choice vis-à-vis competing products. We use a dataset collected from Amazon.com consisting of books, sales ranks, recommendations, reviews, and reviewers. We derive the granular impact of reviews, product referrals, and reviewer opinions on the dynamics of product sales within a competitive market using comprehensive econometric analyses.

Jabar, W. and Z. Zheng. "Know Yourself and Know Your Enemy: An Analysis of Firm Recommendations and Consumer Reviews in a Competitive Environment" *MIS Quarterly* **38** (3), 2014, 635-654.

### **5.1.3. De-biasing the Reporting Bias in Social Media Analytics**

Participants: Hongyu Chen, Eric Zheng, Yasin, Ceran

User-generated contents (UGC) such as online reviews are inherently incomplete since we do not capture the opinions of users who do not write a review. These silent users may be systematically different than those who speak up. Such differences can be driven by users' differing sentiments towards their shopping experiences as well as their disposition to generate UGC. Indiscriminately aggregating UGC across different sentiment levels can lead to an aggregation bias and overlooking the silent users' opinions can result in a reporting bias. We develop a method to model users' UGC generating process and then rectify these two biases simultaneously through an inverse probability weighting (IPW) approach. In the context of users' movie review activities at Blockbuster.com, we found that the average probability for a customer to post a review is 0.06 when the customer is unsatisfied with a movie, 0.23 when indifferent, and 0.32 when satisfied. A user's reporting probability with positive experience first order stochastically dominates the one with negative experience. We then adjust common UGC measures such as review volume and sentiment using these estimated reporting probabilities as weights. We show that these rectified measures yield superior predictive power, as opposed to the raw ones. Our proposed approach provides a realistic solution for business managers to properly utilize incomplete UGC.

Chen, H., Z. Zheng, Y. Ceran. 2015. De-biasing the reporting bias in social media analytics. Forthcoming in *Production and Operations Management*.

#### **5.1.4. Digression and Value-Concatenation to Enable Privacy-Preserving Regression.**

Participants: Xiao-Bai Li and Sumit Sarkar

Regression techniques can be used not only for legitimate data analysis, but also to infer private information about individuals. In this paper, we demonstrate that regression trees, a popular data-analysis and data-mining technique, can be used to effectively reveal individuals' sensitive data. This problem, which we call a "regression attack," has not been addressed in the data privacy literature, and existing privacy-preserving techniques are not appropriate in coping with this problem. We propose a new approach to counter regression attacks. To protect against privacy disclosure, our approach introduces a novel measure, called *digression*, which assesses the sensitive value disclosure risk in the process of building a regression tree model. Specifically, we develop an algorithm that uses the measure for pruning the tree to limit disclosure of sensitive data. We also propose a dynamic value-concatenation method for anonymizing data, which better preserves data utility than a user-defined generalization scheme commonly used in existing approaches. Our approach can be used for anonymizing both numeric and categorical data. An experimental study is conducted using real-world financial, economic and healthcare data. The results of the experiments demonstrate that the proposed approach is very effective in protecting data privacy while preserving data quality for research and analysis.

X. Li and S. Sarkar "Digression and Value-Concatenation to Enable Privacy-Preserving Regression," *MIS Quarterly*, September, 2014, **38**, (3), 679-698

#### **5.1.5. Privacy and Big Data: Scalable Approaches to Maximize the Accuracy of Large Transactional Databases Sanitized for Sharing.**

Participants: Syam Menon and Sumit Sarkar

Scalability and privacy form two critical dimensions that will eventually determine the extent of the success of Big Data analytics. We present scalable approaches to address privacy concerns when sharing transactional databases. Although the benefits of sharing are well documented and the number of firms sharing transactional data has increased over the years, the rate at which this number has grown is not quite what it could have been – concerns about revealing proprietary information have prevented some retailers from sharing, despite its obvious advantages in an increasingly networked economy. In the context of sharing transactional data, sensitive information is typically based on relationships derived from frequently occurring item sets – a result of surprisingly successful promotions by the retailer, or unexpected relationships identified by the retailer while mining the data. Prior work in this area includes optimal approaches based on integer programming to maximize the accuracy of shared databases, while hiding all sensitive item sets. While these approaches were shown to solve problems involving up to 10 million transactions, many transactional databases in the Big Data context are considerably larger and the existing integer programming-based procedures do not scale well enough to solve these larger problems. Consequently, there is no effective solution procedure for such databases in extant literature.

We first present an optimal procedure leveraging intuition from linear programming based *column generation*. Next, we identify a common structure that exists in these problems, and show how it can be taken advantage of through an approach based on sorting and column generation to make the process more efficient. We then illustrate how this structure can be incorporated into the column generation based procedure to develop an effective, scalable heuristic. Computational experiments are conducted on databases with 50 and 100 million transactions, involving problems that could not be solved using existing optimal procedures. These experiments show that the optimal column generation based procedure can solve problem instances significantly larger than those tackled previously, and that the scalable heuristic identifies near-optimal solutions quickly in all instances where the optimal solution is known. We investigate the impact of hiding sensitive itemsets on the quality of a rule-based recommender system derived from the shared data. As expected, recommendation quality decreases as the number of sensitive itemsets increases; however, recommendation accuracy stays above 80% of the original rate when using the unmodified data even when there are 1,000 sensitive itemsets to hide. The effect on recommendation accuracy from using the heuristic relative to the optimal approach was very small – the accuracies with the heuristic were over 97% of the corresponding accuracies with the optimal approach in every experiment, and over 99% in the vast majority.

S. Menon and S. Sarkar “Privacy and Big Data: Scalable Approaches to Maximize the Accuracy of Large Transactional Databases Sanitized for Sharing” forthcoming in *MIS Quarterly*.

### **5.1.6. Privacy Preserving Techniques for Shared Distributed Transactional Databases.**

Participants: Jing Hao, Abhijeet Ghoshal, Syam Menon and Sumit Sarkar

Many retailers, including strong advocates of standardization like Wal-Mart and Macy's, are adapting to a changing economy by increasing customization to accommodate the tastes of local clientele. The effective execution of this transition is facilitated by the advances in data capturing and mining technologies of recent years, which provide retailers with a much better understanding of local buying habits than ever before. Another increasing trend in the retail industry is the sharing of point-of-sale (POS) data with business partners, as the mining of this data can result in significant benefits to all parties involved. The need to hide sensitive information prior to sharing this data has been well documented. The increase in localization makes the hiding of sensitive information far more difficult, as sensitive information can now exist both at the local and corporate levels. Sensitive information in the context of POS data often exists in the form of patterns across items in transactions. In this paper, we present approaches to maximize the accuracy of shared POS databases while hiding sensitive information at both levels. We first present an integer programming formulation to represent this problem. As these formulations are usually too large to be solved directly, we propose three heuristics that exploit the distributed nature of the data by decomposing the larger problem into a series of smaller ones. Extensive computational testing shows that these procedures perform significantly better than existing approaches, and consistently identify optimal or near-optimal solutions. In addition, these tests show that the proposed procedures solve problems that are too large to be solved optimally.

J. Hao, A. Ghosal, S. Menon and S. Sarkar. Privacy Preserving Techniques for Shared Distributed Transactional Databases, Working Paper.

### **5.1.7. Managing Hot Lists in Intrusion Detection and Prevention Systems**

Participants: Vijay Mookerjee, Radha Mookerjee, and Subodha Kumar

We study the problem of minimizing total cost for an Intrusion Detection and prevention Systems (IDPS). The IDPS system monitors the items that are possible courses of attacks. The objective of the monitoring problem is to minimize the sum of attack costs and the monitoring cost. The key tradeoff in our model is that as more items are monitored, the attack costs should reduce. However, the monitoring cost would likely increase with the number of items being monitored. We use a stochastic differential equation model to describe the dynamics of the monitoring process. As key step in solving the problem is to derive the probability density of a system with  $n$  items being monitored with specified elapsed times. Once this probability density is derived, we are able to determine the average attack rate from the hot-list. We next optimize the number of items being monitored by trading off the attack cost saved with the cost of monitoring.

Mookerjee, R., Kumar, S., and Mookerjee, V., “*Managing Hot-Lists in Intrusion Detection and Prevention Systems*,” Conference on Information Systems and Technologies, 2013.

### **5.1.8. Optimal Information Security Investment under Uncertainty**

Participants: Vijay Mookerjee, Monica, Johar and Jing Zhou

This paper presents a control theoretic model to manage a firm's information security level over time in a given planning horizon. Most of the previous literature on information security investment is based on a deterministic analysis, where the security level is managed as a function of the maintenance effort over a given time period. In

reality, however, firms need to maintain information security in a situation where the efforts made to improve the security have a non-deterministic impact on the level security. We study the problem of determining the optimal amount of effort that should be exercised so as to minimize the expected total cost (cost of effort plus vulnerability cost) over a planning horizon. Our findings can help firms decide on how to manage IT security given the characteristics of the security environment and the efficiency of maintenance effort.

Johar, M., Zhou, J., Mookerjee, V. “*Optimal information Security Investment Under Uncertainty*,” Conference on Information Systems and Technologies, 2014

### **5.1.9 Online Rating Games**

Participants: Alain Bensoussan, Celine Hoe, Murat Kantarcioglu

Traditionally, consumer purchase decisions were based on advertisements or product information provided by vendors. With the proliferation of e-commerce and increasing number of Internet review forums, it has been found that consumers have increasingly relied on online reviews for their search of information related to a variety of products. Realizing that online reviews can be a powerful and cheap promotional tool, marketers and vendors have used this medium to reach their customers. Reports have shown that promotional chat has infiltrated the online review forums, and reviews manipulation is known to exist widely in popular websites related to e-commerce, travel, and music. Existing literature focuses on the detection of online manipulative reviews and the impact of online reviews on consumers’ purchase decision. We extend the exploration to incorporate the discussion of (1) Can online sellers such as Amazon be incentivized to adopt appropriate tools to provide objective ratings, and if so, what is their optimal spending, and (2) How can manipulative ratings be discouraged and (3) What is the dynamic equilibrium of online rating environment with manipulation potential from the attacked and the preventive measures taken from the online sellers.

## **5.2. Activities in the Supply Chain Domain**

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.

### **5.2.1. Mean and Mean-Variance Based Policies for an Inventory Model with Incomplete Information**

Participants: Alain Bensoussan, Metin Çakanyildirim, Meng Li, Suresh Sethi

Inventory problems with incomplete demand/inventory information arise frequently in practice, with no simple optimal policies. We develop simple implementable policies based on mean and mean-variance of the inventory level when unmet demand is lost, filled demand is observed as sales and inventory level is detected when it reaches zero. The mean based approximation has the customary dynamic program of the completely observed problem giving rise to a basestock policy, whereas the mean-variance based approximation comes from a novel approach yielding a dynamic program that resembles a mixture of the dynamic programs of the completely and incompletely observed problems. Costs (resp. policies) of these approximations yield lower (resp. upper) bounds for the actual cost, and the bounds obtained from the two moment based approximation are tighter. Moreover, despite having no clear relation to the mean based approximation in terms of information availability, the mean-variance based approximation reduces to the mean based approximation when the variance is zero. While the mean-based policy gives an approximation, the mean-variance based policy provides a better approximation in the sense that the upper and lower bounds exhibit a narrower gap.

### 5.2.2. Inventory Control with a Cash Register: Sales Recorded but Not Demand or Shrinkage

Participants: Alain Bensoussan, Metin Çakanyildirim, Meng Li, Suresh Sethi

Inventory inaccuracy is common at retailers. At many retailers, a cash register records incoming orders and outgoing sales, but not the demand or the shrinkage. The shrinkage refers to spoilage or pilferage of inventory. The demand differs from the sales in the periodic-review lost-sales inventory model presented in this paper. The inventory is subject to an unobserved shrinkage which happens both before and after the demand. When the remaining inventory exceeds the demand, the unmet demand is lost and unobserved. Our objective is to minimize the expected discounted cost related to inventory holding and shortage over an infinite horizon. We use dynamic programming along with the concept of unnormalized probability, and prove the existence of an optimal feedback policy and that the values function is the solution of the dynamic programming equation. We obtain a theoretical lower bound for the cost via the formulation of a fictitious inventory problem. We develop an iterative algorithm, and compare its solution to a myopic solution and a lower bound. We identify many cases of parameter values for which the solution of the iterative algorithm performs significantly better than the myopic solution. Moreover, the achieved cost is close to the lower bound.

Bensoussan, A., Çakanyildirim, M., Li, M and Sethi, S.P. Existence and Uniqueness of Solutions for a Partially Observed Stochastic Control Problem, in *Stochastic Processes, Finance and Control*, A Festschrift in honor Of Robert J. Elliot, Samuel N. Cohen, Dilip Madan, Tak Kuen Siu and Hailiang Yang, (Eds.) World Scientific, 2012 393-43

Bensoussan, A., Çakanyildirim, M., Li, M and Sethi, S.P., “Optimal Inventory Control with Shrinkage and Observed Sales,” *Stochastics: An International Journal of Probability & Stochastic Processes*, Taksar Memorial Issue, 2013, 85(4), 589-603

Bensoussan, A., Çakanyildirim, M., Li, M and Sethi, S.P. “Managing Inventory with Cash Register Information: Sales Recorded but Not Demands,” *Production and Operations Management*, August 2014.

### 5.2.3 “The Impact of Limited Supply on a Firm’s Bundling Decision”,

Participants: Kathryn Stecke, Qingning Cao and Jun Zhang *Production and Operations Management*, forthcoming, 2016

A firm’s two-product bundling decision is examined when the supply of one product is limited and consumer valuations are normally distributed. The firm can choose to sell products separately and/or through a bundle. We find that the impact of limited supply on a firm’s bundling decision depends on the correlation between the consumer valuations of the two products as well as the symmetry level of the two products in terms of their attractiveness (how much they are valued by consumers). When the valuation correlation is high and the symmetry level of the two products is low, limited supply can drive bundling. When the valuation correlation is low or the symmetry level is high, limited supply can drive no bundling. When the attractiveness of both products is low or the valuation correlation is very high, limited supply has no impact on a firm’s bundling decision: The firm should not bundle for all supply levels.

This study offers a new driver for product bundling: the limited supply of a product. The existing bundling literature suggests that a firm should bundle symmetric products that have a low consumer valuation correlation, when bundling is driven by consumer valuation heterogeneity reduction. In contrast, when bundling is driven by limited supply, a firm should bundle asymmetric products with a high consumer valuation correlation. The benefit of supply-driven bundling depends on the severity of supply limitation. When supply limitation is moderate, bundling creates value by expanding the market of the less attractive product. When supply limitation is severe, bundling enables a firm to extract a higher margin from the less attractive product.

#### **5.2.4 “Various Strategies to Handle Cannibalization in a Competitive Duopolistic Market”,**

Participants: Kathryn Stecke, Ernan E. Haruvy and Di Miao, *International Transactions in Operational Research*, Vol 20, No. 2 (March 2013)

We investigate an incumbent’s optimal sequential introduction of new products over two periods in a competitive duopoly setting. On the one hand, the firm would like to preempt and counter competition from a future entrant. On the other hand, the firm should consider that one of its products might decrease sales for another product, a threat commonly known as cannibalization. Three sequential introduction strategies are examined. We find that a firm’s optimal introduction sequence is governed by pressures from competition and cannibalization in the market. In general, competition has greater impact on firms’ profits than cannibalization. Introducing a high-end product before a low-end product can alleviate cannibalization for a weak entrant. In particular, the profit loss caused by competition is greater than that caused by cannibalization. When competition is intense, firms should consider alleviating the profit loss from competition over cannibalization by introducing a low-end product before a high-end product. In that case, the incumbent’s high-end product’s quality must be no lower than the entrant’s quality but the profit is derived mostly from the mark-up on the low end product. Much of the high-end product’s profit is sacrificed in order to maximize profit from the entire product line. When cannibalization is intense and competition is mild (due to a weak entrant), the incumbent’s profit gap between the high-end and low-end products is high. In that case, the firm can no longer afford to sacrifice its high end products’ profit and the order of introduction reverses.

#### **5.2.5 When Does Advance Selling Benefit Manufacturers, Retailers, or Both?”**

Participants: Kathryn Stecke, Xuying Zhao and Zhan Pang

Advance selling (AS) from a retailer to consumers is commonly observed in practice. With an AS capability, a retailer has the option to sell in advance or not. Having the AS option seems to increase flexibility and thus profit for a retailer. However, we show that the AS option can hurt the retailer's profit as well as supply chain performance. We identify two thresholds for a product's marginal production cost. A retailer's AS option benefits both the manufacturer and retailer when the marginal production cost is high, i.e., above both thresholds. It benefits the manufacturer but hurts the retailer when the marginal production cost is moderate, i.e., between the two thresholds. We find that consumer valuation uncertainty under AS is the key driving force for the surprising result that having the retailer's AS option can hurt the retailer. When compared to the scenario where the retailer does not have the AS option, we find that the manufacturer's optimal wholesale price weakly decreases under the retailer's AS option if the marginal production cost is high. The statement is reversed if the marginal production cost is moderate or low.

#### **5.2.6. “An Analysis of Trust, Employee Trustworthiness, Fraud, and Internal Controls”**

Participants: Sanjay Kumar, Ashutosh Deshmukh, Kathryn Stecke and Jiangxia Liu

We analyze important strategic relationships among trust, employee trustworthiness, fraud, and internal controls. A game is modeled between a manager and an employee, two rational decision makers. The manager makes control decisions based on the strength of controls and on employee trustworthiness, which are modeled as functions of monetary and psychic costs and benefits of committing and not committing fraud. We propose a rich definition of trustworthiness that incorporates an employee’s propensity to commit fraud and sensitivity to controls. Equilibrium strategies are identified that could be used to determine the best strategy and the optimum strength of controls to use by identifying trustworthy, untrustworthy, and opportunistically trustworthy employees.

A relationship of trustworthiness with a probabilistic choice of controls by the manager is established. As the strength of controls increases, the trustworthiness of the employees also increases, but a minimum critical level of trustworthiness is required to make controls effective.

A high level of control may be needed to deter fraud. Also, this increase in trustworthiness does not translate to a proportional reduction of controls by the manager. We caution against excessive investments in internal controls. A low strength control with high probability of controls may be a cost effective way to deter fraud. We also explore

the interaction of controls strength with the losses to the manager when fraud is committed. We find that control is not always a viable strategy. Optimal payoffs indicate that, unlike simultaneous decision making, under sequential decision making, the manager's best strategy is to choose controls and auditing an employee. Policy implications and managerial insights of these findings are discussed.

“An Analysis of Trust, Employee Trustworthiness, Fraud and Internal Controls,” K. Strecke, Sanjay Kumar, Ashutosh Deshmukh and Jiangzia Liu, *International Journal of Strategic Decision Sciences*, Vol 4, No. 3, pp 66-89 (2013)

### **5.2.7 Optimal Transshipments and Reassignments Under Periodic or Cyclic Holding Cost Accounting**

Participants: K. Strecke, Nagihan Çömez, me, and Metin Çakanyildirim

In a centrally-managed system, available inventory at a retailer can be transshipped to a stocked-out retailer to meet customer demand. On the other hand, since the inventory at the former retailer may be in demand for future customers of that retailer and transshipment time/cost is non-negligible, it can be more profitable to not transship. An optimal transshipment policy suggests transshipping in some situations, but not always. Unsatisfied customer demand can be backordered. As demand uncertainty resolves over time, the cost trade-off between backordering at the stocked-out retailer and holding inventory at the other retailer changes. Hence reassignment of inventory to a previously backordered demand can perhaps become profitable. Despite this intuition, we prove that *no reassignments* are necessary for cost optimality under periodic holding cost accounting. On the contrary, reassignments are necessary for optimality when holding costs are accounted for only at the end of each cycle. However they save costs not significantly. These results facilitate efficient optimization of transshipments over time.

### **5.2.8 “Optimal Transshipments and Reassignments Under Periodic or Cyclic Holding Cost Accounting,”**

Participants: Nagihan Çömez, Kathryn E. Stecke and Metin Çakanyildirim, *Journal of the Operational Research Society*, Vol 64, Issue 10, pp1517-1539 (October 2013)

### **5.2.9. Analysis of Product Rollover Strategies in the Presence of Strategic Customers**

Participants: Metin Çakanyildirim, Suresh Sethi and Chao Liang

Frequent product introductions emphasize the importance of product rollover strategies. With single rollover, when a new product is introduced, the old product is phased out from the market. With dual rollover, the old product remains in the market along with the new product. Anticipating the introduction of the new product and the potential markdown of the old product, strategic customers may delay their purchases. We study the interaction between product rollover strategies and strategic customer purchasing behavior, and find that single rollover is more valuable when the new product's innovation is low and the number of strategic customers is high. Interestingly and counter to intuition, the firm may have to charge a lower price for the old product as well as receive a lower profit with a higher value disposal (outside) option for the old product under single rollover. Facing a market composed of both strategic and myopic customers, the firm does not necessarily reduce the stocking level as more myopic customers become strategic.

Çakanyildirim, M., Liang, C., and Sethi, S.P., “Analysis of Product Rollover Strategies in the Presence of Strategic Customers,” *Management Science*, 2014, 60(4), 1033-1056.

### **5.2.10. Impact of Strategic Customer Behavior and Rollover Strategies on Product Innovation**

Participants: Metin Çakanyildirim, Suresh Sethi and Chao Liang

We study a monopolistic firm which introduces two product versions sequentially in two periods. We analyze and compare the firm's decisions of the innovation level of the new version, the production quantities and prices of both versions, and the associated profit in four settings:

when the customers are myopic or strategic in period 1 and whether the leftover inventory of the old version is phased out from the market (single rollover strategy) or is sold in the market (dual rollover strategy). In period 2, newcomers who wish to buy the new version arrive in the market. We show that the firm can improve both its profit and its innovation level by adopting an appropriate rollover strategy when selling to strategic customers. This finding underscores the importance of choosing a rollover strategy. Interestingly and differently from the existing literature, we see that strategic waiting behavior can accelerate innovation. These insights remain largely valid when some of the customers who cannot get the old version due to a stockout leave the market before the new version arrives, or when some of the newcomers are interested in the new version as well as the leftover old version.

Çakanyildirim, M., Liang, C., and Sethi, S.P., "Impact of Strategic Customer Behavior and Rollover Strategies on Product Innovation - *Submitted*

### **5.2.11. A New Choice Model Based on Willingness to Pay: Empirical Validation & Pricing Applications**

Participants: Metin Çakanyildirim, Varun Gupta

Willingness-To-Pay (WTP) of customers plays an anchoring role in pricing. This paper proposes a new choice model based on WTP, incorporating sequential decision making, where the products with positive utility of purchase are considered in the order of customer preference. We compare WTP-choice model with the commonly used (multinomial) Logit model with respect to the underlying choice process, information requirement, and independence of irrelevant alternatives. Using WTP-choice model, we find and compare equilibrium and centrally optimal prices and profits without considering inventory availability. In addition, we compare equilibrium prices and profits in two contexts: without considering inventory availability and under lost sales. One of the interesting results with WTP-choice model is the "loose coupling" of retailers in competition; prices are not coupled but profits are. That is, each retailer should charge the monopoly price as the collection of these prices constitutes an equilibrium but each retailer's profit depends on other retailers' prices. Loose coupling fails with dependence of WTPs or dependence of preference on prices. Also we show that competition among retailers facing dependent WTPs can cause price cycles under some conditions. We consider real-life data on sales of yogurt, ketchup, candy melt, and tuna, and check if a version of WTP-choice model (with uniform, triangle or shifted exponential WTP distribution), standard or mixed Logit model fits better and predicts the sales better. These empirical tests establish that WTP-choice model compares well and should be considered as a legitimate alternative to Logit models for studying pricing for products with low price and high frequency of purchase.

### **5.2.12. Inventory Commitment & Prioritized Backlogging Clearance with Alternative Delivery Lead Times**

Participants: Haifeng Wang, Xiaoying Liang, Suresh P. Sethi, and Houmin Yan

We propose a model where customers are classified into two groups: short lead-time customers who require the product immediately and long lead-time customers to whom the supplier may deliver either immediately or in the next cycle. Unmet orders are backlogged with associated costs. Specifically, the supplier faces two problems: how the on-hand inventories should be allocated between the two classes of customers and how the backlogged orders should be cleared when replenishments arrive. We treat the former as an inventory commitment problem and handle the latter with priority rules. We characterize and compare the inventory commitment policies with three priority rules in clearing backlogs. We also explore the optimal inventory replenishment decision and evaluate the performance of each priority rule.

Wang, H., Liang, X., Sethi, S.P., and Yan, H., "Inventory Commitment and Prioritized Backlogging Clearance with Alternative Delivery Lead Times," *Production and Operations Management*, 2014, 23(7), 1227-1242.



### **5.2.13 How Does Pricing Power Affect a Firm's Sourcing Decisions from Unreliable Suppliers?**

Participants: Tao Li, Suresh P. Sethi, and Jun Zhang

We study sourcing decisions of price-setting and price-taking firms with two unreliable suppliers, where a price-setting firm sets the retail price after the supply uncertainty is resolved and a price-taking firm takes the retail price as given. We investigate the impacts of market conditions, suppliers' wholesale prices and their reliabilities on the optimal sourcing decisions of price-setting and price-taking firms, and examine how a firm's pricing power affects these impacts. We define a supplier's reliability in terms of the "size" or the "variability" of his random capacity using the concepts of stochastic dominance. We find that the supplier reliability affects the optimal sourcing decisions differently for price-setting and price-taking firms. Specifically, with a price-setting firm, a supplier can win a larger order by increasing his reliability, it is not always so with a price-taking firm.

Li, T. Sethi, S.P. and Zhang, J., "How Does Pricing Power Affect a Firm's Sourcing Decisions from Unreliable Suppliers?" *International Journal of Production Research*, 51(23-24), 2013, 6990-7005.

### **5.2.14 Inventory Sharing with Transshipment: Impacts of Demand Distribution Shapes and Setup Costs**

Participants: Chao Liang, Suresh P. Sethi, Ruixia Shi, and Jun Zhang

We compare site-to-store and store-to-site strategies for dual-channel integration. The site-to-store (resp., store-to-site) strategy can fill unmet orders in the physical channel (resp., online channel) with the inventory in the online channel (resp., physical channel). With one (physical) retail store, when only one channel should have inventory, it is the channel with stochastically larger or less uncertain demand. Otherwise, with both channels carrying inventory, the optimal channel integration depends on product contribution margin and channel demand distribution shape. When there are multiple retail stores, the site-to-store (resp., store-to-site) strategy becomes more attractive for high-margin (resp., low-margin) products with larger number of retail stores. We propose a heuristic that only requires a comparison of online demand standard deviation and the sum of demand standard deviations of retail stores in identifying an effective integration strategy. Finally, we apply our results to a circular spatial model for dual-channel retailing systems and obtain insights on the impact of customer purchasing behavior on strategy selection.

Liang, C., Sethi, S.P., Shi, R., and Zhang, J., "Inventory Sharing with Transshipment: Impacts of Demand Distribution Shapes and Setup Costs," *Production and Operations Management*, **23** (10). 2014, 1779-1794

### **5.2.15 Managing with Incomplete Inventory Information (i3)**

Participants: Suresh P. Sethi and Ruixia Shi

A critical assumption in the vast literature on inventory management has been that the current level of inventory is known to the decision maker. Some of the most celebrated results such as the optimality of base-stock policies have been obtained under this assumption. Yet it is often the case in practice that the decision makers have incomplete or partial information about their inventory levels. The reasons for this are many: Inventory records or cash register information differ from actual inventory because of a variety of factors including transaction errors, theft, spoilage, misplacement, unobserved lost demands, and information delays. As a result, what are usually observed are some events or surrogate measures, called signals, related to the inventory level. These relationships can provide the distribution of current inventory levels. Therefore, the system state in the inventory control problems is not the current inventory level, but rather its distribution given the observed signals. Thus, the analysis for finding optimal production or ordering policies takes place generally in the space of probability distributions. The purpose of this paper is to review some recent developments in the analysis of inventory management problems with incomplete information.

Sethi, S.P. and Shi, R, “Managing with Incomplete Inventory Information (i3),” *Proceedings of the 7th IFAC Conference on Manufacturing, Modeling, Management and Control (MIM 2013)*, Saint Petersburg, Russia, June 19-21, 2013, 1-6.

### **5.2.16 Supply Diversification with Responsive Pricing**

Participants: Tao Li, Suresh P. Sethi, and Jun Zhang

We study sourcing and pricing decisions of a firm with correlated suppliers and a price-dependent demand. With two suppliers, the insight—cost is the order qualifier while reliability is the order winner—derived in the literature for the case of exogenously determined price and independent suppliers, continues to hold when the suppliers’ capacities are correlated. Moreover, a firm orders only from one supplier if the effective purchase cost from him, which includes the imputed cost of his unreliability, is lower than the wholesale price charged by his rival. Otherwise, the firm orders from both. Furthermore, the firm’s diversification decision does not depend on the correlation between the two suppliers’ random capacities. However, its order quantities do depend on the capacity correlation, and, if the firm’s objective function is unimodal, the total order quantity decreases as the capacity correlation increases in the sense of the super modular order. With more than two suppliers, the insight no longer holds. That is, when ordering from two or more suppliers, one is the lowest-cost supplier and the others are not selected on the basis of their costs. We conclude the paper by developing a solution algorithm for the firm’s optimal diversification problem.

Li, T. Sethi, S.P. and Zhang, J., “Supply Diversification with Responsive Pricing,” *Production and Operations Management*, 22(2) 2013, 447-458

### **5.2.17. Feedback Stackelberg Solutions of Infinite-Horizon Stochastic Differential Games**

Participants: Alain Bensoussan, Shaokuan Chen, and Suresh P. Sethi

We present a sufficient condition for a feedback Stackelberg equilibrium of a stochastic differential game on an infinite horizon. This condition gives rise to a system of elliptic partial differential equations involving a static Stackelberg game at the level of Hamiltonian. As an example, we consider a linear quadratic problem, obtain the corresponding algebraic Riccati equation, and provide its solution in the scalar case.

Bensoussan, A., Chen, S., and Sethi, S.P., “Feedback Stackelberg Solutions of Infinite-Horizon Stochastic Differential Games,” *Models and Methods in Economics and Management Sciences, Essays in Honor of Charles S. Tapiero*, Fouad El Ouardighi and Konstantin Kogan (Eds.), Series 6161, Vol. 198 Springer International Publishing Switzerland, 2014, 3-15..

### **5.218 Feedback Stackelberg Games in Operations Management**

Participants: Suresh P. Sethi and Tao Li

Sethi, S.P. and Li, T., “Feedback Stackelberg Games in Operations Management,” *Handbook on Dynamic Game Theory*, T. Basar and G. Zaccour (Eds.), Birkhäuser, 2016, forthcoming.

### **5.2.19 The Implication of Vendor Inventory Liability Period in a Decentralized Assembly System**

Participants: X. Guan and Suresh P. Sethi

Guan, X., Li, G., Sethi, S.P., “The Implication of Vendor Inventory Liability Period in a Decentralized Assembly System,” *International Journal of Production Research*, 2015, forthcoming.

### **5.2.20 Myopic vs. Farsighted Behaviors in a Revenue-Sharing Supply Chain with Reference Quality Effects**

Participants: Gang Liu, Suresh P. Sethi, and Jun Zhang

In this paper, we consider a dynamic supply chain where a manufacturer produces and distributes a featured product through an exclusive retailer to end consumers. The manufacturer decides the product quality and wholesale price, while the retailer sets the retail price in the presence of a revenue-sharing contract and consumers' reference quality effects. The objective of this study is to investigate the impacts of myopic behaviour regarding the reference quality on the product quality and pricing strategies and profits of both members. Our results suggest that the manufacturer's myopia leads to a higher quality, higher price strategy and a higher quality-price ratio which benefits consumers. Meanwhile, relative to the far-sighted behaviour, myopia results in a more quality-sensitive but less price-sensitive market demand. What's more, we find that the manufacturer is apt to act in a far-sighted way, but the retailer isn't always willing to cooperate with a far-sighted manufacturer. Taking myopic strategies for both members is likely to gain a high profit of the whole supply chain for a relatively high marginal contribution of product quality on demand and a relatively low revenue-sharing proportion.

Liu, G., Sethi, S.P., and Zhang, J. "Myopic vs. Farsighted Behaviors in a Revenue-Sharing Supply Chain with Reference Quality Effects," *International Journal of Production Research*, 2015, forthcoming.

### **5.2.21 Integrating Equipment Investment Strategy with Maintenance Operations under Uncertain Failures**

Participants: Alain Bensoussan, Qi Feng, and Suresh P. Sethi

This paper studies the issue of coordinating equipment maintenance operations with capital investment strategy in the presence of random equipment failures. The traditional approach, developed by Kamien and Schwartz (KS) in their celebrated paper published in 1971, is to formulate the problem as a deterministic optimal control problem with the probability of machine failure as the state variable. With this approach, the optimal policy is deterministic. As a major departure from the KS approach, we explicitly model the underlying stochastic process of machine failures. Our analysis of the stochastic dynamic programming model offers new insights into the problem. Under a long planning horizon with a limited replacement opportunity, each individual machine serves as a revenue generator and contributes a significant amount to the profit of the system. In contrast, when the replacement budget is quite generous over a relatively short planning horizon, adding one extra machine only helps as a backup for unexpected failures of the machines purchased before it. An interesting result derived from this comparison is that a deterministic policy turns out to be optimal for the former, while a state-contingent policy must be applied to the latter. In other words, the deterministic KS approach does not work in general when a chain of machine replacement is considered. We further characterize the effects of the discount rate, productivity deterioration, learning, decision delay, and technology advancement on the optimal policy.

Bensoussan, A., Feng, Q., and Sethi, S.P., "Integrating Equipment Investment Strategy with Maintenance Operations under Uncertain Failures," *Annals of Operations Research*, 2015, forthcoming.

### **5.2.22 Competing with Bandit Supply Chains**

Participants: Meng Li, Suresh P. Sethi, and Jun Zhang

Bandit products have captured significant market shares in China and have started to expand throughout the world. A striking feature of supply chains for bandit products is decentralization, where the upstream firm determines the product quality and the downstream firms compete on prices. We study the competition between a centralized mainstream firm and a decentralized bandit supply chain. We demonstrate that the structural difference between the mainstream firm and the bandit supply chain reduces competition intensity and the quality difference between their products. Surprisingly, the inherent inefficiency in a bandit supply chain, combined with

the force of competition, actually leads to both higher product quality and higher price. Furthermore, due to the free-riding effect, the bandit supply chain may even offer higher quality products than the mainstream firm. The mainstream firm's profit as a function of the free-riding effect is U-shaped, so that free-riding by the bandit supply chain may eventually benefit the mainstream firm. Finally, decentralization benefits the bandit supply chain when the competition is on product features.

Li, M., Sethi, S.P., and Zhang, J., "Competing with Bandit Supply Chains," *Annals of Operations Research*, 2015, forthcoming.

### **5.2.23 New Results on the Newsvendor Model and the Multi-Period Inventory Model with Backordering**

Participants: G. Janakiraman, S. Park, S. Seshadro and Q. Wu

We analyze the newsvendor model and the multi-period inventory model, and provide some new results. For the newsvendor model, the best case newsvendor cost over all demand distributions with a given demand mean and variance is zero. In addition, under symmetric demand distributions, the newsvendor's costs remain the same when the holding and shortage costs are switched. For the multi-period inventory model with stochastic lead times, a dilation ordering of lead times implies an ordering of optimal costs.

G. Janakiraman, S. Park, S. Seshadro and Q. Wu, New Results on the Newsvendor Model and the Multi-Period Inventory Model with Backordering, *Operations Research Letters*. 2013 **41**: 4: 373-376

### **5.2.24 Integrality in Stochastic Inventory Models**

Participants: W.Chen, M. Dawande and G. Janakiraman

We study several dynamic, stochastic inventory control models with integer demands: the newsvendor model, its multi-period extension and a single-product, multi-echelon assembly model. Equivalent linear programs are formulated for the corresponding stochastic dynamic programs, and integrality results are derived based on the total unimodularity of the constraint matrices. Specifically, for all these models, starting with integer inventory levels, we show that there exist optimal policies that are integral. For the most general single product, multi-echelon assembly system model, integrality results are also derived for a practical alternative to stochastic dynamic programming, namely rolling-horizon optimization by a similar argument. We also present a different approach to prove integrality results for stochastic inventory models. This new approach is based on a generalization we propose for the one dimensional notion of piecewise linearity with integer breakpoints to higher dimensions. The usefulness of this new approach is illustrated by establishing the integrality of both the dynamic programming and rolling-horizon optimization models of a two-product capacitated stochastic inventory control system.

W. Chen, M. Dawande and G. Janakiraman Integrality in Stochastic inventory Models. *Production and Operations Management*. 2014 **23**:9

### **5.2.25 Managing Inventory with Cash Register Information: Sales Recorded but Not Demands**

Participants: Alain Bensoussan, Metin Çakanyıldırım, Meng Li, and Suresh P. Sethi

Inventory inaccuracy is common in many businesses. While retailers employ cash registers to enter incoming orders and outgoing sales, inaccuracy arises because they do not record invisible demand such as spoilage, damage or pilferage. This setting results in incomplete inventory and demand information. An important inventory control problem therefore is to maximize the total expected discounted profit under this setting. Allowing for dependence between demand and invisible demand, we obtain the associated dynamic programming equation with an infinite dimensional state space, and reduce it to a simpler form by employing the concept of un-normalized probability. We develop an analytical upper bound on the optimal profit as well as an iterative algorithm for an approximate solution of the problem. We compare the iterative solution to the myopic solution and the achieved profit to the upper bound. We show that our solution performs better than the myopic

solution, and significantly so in many cases. Furthermore, the iterative solution gives a profit not far from the upper bound, and is therefore close to optimal. Using our results, we also discuss meeting inventory service levels, inventory counting, and parameter estimation.

Bensoussan, A., Çakanyildirim, M., Li, M., and Sethi, S.P., “Managing Inventory with Cash Register Information: Sales Recorded but Not Demands,” *Production and Operations Management*, 2015, forthcoming.

### **5.2.26 Inventory Theory**

Participants: Suresh P. Sethi

This entry is a brief survey of classical inventory models and their extensions in several directions such as world-driven demands, presence of forecast updates, multi-delivery modes and advanced demand information, incomplete inventory information, and decentralized inventory control in the context of supply chain management. Important references are provided. We conclude with suggestions for future research.

Sethi, S.P., “Inventory Theory,” *Encyclopedia of Systems and Control*, J. Baillieul and T. Samad (Eds.), Springer-Verlag London, 2015, 591-595.

### **5.2.27 Contingent Sourcing under Supply Disruption and Competition**

Participants: Varun Gupta, Bo He, and Suresh P. Sethi

With the increasing awareness of the serious consequences of supply disruption risk, firms adopt various kinds of strategies to mitigate it. We consider a supply chain in which two suppliers sell components to two competing manufacturers producing and selling substitutable products. Supplier U is unreliable and cheap, while Supplier R is reliable and expensive. Firm C uses a contingent dual-sourcing strategy and Firm S uses a single-sourcing strategy. We study the implications of the contingent sourcing strategy under competition and in the presence of a possible supply disruption. The time of the occurrence of the supply disruption is uncertain and exogenous, but the procurement time of components is in the control of the firms. We show that supply disruption and procurement times jointly impact the firms’ buying decisions. We characterize the firms’ optimal order quantities and their expected profits under different cases. Subsequently, through numerical computations, we obtain additional managerial insights. Finally, as extensions, we study the impact endogenizing equilibrium sourcing strategies of asymmetric and symmetric firms, and of capacity reservation by Firm C with Supplier R to mitigate disruption.

Gupta, V., He, B., and Sethi, S.P., “Contingent Sourcing under Supply Disruption and Competition,” *International Journal of Production Research*, 53(10), 2015, 3006-3027.

### **5.2.28 Dynamic Pricing, Procurement, and Channel Coordination with Stochastic Learning**

Participants: Tao Li, Suresh P. Sethi, and Xiuli He

We consider a decentralized two-period supply chain in which a manufacturer produces a product with benefits of cost learning, and sells it through a retailer facing a price-dependent demand. The manufacturer’s second-period production cost declines linearly in the first-period production, but with a random learning rate. The manufacturer may or may not have the inventory carryover option. We formulate the resulting problems as two period Stackelberg games and obtain their feedback equilibrium solutions explicitly. We then examine the impact of mean learning rate and learning rate variability on the pricing strategies of the channel members, on the manufacturer’s production decisions, and on the retailer’s procurement decisions. We show that as the mean learning rate or the learning rate variability increases, the traditional double marginalization problem becomes more severe, leading to greater efficiency loss in the channel. We obtain revenue sharing contracts that can coordinate the dynamic supply chain. In particular, when the manufacturer may hold inventory, we identify two major drivers for inventory carryover: market growth and learning rate variability. Finally, we demonstrate the robustness of our results by examining a model in which cost learning takes place continuously.

Li, T., Sethi, S.P., and He, X., "Dynamic Pricing, Procurement, and Channel Coordination with Stochastic Learning," *Production and Operations Management*, 24(6), 2015, 857-882.

### **5.2.29 The Maximum Principle for Global Solutions of Stochastic Stackelberg Differential Games**

Participants: Alain Bensoussan, Shaokuan Chen and Suresh P. Sethi

For stochastic Stackelberg differential games played by a leader and a follower, there are several solution concepts in terms of the players' information sets. In this paper we derive the maximum principle for the leader's global Stackelberg solution under the adapted closed-loop memoryless information structure, where the term global signifies the leader's domination over the entire game duration. As special cases, we study linear quadratic Stackelberg games under both adapted open-loop and adapted closed-loop memoryless information structures, as well as the resulting Riccati equations.

Bensoussan, A., Chen, S., and Sethi, S.P., "The Maximum Principle for Global Solutions of Stochastic Stackelberg Differential Games," *SIAM Journal on Control and Optimization*, 53(4), 2015, 1956–1981.

### **5.2.30 Optimal Software Design Reuse Policies: A Control Theoretic Approach**

Participants: Monica Johar, Vijay Mookerjee, and Suresh P. Sethi

We study optimal policies for design reuse in a software project using a control theoretic approach. A project needs to be developed in minimum time by optimally choosing the proportion of effort allocated towards design activities. We first consider a local case, where the benefits of design activities are restricted within the project. Here the optimal policy follows a bang-bang structure: invest fully in design followed by investing fully in implementation. Next we consider two sequentially linked projects where design capital built in the first project can be reused by the downstream project. For the two project case, the design investment in the upstream project first increases and then decreases with the ability to utilize design capital accumulated in the first project for the second project. We also propose a coordination scheme that rewards the upstream project team so that design investment in this project is chosen in a globally optimal manner.

Johar, M., Mookerjee, V., and Sethi, S.P., "Optimal Software Design Reuse Policies: A Control Theoretic Approach," *Information Systems Frontiers*, 17(2), 2015, 439-453.

### **5.2.31 Inventory Management with Overlapping Shrinkages and Demands**

Participants: Alain Bensoussan, Metin Çakanyıldırım, Meng Li, and Suresh P. Sethi

Bensoussan, A., Çakanyıldırım, M., Li, M, and Sethi, S.P., "Inventory Management with Overlapping Shrinkages and Demands," *Risk and Decision Analysis*, 5(4), 2014, 189-210.

### **5.2.32 Supply Diversification with Isoelastic Demand**

Participants: Tao Li, Suresh P. Sethi, and Jun Zhang

We study a firm's sourcing strategy when facing two unreliable suppliers and a price-dependent isoelastic demand. At optimality, the firm always orders at least from the low-cost supplier. The firm also orders from the high-cost supplier if and only if the effective purchase cost from the low-cost supplier is greater than the actual purchase cost from the high-cost supplier. We also find that when the firm orders from both suppliers, the total order quantity decreases as the correlation between the suppliers' capacities increases.

Li, T. Sethi, S.P. and Zhang, J., "Supply Diversification with Iseolastic Demand," *International Journal of Production Economics*, 157, 2014, 2-6.

### **5.2.33 Pricing, Production, and Channel Coordination with Stochastic Learning**

Participants: Tao Li, Suresh P. Sethi, and Xiuli He

We study a two-period supply chain in which a manufacturer produces a product, learns to reduce cost, and sells it through a retailer with a price-dependent demand. The manufacturer's second-period production cost declines linearly in the first-period production with a random learning rate. The manufacturer may or may not have the option to carry inventory. We investigate the impact of mean learning rate and learning rate variability on the manufacturer's production and pricing decisions, as well as on the retailer's procurement and pricing decisions. We demonstrate that as the mean learning rate or the learning rate variability increases, the traditional double marginalization problem becomes more severe, leading to greater efficiency loss in the channel. We provide revenue sharing contracts that can coordinate the dynamic supply chain. In particular, when the manufacturer may hold inventory, we identify two major drivers for inventory carryover: market growth and learning rate variability. Lastly, we demonstrate the robustness of our results by examining a model in which learning takes place continuously.

Li, T., Sethi, S.P., and He, X., "Pricing, Production, and Channel Coordination with Stochastic Learning," *Proceedings of the 15th Asia Pacific Industrial Engineering & Management Systems Conference (APIEMS 2014)*, Jeju, Korea, October 12-15, 2014.

### **5.2.34 Buyback Contracts with Price-Dependent Demands: Effects of Demand Uncertainty**

Participants: Yingxue Zhao, Tsan-Ming Choi, T.C.E. Cheng, Suresh P. Sethi, and Shouyang Wang

We explore buyback contracts in a supplier–retailer supply chain where the retailer faces a price-dependent downward-sloping demand curve subject to uncertainty. Differentiated from the existing literature, this work focuses on analytically examining how the uncertainty level embedded in market demand affects the applicability of buyback contracts in supply chain management. To this end, we seek to characterize the buyback model in terms of only the demand uncertainty level (DUL). With this new research perspective, we have obtained some interesting new findings for buyback. For example, we find that (1) even though the supply chain's efficiency will change over the DUL with a wholesale price-only contract, it will be maintained constantly at that of the corresponding deterministic demand setting with buyback, regardless of the DUL; (2) in the practice of buyback, the buyback issuer should adjust only the buyback price in reaction to different DULs while leave the wholesale price unchanged as that in the corresponding deterministic demand setting; (3) only in the demand setting with an intermediate level of the uncertainty (which is identified quantitatively in Theorem 5), buyback provision is beneficial simultaneously for the supplier, the retailer, and the supply chain system, while this is not the case in the other demand settings. This work reveals that DUL can be a critical factor affecting the applicability of supply chain contracts.

Zhao, Y., Choi, T.-M., Cheng, T.C.E., Sethi, S.P., and Wang, S., "Buyback Contracts with Price-Dependent Demands: Effects of Demand Uncertainty," *European Journal of Operational Research*, 239, 2014, 663-673.

### **5.2.35 Analysis of Product Rollover Strategies in the Presence of Strategic Customers**

Participants: Metin Çakanyıldırım, Chao Liang, and Suresh P. Sethi

Frequent product introductions emphasize the importance of product rollover strategies. With single rollover, when a new product is introduced, the old product is phased out from the market. With dual rollover, the old product remains in the market along with the new product. Anticipating the introduction of the new product and the potential markdown of the old product, strategic customers may delay their purchases. We study the interaction between product rollover strategies and strategic customer purchasing behavior and find that single

rollover is more valuable when the new product's innovation is low and the number of strategic customers is high. Interestingly and counter to intuition, the firm may have to charge a lower price for the old product as well as receive a lower profit with a higher value disposal (outside) option for the old product under single rollover. Facing a market composed of both strategic and myopic customers, the firm does not necessarily reduce the stocking level as more myopic customers become strategic.

Çakanyildirim, M., Liang, C., and Sethi, S.P., "Analysis of Product Rollover Strategies in the Presence of Strategic Customers," *Management Science*, 60(4), 2014, 1033–1056.

### **5.2.36 Optimal Batch Ordering over a Finite Horizon**

Participants: Abdullah O. Alsuwainea, Lakdere Benkherouf, and Suresh P. Sethi

This paper is concerned with finding an optimal inventory policy for a finite horizon, two-stage inventory model. In this model, products may be manufactured in two stages. The first stage uses raw material from an external supplier and the second stage uses raw material from defective items that were returned and repaired during the first stage. The problem of jointly finding the optimal procurement of raw materials and the production plan is formulated as a mixed-integer, non-linear programming problem. A solution procedure for the problem is proposed. The suggested procedure is based on the work of Benkherouf and Gilding (2009).

Alsuwainea, A., Benkherouf, L., and Sethi, S.P., "Optimal Batch Ordering over a Finite Horizon," *International Journal of Operational Research*, 19(4), 2014, 385-406.

### **5.2.37 A Feedback Stackelberg Game of Cooperative Advertising in a Durable Goods Oligopoly**

Participants: Anshuman Chutani and Suresh P. Sethi

Cooperative advertising is an important mechanism used by manufacturers to influence retailers' promotional decisions. In a typical arrangement, the manufacturer agrees to reimburse a fraction of a retailer's advertising cost, known as the subsidy rate. We consider a case of new product adoption of a durable good with retail oligopoly, in which a manufacturer sells through a number of independent and competing retailers. We model the problem as a Stackelberg differential game with the manufacturer as the leader and the retailers as followers. The manufacturer announces his subsidy rates for the retailers, and the retailers in response play a Nash differential game to increase their cumulative sales and choose their optimal advertising efforts. We obtain feedback Stackelberg strategies consisting of manufacturer's subsidy rates and retailers' optimal advertising efforts. We obtain the conditions under which it is optimal for the manufacturer to not offer any advertising subsidy and study the role of retail competition on the manufacturer's subsidy rates decisions. For a special case of two retailers, using a linear demand formulation, we present managerial insights on issues such as: dependence of subsidy rates on key model parameters, impact on channel profits and channel coordination, and finally, a case of an anti-discrimination legislation which restricts the manufacturer to offer equal subsidy rates to the two retailers.

Chutani A. and Sethi, S.P., "A Feedback Stackelberg Game of Cooperative Advertising in a Durable Goods Oligopoly," *Dynamic Games in Economics, Dynamic Modeling and Econometrics in Economics and Finance*, Vol. 16, J.L. Haunschmied, S. Wrzaczek, & V. Veliov (Eds.), Springer, 2014, 89-114.

### **5.2.38 Analysis of Tailored Base-Surge Policies in Dual Sourcing Inventory Systems**

Participants: G. Janakiraman, S. Seshadri and A. Sheopuri

We study a model of a firm managing its inventory of a single product by sourcing supplies from two supply sources, a regular supplier who offers a lower unit cost and a longer lead time than a second, emergency, supplier. A practically implementable policy for such a firm is a Tailored Base-Surge (TBS) Policy (Allon and van Mieghem, 2010) to manage its inventory: Under this policy, the firm procures a constant quantity from the regular supplier in every period and dynamically makes procurement decisions for the emergency supplier. Allon and Van Mieghem



describe this practice as using the regular supplier to meet a base level of demand and the emergency supplier to manage demand surges, and they conjecture that this practice is most effective when the lead time difference between the two suppliers is large. We confirm these statements in two ways. First, we show the following analytical result: When demand is composed of a base demand random component plus a surge demand random component, which occurs with a certain small probability, the best TBS Policy is close to optimal (over all policies) in a well-defined sense. Second, we also numerically investigate the cost-effectiveness of the best TBS policy on a test bed of problem instances. The emphasis of this investigation is the study of the effect of the lead time difference between the two suppliers. Our study reveals that the cost difference between the best TBS policy and the optimal policy decreases dramatically as the lead time of the regular supplier increases. On our test bed, this cost difference decreases from an average (over the test bed) of 21 \% when the lead time from the regular supplier is two periods (the emergency supplier offers instant delivery) to 3.5 \% when that lead time is seven periods.

G. Janakiraman, S. Seshadri and A. Sheopuri, Analysis of Tailored Base-Surge Policies in Dual Sourcing Inventory Systems. *Management Science*. 2015 **61**.7

### 5.2.39 Robustness of Order-up-to Policies in Lost-Sales Inventory Systems

Participants: M. Bijvank, W.T. Huh, G. Janakiraman and W. Kang

We study an inventory system under periodic review when excess demand is lost. It is known [Huh et al., 2009] that the best base-stock policy is asymptotically optimal as the lost-sales penalty cost parameter grows. We now show that this result is robust in the following sense: Consider the base-stock level which is optimal in a backordering system (with a per-unit-per-period backordering cost) in which the backorder cost parameter is a function of the lost-sales parameter in the original system. Then, there is a large family of functions (mapping the lost-sales cost parameter to the backorder cost parameter) such that the resulting base-stock policy is asymptotically optimal. We also demonstrate the robustness phenomenon through a second result. We consider the base-stock level which is optimal in a backordering system in which a unit of backorder is charged a penalty cost only once (such a system has been studied by Rosling [2002]). More specifically, Archibald [1981] proposes to subtract the expected number of backorders from the best base-stock level when this per-unit backorder cost equals the lost-sales penalty cost as a heuristic to set the base-stock level in a lost-sales inventory system. This approach has not been studied in the literature. We prove that the asymptotic optimality result is also preserved for this base-stock policy. In particular, we numerically test the performance of this heuristic policy for a wide spectrum of values for the lost-sales penalty cost parameter and illustrate its superior performance.

M. Bijvank, W.T. Huh and G. Janakiraman and W. Kang, Robustness of Order-up-to Policies in Lost-Sales Inventory Systems, *Operations Research* 2014 **62**.5

### 5.2.40 Fixed-Dimensional Stochastic Dynamic Programs:

Participants: W. Chen, M. Dawande and G. Janakiraman

We study fixed-dimensional stochastic dynamic programs in a discrete setting over a finite horizon. Under the primary assumption that the cost-to-go functions are discrete  $L$ - $\zeta$ -convex, we propose a pseudo-polynomial time approximation scheme that solves this problem to within an arbitrary pre-specified additive error of  $\epsilon > 0$ . The proposed approximation algorithm is a generalization of the explicit-enumeration algorithm and offers us full control in the tradeoff between accuracy and running time. The main technique we develop for obtaining our scheme is approximation of a fixed-dimensional  $L$ -*natural*-convex function on a bounded rectangular set, using only a selected number of points in its domain. Furthermore, we prove that the approximation function preserves  $L$ - $\zeta$ -convexity. Finally, to apply the approximate functions in a dynamic program, we bound the error propagation of the approximation. Our approximation scheme is illustrated on a well-known problem in inventory theory, namely the single-product problem with lost sales and lead times (Morton 1969, Zipkin 2008b). We demonstrate the practical value of our scheme by implementing our approximation scheme and the explicit-enumeration algorithm on instances of this inventory problem.

W. Chen, M. Dawande and G. Janakiraman, Fixed-Dimensional Stochastic Dynamic Programs: An Approximation Scheme and Inventory Applications, *Operations Research*, 2014, **62**, (1), 81-103.

### 5.2.41 Capacitated Serial Inventory Systems: Bounds for Simple Policies

Participants: W. T. Huh, G. Janakiraman, M. Nagarajan

We study the following prototypical model of a large scale supply chain: A periodically reviewed multi-echelon serial inventory system with a capacity constraint on the order quantity at every stage. Our goal is to find policies that minimize the sum of the expected long run average holding and shortage costs for this system. It is well known that for this problem, characterizing the structure of the optimal policy and computing it are very difficult. This problem is a generalization of two well-understood and fundamental building blocks in inventory theory, namely the one of managing incapacitated multi-echelon serial systems and that of managing capacitated single location inventory systems. We consider the use of echelon base stock policies for our system (even though they are known to be sub-optimal) and propose algorithms for finding base-stock levels. Our algorithms are based on integrating existing optimal or near-optimal algorithms for the two building blocks and therefore easy to understand and implement (in fact, two of our three algorithms only involve newsvendor computations). We derive bounds on the ratios between the costs achieved by our algorithms and the optimal costs (over all policies). Our algorithms are shown to be asymptotically optimal in the sense that our bounds are close to one in high service-level environments. Next, we perform a computational investigation of the performance of our algorithms on a sample bed of problem instances in which the service levels range from modestly high (67%) to very high (99%). On each problem instance, we evaluate the costs of our algorithms and compare them with the cost of the best base-stock policy and with a lower bound on the optimal cost. The best of our algorithms achieves a cost which is only 1.7% more, on an average, than the cost of the best base-stock policy. Further, our computational investigation reveals that the cost of the best base-stock policy is, on an average, no more than 0.6% higher than a lower bound on the optimal cost. This seems to confirm that base-stock policies are effective (even though sub-optimal, in general) for managing capacitated serial inventory systems. Finally, the development of our algorithms is robust in that they can immediately exploit advances made by researchers in the computations of policies for the two building blocks to provide heuristics for serial capacitated inventory systems.

W.T. Huh, G. Janakiraman and M. Nagarajan, Capacitated Serial Inventory Systems: Bounds for Simple Policies (Under revision for resubmission to *MSOM* by Fall 2015.)

### 5.2.42 Optimal Descending Mechanisms for Constrained Procurement

Participants: W. Chen, M. Dawande, S. Gupta and G. Janakiraman,

In this paper, we examine a class of auction mechanisms – Generalized Reverse Japanese (GRJ) auctions – for e-Procurement. GRJ auctions are endowed with the attractive property of simplicity from the viewpoint of suppliers: They find the rules of the auction easy to understand and are also able to trivially identify their bidding strategies. We are interested in the following question: For which procurement problems that incorporate commonly-occurring operational constraints is a suitably-defined GRJ auction an optimal mechanism (i.e., minimizes the buyer's expected cost)? We answer this question in the affirmative for three problems.

W. Chen, M. Dawande, S. Gupta and G. Janakiraman, Optimal Descending Mechanisms for Constrained Procurement, *Production and Operations Management* (Forthcoming)

### 5.2.43 Optimal Procurement Auction under Multi-Stage Supplier Qualification

Participants: W. Chen, M. Dawande, and G. Janakiraman,

A firm is soliciting bids from a fixed-size pool of yet-to-be-qualified suppliers for an indivisible sourcing contract. The contract can only be awarded to a supplier who passes a multi-stage qualification process. For each stage of qualification, the buyer selects a subset of those suppliers who have passed all previous stages and tests them simultaneously. In each stage, the buyer incurs a fixed testing cost for each supplier she chooses to test in that stage; these fixed costs differ across stages. The buyer seeks an optimal mechanism, i.e., one that minimizes her total expected procurement cost, which consists of the qualification cost and the procurement cost. Our main results are

optimal mechanisms (auctions) for (i) a symmetric setting, where the suppliers' private costs are realized from the same distribution and the passing probability in a stage is the same for the suppliers admitted to that stage, and (ii) an asymmetric setting, where there are two different pools of suppliers – new and mature – that differ both in their costs and passing probabilities. In particular, we show that the optimal admission policy for supplier selection in each stage is based on non-uniform reserve prices. We also present supplier-friendly descending implementations of our optimal auctions. Technically, the novelty of our approach for deriving the optimal mechanisms lies in three steps: (i) reduction of the mechanism design problems to equivalent stochastic DPs that capture the dynamic supplier-qualification process and involve set-based decisions, (ii) conversion of set-based decisions into cardinality-based decisions to reduce the feasible action space, and (iii) exploitation of special structural properties of these DPs; e.g., convexity of the cost-to-go functions, and monotonicity and special relationships in other associated functions, and establishing their preservation through the DP recursion.

W. Chen, M. Dawande, and G. Janakiraman, Optimal Procurement Auction under Multi-Stage Supplier Qualification (under review for resubmission to *MSOM*)

#### **5.2.44 FTL vs. LTL Shipments: Integral Policies in Stochastic Distribution Systems**

Participants: Y. Bo, M. Dawande, G. Janakiraman and T. McCormick

The integrality question for dynamic optimization models of inventory control asks if there exists an integral optimal policy, given integral initial inventory levels, capacities and demand realizations. One practical implication of this question lies in whether or not full-truckload shipping is optimal if customer demand is in integral number of truckloads. For single-product, deterministic- and stochastic-demand problems in multi-echelon assembly systems, the answer to the integrality question is yes (Chen et al. 2013), thus implying the optimality of Full-Truckload shipping. In this note, we show the following for single-product, multi-echelon distribution systems: Integrality holds under deterministic demands, but fails to hold under stochastic demands. In distribution systems with stochastic demands, Less-Than-Truckload shipping can be significantly cheaper than the cost of the optimal Full-Truckload shipping solution, even in the presence of economies of scale. This statement continues to hold even if we impose the additional restriction that the shipments from the retail locations to the customers be in full truckloads. The same result holds for assembly- distribution networks, in which assembly is followed by distribution. For distribution-assembly networks, in which distribution is followed by assembly, integrality can fail even with deterministic demands.

Y. Bo, M. Dawande, G. Janakiraman and T. McCormick, FTL vs. LTL Shipments: Integral Policies in Stochastic Distribution Systems (under review in *Operations Research*)

#### **5.2.45 A Stochastic Inventory Model With Fast-Ship Commitments**

Participants: H.W. Chen, D. Gupta, H. Gurnani and G. Janakiraman

We present a multi-period model of a retail supply chain, consisting of a single supplier and a single retailer, in which regular replenishment occurs periodically but players have the option to support fast delivery when customers experience a stock out during a replenishment period. Because expedited shipments increase the supplier's transportation cost, and possibly production/inventory costs, the supplier typically charges a markup over and above the prevailing wholesale price for fast-shipped items. When fast shipping is not supported, items are backordered if customers are willing to wait until the start of the next replenishment period. We characterize the retailers and the supplier's optimal stocking and production policies and then utilize our analytical framework to study how the two players respond to changes in supply chain parameters. We identify a sufficient condition such that the centralized supply chain is better off with the fast-ship option. We find a range of markups for fast-ship orders such that the fast-ship option is preferred by both the supplier and the retailer in a decentralized chain. However, a markup that is a win-win for both players may not exist even when offering fast-ship option is better for the centralized chain. Our analysis also shows that depending on how the markup is determined, greater customer participation in fast-ship orders does not necessarily imply more profits for the two players. For some predetermined markups, the retailer's profit with the fast-ship option is higher when more customers are willing to wait. However, the retailer may not be able to benefit from the fast-ship option because the supplier may choose not to support the fast-ship option when

fast-ship participation increases due to the fact that the fast-ship participation rate adversely affects the initial order size.

H.W. Chen, D. Gupta, H. Gurnani and G. Janakiraman (Accepted by *Production and Operations Management*)

#### **5.2.46 Managing Nonperishable Inventories with Learning on Stock-out Times**

Participants: A. Bensoussan and Pengfei Guo

We consider the dynamic inventory management of nonperishable products with a Poisson demand process and learning on the demand rate through past sales. We consider three information scenarios on past sales: no, partial and full. The no- and full-information scenarios represent, respectively, unobservable and observable lost sales cases. The partial information represents the case where lost sales are unobservable whereas the stock-out times are observable. We show that system performance is always improved with more information and the optimal decision under partial information is larger than the one under full information. Our results generalize the past literature on Bayesian inventory management into richer information scenarios and provide a parsimonious information updating device for solving other Bayesian inventory management problems.

#### **Managing Nonperishable Inventories with Learning about Demand Arrival Rate Through Stock-out Times**

A. Bensoussan, Pengfei Guo *Operations Research* (May 13, 2015) 1 - 8

#### **5.2.47 Competing on Time: An Integrated Framework to Optimize Dynamic Time-to-Market and Production Decisions.**

Participants: Özer, Ö and O. Uncu

This study develops a comprehensive framework to optimize new product introduction timing and subsequent production decisions faced by a component supplier. Prior to market entry, the supplier performs process design activities, which improve manufacturing yield and the chances of getting qualified for the customer's product. However, a long delay in market entry allows competitors to enter the market and pass the customer's qualification process before the supplier, reducing the supplier's share of the customer's business. After entering the market and if qualified, the supplier also needs to decide how much to produce for a finite planning horizon by considering several factors such as manufacturing yield and stochastic demand, both of which depend on the earlier time-to-market decision. To capture this dependency, we develop a sequential, nested, two-stage decision framework to optimize the time-to-market and production decisions in relation to each other. We show that the supplier's optimal market entry and qualification timing decision need to be revised in real time based on the number of qualified competitors at the time of market-entry decision. We establish the optimality of a threshold policy. Following this policy, at the beginning of each decision epoch, the supplier should optimally stop preparing for qualification and decide whether to enter the market if her order among qualified competitors exceeds a predetermined threshold. We also prove that the supplier's optimal production policy is a state-dependent, base-stock policy, which depends on the time-to-market and qualification decisions. The proposed framework also enables a firm to quantify how market conditions (such as price and competitor entry behavior) and operating conditions (such as the rate of learning and inventory/production-related costs) affect time-to-market strategy and post-entry production decisions

Özer, Ö and O. Uncu. Competing on Time: An Integrated Framework to Optimize Dynamic Time-to-Market and Production Decisions. *Production and Operations Management* 22(3) pp. 473-488, 2013.

#### **5.2.48 Mechanism Design for Capacity Planning under Dynamic Evolutions of Asymmetric Demand Forecasts**

Participants: OH, S. and Ö. Özer.

This paper investigates the role of time in forecast information sharing and decision making

under uncertainty. To do so, we provide a general framework to model the evolutions of forecasts generated by multiple decision makers who forecast demand for the same product. We also model the evolutions of forecasts when decision makers have asymmetric demand information and refer to it as the Martingale Model of Asymmetric Forecast Evolutions. This model helps us study mechanism design problems in a dynamic environment. In particular, we consider a supplier's (principal's) problem of eliciting credible forecast information from a manufacturer (agent) when both firms obtain a symmetric demand information for the end product over multiple periods.

The supplier uses demand information to better plan for a capacity investment decision. When the supplier postpones building capacity and screening the manufacturer's private information, the supplier and the manufacturer can obtain more information and update their forecasts. This delay, however, may increase (respectively, decrease) the degree of information asymmetry between the two firms, resulting in a higher (respectively, lower) cost of screening. The capacity building cost may also increase because of a tighter deadline for building capacity. Considering all such trade-offs, the supplier has to determine (i) when to stop obtaining new demand information and build capacity, (ii) whether to offer a screening contract to credibly elicit private forecast information or to determine the capacity level without information sharing, (iii) how much capacity to build, and (iv) how to design the overall mechanism so that both firms benefit from this mechanism. This paper provides an answer to these questions. In doing so, we develop a new solution approach for a class of dynamic mechanism design problems. In addition, this paper provides a framework to quantify the option value of time for a strategic investment decision under the dynamic evolutions of asymmetric forecasts.

Oh, S. and Ö. Özer. *Mechanism Design for Capacity Planning under Dynamic Evolutions of Asymmetric Demand Forecasts.*, Management Science, **59(4)** pp. 987-1007, 2013.

#### **5.2.49 All You Need is Trust? An Examination of Interorganizational Supply Chain Projects**

Participants: Brinkhoff, A., Ö. Özer., Sargut G.

This study examines the antecedents of supply chain project success. We first propose and test a model that describes the roles relationship-level factors (trust and asymmetric dependence) and project-level factors (between-firm communication and within-firm commitment) in determining supply chain project success. We find that project-level factors completely mediate the effect of trust on project success. We conclude that trust, despite being a stronger predictor compared to asymmetric dependence, is necessary but not sufficient for supply chain project success. We then proceed to further explore the role of these factors by introducing a categorical scheme that differentiates supply chain projects based on the decision rights configuration of each project. This categorization enables us to explore how relationship-level and project-level factors can have different impact on performance based on the characteristics of a supply chain project. The findings offer insights into how to effectively manage supply chain projects and inter-firm alliances.

Brinkhoff, A., Ö. Özer., Sargut, G. "All You Need is Trust? An Examination of Interorganizational Supply Chain Projects," POMS May 8, 2014 forthcoming.

#### **5.2.50 Trust, Trustworthiness and Information Sharing in Supply Chains Bridging China and the U.S.**

Participants: Ö. Özer., Zheng, Y., Ren, Y.

Whether and how trust and trustworthiness differ between a collectivist society, e.g., China, and an individualistic one, e.g., the U.S., generate much ongoing scientific debate and bear significant practical values for managing cross-country transactions. We experimentally investigate how supply chain members' countries of origin -- China versus the U.S. -- affect trust, trustworthiness, and strategic information sharing behavior in a cross-country supply chain. We consider a two-tier supply chain in which the upstream supplier solicits demand forecast information from the

retailer to plan production; but the retailer has an incentive to manipulate her forecast to ensure abundant supply. The levels of trust and trustworthiness in the supply chain and supplier's capability to determine the optimal production quantity affect the efficacy of forecast sharing and the resulting profits. We develop an experimental design to disentangle these three aspects and to allow for real-time interactions between geographically distant and culturally heterogeneous participants. We observe that, when there is no prospect for long-term interactions, our Chinese participants consistently exhibit lower spontaneous trust and trustworthiness than their U.S. counterparts do. We quantify the differences in trust and trustworthiness between the two countries, and the resulting impact on supply chain efficiency. We also show that Chinese individuals exhibit higher spontaneous trust towards U.S. partners than Chinese ones, primarily because they perceive that individuals from the U.S. are more trusting and trustworthy in general. This positive perception towards U.S. people is indeed consistent with the U.S. participants' behavior in forecast sharing. In addition, we quantify that a Chinese supply chain enjoys a larger efficiency gain from repeated interactions than a U.S. one does, as the prospect of building a long-term relationship successfully sustains trust and trustworthiness by Chinese partners. We advocate that companies can reinforce the positive perception of Westerners held by the Chinese population and commit to long-term relationships to encourage trust by Chinese partners. Finally, we also demonstrate that both populations exhibit similar pull-to-center bias when solving a decision problem under uncertainty (i.e., the newsvendor problem).

Ö. Özer, Zheng, Yanchong and Ren, Yufei, “*Trust, Trustworthiness and Information Sharing in Supply Chains Briding China and the U.S.* Management Science, January 1, 2014 *Forthcoming*

## 5.2.51

### A Strategic Approach to Collaborative Inventory Management

Participants: Alain Bensoussan, Bharadwaj Kadiyala, Özalp Özer

This paper studies an inventory control problem faced by an upstream supplier who is in a collaborative agreement, such as vendor-management inventory (VMI), with a retailer. VMI partnership provides the supplier a unique opportunity to manage inventory for the supply chain, in exchange for point-of-sales (POS) and inventory level information from the retailer. However, as is increasingly the case in retail industry, big-box retailers capture and analyze customer purchasing behavior beyond the traditional POS data.

Such analysis provides the retailer, access to market signals that are otherwise, hard to capture using POS information. In the absence of a credible channel for communication between the parties, the value of these signals to the supply chain operations can be limited. We demonstrate and quantify the implication of the incentive issue in VMI that renders communication of such important market signals as non-credible. To help institute a sound VMI collaboration, we propose a dynamic inventory mechanism for the supplier, to manage inventory and information in the supply chain. The proposed mechanism combines the ability of the supplier to learn about market conditions from POS data (over multiple selling periods) and to dynamically determine when to screen the retailer and acquire his demand information. We show that the dynamic mechanism significantly improves the supplier's expected POS and increases the efficiency of the overall supply chain operations under a VMI agreement. We also show that inventory decisions serve a strategic purpose in addition to their classic role of satisfying customer demand.

Alain Bensoussan, Bharadwaj Kadiyala, Özalp Özer, *Submitted to Management Sciences, October 2015*

## 5.3. Activities in Finance and Economics

### 5.3.1. Real Options and Game Models

Participants: Alain Bensoussan, 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. A regime-switching model is also introduced to catch cash flow variations caused by switching among different market modes. 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.

Bensoussan, A., S. Hoe. Real Options with Competition and Incomplete Markets, in *Inspired by Finance: The Musiela Festschrift*. Yuri Kabanov, Marek Rutkowski, and Thaleia Zariphopoulou, eds., Springer (2013).

Bensoussan, A., S. Hoe. Real Options Games - Stackelberg Competition vs. Pre-emption in Complete and Incomplete Markets"

Bensoussan, A., S. Hoe, Z. Yang, and G. Yin. Real Options with Competition and Regime Switching Mathematical Finance, Forthcoming

### **5.3.1 Real Options with Mean Field Games and Mean Field Type Control**

**Participants: Alain Bensoussan, Celine Hoe, ZhongFeng Yan**

Expanding the game models studied in previous works (see section 5.3.1), we explore the industry dynamic equilibrium of a firm's capital stock investment with many firms, facing stochastic physical capital stock depreciation with quadratic adjustment cost. We study the problem through mean field games where HJB-FKP system equations are proposed. As a byproduct of this study, we investigate another problem where a firm's physical capital investment decision depends not only on the capital stock evolution but also the stochastic product price. In this study, different from the abovementioned mean-field game model, the uncertainty is related to the product price. In the framework, a firm's profit flow depends on the mean of market price due to the dependence of wage and the product market price. We solve a firm's optimal physical capital investment decision under uncertainty through mean-field type control.

### **5.3.2 Entrepreneurial Decisions on Effort and Project with a Non-Concave Objective Function**

**Participants: A. Bensoussan, A. Cadenillas, H.K. Koo**

We propose and solve a general entrepreneurial/managerial decision making problem. Instead of employing concave objective functions, we use a broad class of non-concave objective functions. We approach the problem by a martingale method. We show that the optimization problem with a non-concave objective function has the same solution as the optimization problem when the objective function is replaced by its concave hull, and thus the problems are equivalent to each other. The value function is shown to be strictly concave and to satisfy the Hamilton-Jacobi-Bellman equation of dynamic programming. We also show that the final wealth cannot take values in the region where the objective function is not concave; the entrepreneur would like to avoid her/his wealth ending up in the non-concave region. Because of this, her/his risk taking explodes as time nears maturity if her/his wealth is equal to the right end point of the non-concave region.

Bensoussan, A., Cadenillas, A., H-K Koo, “*Entrepreneurial Decisions on Effort and Project with a Non-Concave Objective Function*, Mathematics of Operations Research, October, 2014 forthcoming.

### **5.3.3 Optimal Retirement with Unemployment Risks in an Incomplete Market**

Participants: A. Bensoussan, Bong-Gyu Jang and Seyoung Park

In this work, one investigates the optimal retirement of an individual in the presence of involuntary unemployment risks and borrowing constraints in an incomplete market. We provide a solution when the degree of incompleteness is small. Our numerical calculations show some robustness of our solution. We plan to submit a paper in the near future. (*Paper submitted to O.R.*)

## **5.4. Activities in Alternative Energies**

### **5.4.1. Estimation of the annual wind power production**

Participants: A. Bensoussan, P. Bertrand and A. Brouste

We have developed a new approach concerning the forecast of annual production of wind energy by a windmill. This is important at the investment level, since it is essential to obtain an accurate estimate of the potential energy to assess the profitability. As a matter of fact, we have shown that a substantial amount of uncertainty is overlooked by the current approaches, both in the literature and in the practitioners’ techniques. This uncertainty is structural; it is not linked to the estimation errors. It is linked to the randomness of wind. In fact, we noticed that the correlation between successive periods is at the origin of most of the volatility. At the beginning, we have neglected seasonality. We then developed a more accurate model of seasonality, with two sources of periodicity, day and night, and winter, autumn, spring, summer. We get more complex forecasting formulas, but thanks to them, we can lower the estimate of the structural volatility.

A. Bensoussan, P. Bertrand, A. Brouste, N. Haouas, M. Fhima and D. Koulibaly (2014) *Confidence intervals for annual wind power production*, ESAIM Proceedings, 44, 150-158.

A. Bensoussan, P. Bertrand and A. Brouste (2014) *A generalized linear model approach to seasonal aspects of wind speed modeling*, Journal of Applied Statistics, 41(8), 1694-1707.

A. Bensoussan, P. Bertrand and A. Brouste (2014) “*Estimation Theory for GLM in future Perspectives*” in Risk Models and Finance edited by A. Bensoussan, D. Guegan and C. Tapiero, Springer-Verlag.

### **5.4.2 Wind Speed Modeling for Short-Term Forecasting**

Wind model for short-term forecasting is a key element in the operational management of a wind farm. The type of problem to be faced by the provider is to guarantee a given amount of energy, for a given duration, at a given price. One of the major difficulties is that the capacity of production comes from wind turbines and solar plants. Therefore, this capacity is highly dependent on the wind speed and direction, or sun availability. We already proposed calibration methods for static models with seasonal parameters; this method used Generalized Linear Models theory.

Bensoussan, A., Bertrand, P.R. and Brouste A. “*A GLM Approach to Seasonal Aspects of Wind Speed Modeling*,” Journal of Applied Statistics **42 (8)**, (January, 2014) 1694-1707

Bensoussan, A., Bertrand P.R. and Brouste A., “*Estimation Theory for GLM in future Perspectives*” in Risk Models and Finance edited by A. Bensoussan, D. Guegan and C. Tapiero, Springer-Verlag 2014



Alain Bensoussan, Pierre Raphaël Bertrand, Alexandre Brouste, Nabihha Haouas, Medhi Fhima, Daouda Koulibaly. "Confidence Intervals for Annual Wind Power Production," *ESAIM Proceedings*, **44**, (January, 2014) 150-158

## 5.5. Activities in Risks on Technical Systems

### 5.5.1. Elastic-Plastic Systems Excited by Non-White Noise

Participants: Alain Bensoussan, Laurent Mertz

A stochastic variational inequality is proposed to model an elasto-plastic oscillator excited by a filtered white noise. We prove the Ergodic property of the process and characterize the corresponding invariant measure. This extends Bensoussan-Turi's method (Degenerate Dirichlet Problems Related to the Invariant Measure of Elasto-Plastic Oscillators, *AMO*, 2008) with a significant additional difficulty of increasing the dimensions. Two points boundary value problem in dimension 1 is replaced by elliptic equations in dimension 2. In the present context, Khasminskii's method (Stochastic Stability of Differential Equations, Sijthoff and Noordhof, 1980) leads to the study of degenerate Dirichlet problems with partial differential equations and nonlocal boundary conditions.

Bensoussan A., Mertz L., Degenerate Dirichlet Problems Related To the Ergodic Property of an Elasto-Plastic Oscillator Excited By A Filtered White Noise, *IMA Journal of Applied Mathematics* (2015) **80** (5) 1387-1408

Participants: Alain Bensoussan, Laurent Mertz and Sheung Chi Phillip Yam

In the literature, before our present work, failure risk analysis on most elasto-perfectly-plastic (EPP) oscillators is essentially focused on those excited by a white noise, which is rather restrictive from the modeling perspective. Our present article aims to generalize the models so as to provide a comprehensive study of the stochastic variational inequality (SVI) for elasto-plastic oscillators excited by a filtered noise. We characterize the solutions of the SVI by introducing a class of partial differential equations (PDEs) with nonlocal Dirichlet conditions. We establish the unique existence of solutions of these PDEs by extending the method developed in an earlier work by the first author and Janos Turi; a major mathematical challenge here is to carry out the analysis of boundary value problems for elliptic equations in dimension 2 rather than that in dimension 1. Finally, a probabilistic interpretation of these solutions is provided.

Bensoussan A., Mertz L., Yam P., Stochastic variational inequality for an elasto-plastic oscillator excited by a filtered noise, preprint

### 5.5.2. New Results on the long time behavior of Elastic-Plastic Systems

Several works related to this domain are collected here:

Participants: Alain Bensoussan, Cyril Feau, Laurent Mertz and Sheung Chi Phillip Yam

Since a few decades ago, there has been a huge amount of studies of plastic deformation of elasto-plastic oscillators in the engineering literature. In one of our recent works/cite {BenMerYam}, we introduced a novel notion of long cycle behavior of the Markovian solution of the corresponding stochastic variational inequality of an elasto-perfectly-plastic oscillator, which can characterize in a probabilistic framework the variance of the plastic deformation. In this paper, we provide an analytical formula for the characteristic function of the probability distribution of the plastic deformation on long cycles; from our result we also derive a deterministic representation of the variance of the plastic deformation on long cycles.

Bensoussan A., Mertz L., Yam P., An analytical approach for the growth rate of the variance of the deformation related to an elasto-plastic oscillator excited by a white noise, *Appl. Math. Res. Express. AMRX* 2015, **1**, 99–128.

### 5.5.3 Approximate solutions of a stochastic variational inequality modeling an elasto-plastic problem with noise

Participants: Héctor Jasso-Fuentes H., Laurent Mertz and Sheung Chi Phillip Yam

An important issue in failure analysis of some mechanical structures under seismic forcing is to estimate statistics of the response of an elasto-perfectly-plastic oscillator with noise. In a previous work, we noticed that due to the noise numerous and negligible plastic phases occur in the response on small time intervals at the instants of phase transition, therefore we gave an empirical criterion based on mathematical tools related to a stochastic variational inequality (SVI) to remove this phenomenon from relevant statistics. Recently, we proposed a SVI with jumps to separate clearly the phases. We showed that the approximate solution converges, as the size of jumps goes to 0. The present work is in the straightforward line of these two studies. Here, an asymptotic study of ergodic measures of approximate solutions of the SVI is investigated by a combination of a theoretical and an empirical analysis. First, we show that these measures converge as  $\epsilon$  goes to 0. Then, numerical experiments on the convergence reveal, on the one hand, that the rate of convergence behaves as  $A \exp(-B/\epsilon)$  where  $A$  and  $B$  are positive numbers and, from the other hand, there exists an empirical small number for which the measures have numerically converged. In terms of engineering interests, we provide an interesting criterion using to calibrate the model with jumps discarding the negligible plastic phases and to estimate statistics of plastic deformations.

Jasso-Fuentes H., Mertz L. and Yam P. Approximate solutions of a stochastic variational inequality modeling an elasto-plastic problem with noise, *Appl. Math. Res. Express. AMRX* 2014, **1** 52–73.

### 5.5.4 Penalization of a stochastic variational inequality modeling an elasto-plastic problem with noise

Participants: Laurent Mertz and Mathieu Laurière

In a recent work of A. Bensoussan and J. Turi Degenerate Dirichlet Problems Related to the Invariant Measure of Elasto-Plastic Oscillators, *AMO*, 2008, it has been shown that the solution of a stochastic variational inequality modeling an elasto-plastic oscillator excited by a white noise has a unique invariant probability measure. The latter is useful for engineering in order to evaluate statistics of plastic deformations for large times of a certain type of mechanical structure. However, in terms of mathematics, not much is known about its regularity properties. From then on, an interesting mathematical question is to determine them. Therefore, in order to investigate this question, we introduce in this paper approximate solutions of the stochastic variational inequality by a penalization method. The idea is simple: the inequality is replaced by an equation with a nonlinear additional term depending on a parameter  $n$  penalizing the solution whenever it goes beyond a pre-specified area. In this context, the dynamics is smoother. In a first part, we show that the penalized process converges towards the original solution of the aforementioned inequality on any finite time interval as  $n$  goes to  $\infty$ . Then, in a second part, we justify that for each  $n$  it has at least one invariant probability measure. We conjecture that it is unique, but unfortunately we are not (yet) able to prove it. Finally, we provide numerical experiments in support of our conjecture. Moreover, we give an empirical convergence rate of the sequence of measures related to the penalized process.

Laurière M., Mertz L., Penalization of a stochastic variational inequality modeling an elasto-plastic problem with noise, *ESAIM: PROCEEDINGS AND SURVEYS*, January 2015, Vol. 48, p. 226–247.

### 5.5.5

Participants: Laurent Mertz and Mathieu Laurière

The risk of failure of mechanical structures under random forcing is an important concern in earthquake engineering. For a class of simple structures that can be modeled by an elasto-plastic oscillator, the risk of failure can be expressed in terms of the probability that, on a certain interval of time, the plastic deformation goes beyond a thresh-old related to a failure zone. In this note, asymptotic formulae for the risk of failure of an

elasto-perfectly-plastic oscillator excited by a white noise are proposed. Our method exploits the long cycle (repeating pattern) property of the aforementioned oscillator as introduced in A.Bensoussan, L.Mertz, S.C.P.Yam, Long cycle behavior of the plastic deformation of an elasto-perfectly-plastic oscillator with noise, C. R. Acad. Sci. Paris Ser. I, 2012. We show that asymptotically the plastic deformation behaves like a Wiener process for which analytical formulae are available. Our result is a consequence of the Anscombe-Donsker Invariance Principle. Numerical experiments and comments are carried out.

Feau C., Laurière M., Mertz L., A note on asymptotic formulae for the risk of failure of an elasto-perfectly-plastic oscillator excited by a white noise, preprint.

## 7. Publications

2013

### EDITED BOOK

#### *Real Options, Ambiguity, Risk and Insurance*

A. Bensoussan, Shige Peng, Jaeyoung Sung  
Netherlands, IOS Press, (May 31, 2013)

### BOOK

#### *Mean Field Games and Mean Field Type Control Theory*

Alain Bensoussan, Jens Frehse, Phillip Yam  
New York Heidelberg Dordrecht London, Springer Brief (Oct 31, 2013)

### PAPERS

#### **Linear Quadratic Differential Games with Mixed Leadership: The Open-Loop Solution,**

A. Bensoussan, Shaokuan Chen, Suresh P. Sethi  
*Numerical Algebra Control and Optimization* **3 (1)** (March 2013) 95-108

#### **Optimal Inventory Control with Shrinkage and Observed Sales - In Memory of Michael Taksar**

A. Bensoussan, M. Çakanyldirim, M. Li, S.P. Sethi  
*Stochastics: An International Journal of Probability and Stochastic Processes* **85** (July 2013) 589-603

#### **Control and Nash Games with Mean Field Effect**

A. Bensoussan, Jens Frehse  
*Chinese Annals of Mathematics* **34 (2)** (April 2013) 161 -192

#### **Unemployment Risks and Optimal Retirement in an Incomplete Market,**

A. Bensoussan, Bong-Gyu Jang, Seyoung Park  
*Chinese International Conference in Finance*, (July 10-13, 2013), Shanghai, China

#### **Optimizing Production and Inventory Decisions in a Supply Chain with Lot Size, Production Rate and Lead Time Interactions**

Hua-Ming Song, Hui Yang, A. Bensoussan  
*Applied Mathematics and Computation* **224** (November 2013) 150-165

**Time-Consistent Portfolio Selection under Short-Selling Prohibition: From Discrete to Continuous Setting,**

A. Bensoussan, K.C. Wong, S.C.P. Yam, S.P Yung  
*SIAM J. Finance Math* **5** (1) (November 2013) 153-190

**Linear-Quadratic Time-Inconsistent Mean Field Games**

A. Bensoussan, K.C.J. Sung, S.C.P. Yam  
*Dynamic Games and Applications* **3** Issue **4**, (December 2013) 537-552

**PRESENTATIONS AT CONFERENCES**

**The Maximum Principle for Global Solutions of Stochastic Stackelberg Differential Games**

A. Bensoussan, Shaokuan Chen, S.P Sethi **Presenter:** Shoakuan Chen  
*INFORMS, Minneapolis, Minnesota* (October 6 – 9, 2013)

**Feedback Stackelberg Solutions Of Infinite-Horizon Stochastic Differential Games**

A. Bensoussan, Shoakuan Chen, S.P. Sethi **Presenter:** S.P. Sethi  
*9<sup>th</sup> International Society of Dynamic Games*, Barcelona, Spain (July 5-6, 2013)

**Feedback Stackelberg Solutions of Infinite-Horizon Stochastic Differential Games**

A. Bensoussan, Shaokuan Chen, S.P. Sethi **Presenter:** S.P. Sethi  
*INFORMS, Applied Probability Society Conference*, San Jose, Costa Rica, (July 15-17, 2013)

**SPEAKER INVITATIONS:**

**Mean Field Games and Related Topics**

*Control & Game Theory Colloquium*  
Warwick University, UK (May 7-10, 2013)

**Mean Field Games and Related Topics**

*Departimento di Martematica*,  
Padua University, Padua, Italy (September 4-6, 2013)

**Mean Field Games**

*Magno Coloquio de Doctorantes en Economía de la República Mexican*,  
Mexico City, Mexico, (November 14, 2013)

**Control Theory, What Changes in 50 Years**

*INRIA, #30<sup>th</sup> Anniversary Colloquium*  
Sophia Antipolis, France (November 28, 2013)

***Mean Field Type Control***

ECM 2013 – Computational & Mathematical Finance  
Hong Kong Polytechnic University, Hong Kong, PRC (December 2013)

2014

**BOOK CHAPTER(S)**

**Feedback Stackelberg Solutions of Infinite-Horizon Stochastic Differential Games**

A. Bensoussan, Shaokuan Chen, Suresh P. Sethi

*Models and Methods in Economics and Management Sciences* ed by Fouad El Ouardighi, Konstantin Kogan  
Switzerland: Springer International Publishing (January 2014) 3-15

**Real Options with Competition and Incomplete Markets**

A. Bensoussan, Sing Ru (Celine) Ho

Inspired by Finance, ed. by Yuri Kabanov, Marek Rutkowski, Thaleia Zariphopoulou  
Switzerland, Springer (2014) 29-45

**PAPERS**

**Optimal Control of Hidden Markov Models w/ Binary Observations**

A. Bensoussan, Arash Komae

*IEEE Transactions on Automatic Control* V **59**, **1** (January 2014) 64-77

**A GLM Approach to Seasonal Aspects of Wind Speed Modeling**

Alain Bensoussan, Pierre Bertrand, Alexandre Brouste

*Journal of Applied Statistics* **41** Issue **8** (January 2014) 1694-1707

**Optimal Decision Making in Multi-Product Dual Sourcing Procurement w/ Demand Forecast Updating,**

Alain Bensoussan, Hua-Ming Song, Hui Yang, Ding Zhang

*Computers & Operations Research*, **41** (January, 2014) 200-308

**Confidence Intervals for Annual Wind Power Production**

Alain Bensoussan, Pierre Raphaël Bertrand, Alexandre Brouste, Nabiha Haouas, Medhi Fhima, Daouda Koulibaly

*ESAIM Proceedings*, **44**, (January, 2014) 150-158

**Mean-Variance Pre-Commitment Policies revised via a Mean-Field Technique**

A. Bensoussan, K.C. Wong, S.C.P. Yam

*2012 Recent Advances in Financial Engineering* ed. by Akhiko Takahashi, Yukio Muromachi, Takashi Shibata  
World Scientific Publisher (April 2014), 177-198

**A Class of Nonzero-Sum Stochastic Differential Investment and Reinsurance Games**

A. Bensoussan, Chi Chung Siu, Sheung Chi Phillip Yam, Hailiang Yang

*Automatica* (April 2014)

**Stochastic Differential Games with a Varying Number of Players**

A. Bensoussan, Jens Frehse, Christine Grün

*Communications on Pure & Applied Analysis*, **13**, Number **5**, (September 2014)

**Real Options with Competition and Regime Switching**

A. Bensoussan, SingRu Hoe, ZhongFeng Yan, G. Yin

*Mathematical Finance*, (announced 2014)

**PRESENTATIONS AT CONFERENCE(S)**

**Feedback Stackelberg Equilibrium in Mixed Leadership Games with an Application to Cooperative Advertising**

A. Bensoussan, Shaokuan Chen, Anshuman Chutani, Suresh P. Sethi **Presenter:** S.P. Sethi  
“16th International Symposium on Dynamic Games and Applications,” Amsterdam, Netherlands, July 9-12, 2014.

**Uncertainties and Competition – Challenges for Real Life, Opportunities for Research**

A. Bensoussan  
“Korean Association of Financial Engineering” 2014 Annual Meeting,” Busan, South Korea, August 22-23, 2014

**SPEAKER INVITATIONS**

**The Master Equation in Mean Field Theory**

*Sino-French Conference on Computational & Applied Mathematics*  
Fujian, China (June 2, 2014)

**W.T. and Idalia Reid SIAM AWARD Lecture**

*SIAM Annual Conference*  
Chicago, Illinois (July 7-11, 2014)

**University of Illinois - College of Business**

*Control of Partially Observable Inventory Systems*  
Urbana-Champaign, Illinois (September 8, 2014)

**The Chinese University of Hong Kong**

*Dynamic Programming in Mathematical Finance*  
Hong Kong, China (December 22-23, 2014)

**2015**

**BOOK CHAPTERS**

**Estimation Theory for Generalized Linear Models**

A. Bensoussan, Pierre Bertrand, Alexandre Brouste  
*Future Perspectives in Risk Models and Finance eds; A. Bensoussan, Dominique Guegan, Charles S. Tapiero*  
Heidelberg, New York, Dordrecht, London, Springer **V211**, 1-69, (2015)

**PAPERS**

**The Maximum Principle for Global Solutions of Stochastic Stackelberg Differential Games**

A. Bensoussan, Shaokuan Chen, S.P. Sethi  
*SIAM Control & Optimizations*, Springer (2015) *To be published*

**On a System of PDE's Associated to A Game with A Varying Number of Players**

A. Bensoussan, J. Frehse, C. Grün  
*Communications in mathematical Sciences - Special Issue I Honor of George Papanicolaou's 70<sup>th</sup> Birthday Part I*,  
V13, (3), (2015) 623-639

**Entrepreneurial Decisions on Effort and Project with a Non-Concave Objective Function**

A. Bensoussan, A. Cadenillas, H. K. Koo

*Mathematics of Operations Research* (March 12, 2015)

**Integrating Equipment Investment Strategy with Maintenance Operations under Uncertain Failures**

A. Bensoussan, Q. Feng, S.P. Sethi

*Annals of Operations Research, Springer* (May 1, 2015)

**Managing Nonperishable Inventories with Learning about Demand Arrival Rate Through Stock-out Times**

A. Bensoussan, Pengfei Guo

*Operations Research* (May 13, 2015) 1 - 8

**Mean Field Games with a Dominating Player**

A. Bensoussan, M.H.M. Chau, S.C.P. Yam

*Applied Mathematics and Optimization* (July 2, 2015)

**Mean Field Stackelberg Games: Aggregation of Delayed Instructions**

A. Bensoussan, M.H. M Chau, S.C.P. Yam

*SIAM, J. Control Optim* **54** (4), (August 4, 2015) 2237-2266

**Control Problem On Space Of Random Variables and Master Equation**

A. Bensoussan, Sheung Chi Phillip Yam

*Posted at arXiv on August 4, 2015*

**Existence and Uniqueness of Solutions for Bertrand and Cournot Mean Field Games**

P. Jameson Graber, Alain Bensoussan

*Posted at arXiv on August August 21, 2015*

**Cox-Ingersoll-Ross Model for Wind Speed Modeling and Forecasting**

A. Bensoussan, Alexandre Brouste

*John Wiley & Sons, Wind Energy*, (August 27, 2015)

**Managing Inventory with Cash Register Information: Sales Recorded But Not Demands**

A. Bensoussan, Metin Çakanyildirim, Meng Li, Suresh P. Sethi

*Production and Operations Management* **24** (9) (September, 2015)

**Well-Posedness of Mean-Field Type Forward-Backward Stochastic Differential Equations**

A. Bensoussan, S.C.P Yam, Z. Zhang

*Stochastic Processes and Their Applications*. **125** (9) (September, 2015) 3327-3354

A. Bensoussan, S.C.P. Yam, Z. Zhang

**Linear-Quadratic Mean Field Games**

A. Bensoussan, K.C.J. Sung, S.C.P. Yam, S. P. Yung

*Submitted to JOTA – Journal of Optimization Theory and Applications – to be published*

**SPEAKER INVITATIONS**

***Dynamic Programming in Mathematical Finance***

Workshop, N.U.S. University Paris Diderot

Singapore, (Feb 3-4, 2015)

***On The Master Equation Interpretation***

13<sup>th</sup> Viennese Workshop on Optimal Control and Dynamic Games  
Vienna (May 12 – 15, 2015)

***On The Master Equation Interpretation***

Workshop “Mean-Field Games and Related Topics – 3”  
Paris (June 10 – 12, 2015)

***On The Master Equation Interpretation***

SIAM-SIAG Conference, Paris  
(July 8 – 10, 2015)

***Base Stock List Price Policy in Continuous Time***

University of Texas at Dallas  
Operations Management Seminar Series  
(Sept 4, 2015)

***Application of Control Theory to Cyber-Security***

Imperial College – Dept of Electrical & Electronic Engineering  
A Symposium Honoring “Professor Erol Gelenbe”  
(Sept 21-24, 2015)

***On The Master Equation Interpretation***

Stanford University - Applied Mathematics Seminar  
(October 21, 2015)

***On The Master Equation Interpretation***

NYU Shanghai  
(November 21-26, 2015)

**SUBMITTED**

**A Splitting Method for Band Control of Brownian motion: Application to Mutual Reserve Optimization**

A. Bensoussan, J. Liu, J. Yuan  
*Submitted to OR (2011)*

**Unemployment Risks and Optimal Retirement in an Incomplete Market**

A. Bensoussan, Bong-Gyu Jang, Seyoung Park  
*Submitted to Operations Research (Feb, 2013)*  
*Under Revision*

**Ergodic Control for a Mean Reverting Inventory Model**

J.Z. Liu, K.F.C. Yiu, A. Bensoussan  
*Submitted to JIMO – Journal of Industrial and Management Optimization May 29, 2015*

**Impact of Seasonality on Interquartile Range for Annual Wind Power Production**

A. Bensoussan, Pierre Raphaël Bertrand, Alexandre Brouste, Nabiha Haouas



*Submitted to Journal of Applied Statistics, June 27, 2013*

**Inventory Control with a Cash Register: Sales Recorded But Not Demand or Shrinkage**

A. Bensoussan, M. Çakanyildirim, Meng. Li, S.P. Sethi

*Submitted to MSOM (September 3, 2013)*

*Under revision*

**The Optimal Mean Variance Problem with Inflation**

J.Z. Liu, K.F.C. Yiu, A. Bensoussan

*Submitted to Quantitative Finance (Sept 8, 2013)*

**Mean and Mean-Variance Based Policies for an Inventory Model with Incomplete Information**

A. Bensoussan, Metin Çakanyildirim, Celine Hoe, Meng Li, Suresh Sethi

*Submitted to Operations Research (April, 2014, Sept, 2015)*

**Marginal Weibull Diffusion Model for Wind Speed Modeling and Short-Term Forecasting**

A. Bensoussan, Alexandre Brouste

*Submitted to Renewable Energy Journal (RENE) July 10, 2015*

**Optimality of Coordinating Pricing and Inventory Control Strategies with General Demand Functions**

A. Bensoussan, Yangyang Xie, Houmin Yan

*Submitted to Operations Research on August 6, 2015*

**On the Interpretation of the Master Equation**

A. Bensoussan, J. Frehse, S.C.P. Yam

*Posted to arXiv in 2015*

**A Strategic Approach to Collaborative Inventory Management**

A. Bensoussan, Bharadway Kadiyala, Özalp Özer

*Submitted to Management Sciences in Oct, 2015*

**WORK-IN-PROGRESS PAPERS**

**Base Stock List Price Policy in Continuous Time**

A. Bensoussan, S. Skaaning

**Real Options in a Stackelberg and a Pre-Emption Game with a Geometric Brownian Motion Stochastic Demand**

A, Bensoussan, S. Hoe

**A Game-Theoretical Risk Management Model for Botnet Defense**

A. Bensoussan, S. Hoe, Murat Kantarcioglu

**Managing Information Security under Continuous Drift and Sudden Shocks**

Radha Mookerjee, Vijay Mookerjee, Wei T. Yue, A. Bensoussan

**Differential Games W/ Mixed Leadership: The Feedback Solution**

A. Bensoussan, Shaokuan Chen, S.P. Sethi

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