ICDRiA

INTERNATIONAL CENTER FOR DECISION AND RISK ANALYSIS

Activity Report

December 5th, 2016

UTD

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ICDRiA Activity Report 2016

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 2016. The cooperation with the Johnson School of Engineering and Computer Science, on the domains of cyber security, systems engineering and energy management is expanding. There is an active cooperation with the mathematics department.   The cooperation with City University Hong Kong is developing with visits of PhD students and active collaboration with faculty.

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 is associated with the center.

2.2 Mean Field Games, Mean Field Type Control and Extensions
National Science Foundation
Alain Bensoussan (PI)
$ 339,572, October 1, 2013- September 30, 2017

2.3 New Problems in Mean Field Control Theory
National Science Foundation
Alain Bensoussan (PI), Jameson Graber (co-PI)
$ 208,559. October 1, 2016 – September 30, 2019

2.4 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

2.5 RGC, General Research Fund, Hong Kong
Mean Field Control with Partial Information
Alain Bensoussan (PI)
HK$ 727,647. January 1, 2017 – December 31, 2019

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.

Last year we developed short term forecasting models for wind speed. This year, we go further in defining the level of storage needed to achieve an optimized profitability. The storage reduces the risk of not producing an amount compatible with commitments in which case a penalty occurs. On the other hand this storage capacity, obtained with batteries is a costly investment. The problem is to find the right capacity of the battery.

Concerning NSF, we have succeeded in obtaining 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 with a successful result.

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. After initial ICDRiA involvement, the course has been directly taught within the finance area. The curriculum has been restructured and this class has been merged with financial engineering.

The major effort is now devoted to the new class "Stochastic Dynamic Programming and applications to Operations Management and Finance" which started 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 incentive 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 which 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.

The model developed so far is binary. The system is infected or not, there is defense or not. We want now to consider a level of infection which is continuous, as well as a continuous level of defense.

We have been asked to participate in a MURI proposal for the ONR Program. "Cyber Deception through Active Leverage of Adversaries Cognition Process." This team has been formed by UMD, with UMich and our group at UTD. We have sent a proposal called "Cognitive Security: Combining human factors, honey schemes, game theory and on line learning." A white paper has been accepted by ONR.
More globally, we are very happy to be associated with the center for cybersecurity at UTD. It 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. Our approach is now commonly referred in the field. We have provided a comparative analysis of approximations in order to define relatively simple solutions, still sufficiently accurate. The mean variance approximation is an innovative one, representing a meaningful example.

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 may combine both.

A general situation in which the methodology works well is *learning*. This is a common situation in which 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.

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 that 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. We have enhanced our previous results, by incorporation the possibility that the agent rejects the offer of the principal in which case the current arrangement is continued. So the principal should propose a contract at least as favorable as the current one.

The second direction initiated in Hong Kong 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 has never been considered in the literature. 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 have also worked on the case of 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.

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 for 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. On the contrary, 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. 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.

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 to 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 NSF grants and RGC-GRF grants. With Jameson Graber we have obtained significant results in Mean Field Games application to economic problems, related to the exploitation of exhaustible resources. As mentioned above, cybersecurity offers interesting possibilities of using mean field concepts.

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.

At the operational level, the first problem is to obtain 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 viable. 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 are now entering in the situation of assessing the level of storage which is needed, in concrete investments. For a given level of storage, we can optimize the profit, resulting from a commitment level, which is a daily decision. We can then proceed with a cost-benefit analysis, to define the optimal level of storage.

4.5. RISKS IN TECHNICAL SYSTEMS

As mentioned in the previous report, we do not benefit anymore of financial support in this domain. Nevertheless we continue a scientific cooperation with Dr. Laurent Mertz, currently Professor at NYU Shanghai.

We have a good record of publications in this area. It is rich in challenging problems and we are eager to continue our active research.

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. When Being Hot is Not Cool: Managing Hot Lists in Intrusion Detection and Prevention Systems

Participants: Vijay Mookerjee, Yonghua Ji, 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 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.

Yonghua Ji, Kumar, S., and Mookerjee, V., *"When Being Hot is Not Cool: Managing Hot-Lists in Intrusion Detection and Prevention Systems,"* Information Systems Research (Forthcoming).

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 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. Activities in the Supply Chain Domain

5-2-1 Partially Observed Inventory Systems

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.

a) 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.

b) 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. "Managing Inventory with Cash Register Information: Sales Recorded but Not Demands," *Production and Operations Management,* January 2016, Vol 25. No.1, 206. 9-21

c) Managing Inventory with Cash Register Information: Sales Recorded but Not Demands

<u>Participants:</u> 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*, 25(1), 2016, 9-21.

d) Inventory Management with Overlapping Shrinkages and Demands

<u>Participants:</u> Alain Bensoussan, Metin Çakanyıldırım, Meng Li, and Suresh P. Sethi

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

e) Evaluating Long-Term Service Performance under Short-Term Forecast Updates

<u>Participants:</u> Alain Bensoussan, Qi Feng, Sirong Luo and Suresh P. Sethi

Managing product availability in a cost-effective way has always been a major challenge faced by inventory managers. We study the problem of a firm selling a perishable product with short-term demand patterns and a long-term service target using the newsvendor framework. The newsvendor determines his long-term order at the first stage, and revises the order according to a short-term forecast update at the second stage. He also evaluates a long-term service target for his overall performance on product availability across all possible forecast updates. We characterize his optimal inventory policy that minimizes the expected inventory cost while meeting the long-term service target. Both in-stock rate and fill rate targets are examined.

Bensoussan, A., Feng, Q., S. Luo, and Sethi, S.P., "Evaluating Long-Term Service Performance under Short-Term Forecast Updates," *International Journal of Production Research*, 54(17), 2016, 5236-5249.

f) Mitigating Supply Uncertainty: The Interplay between Diversification and Pricing

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

We consider a firm's sourcing problem from one reliable supplier and one unreliable supplier in two price-setting scenarios. In the committed pricing scenario, the firm makes the pricing decision before the supply uncertainty is resolved. In the responsive pricing scenario, the firm's pricing decision is made after the supply uncertainty is resolved. For the committed pricing scenario, we develop a condition on supply uncertainty that guarantees the unimodality of the firm's objective function. By comparing the firm's optimal diversification decisions in the two pricing scenarios, we examine the interplay of supply diversification strategy and responsive pricing strategy in mitigating supply uncertainty. While both strategies are effective in mitigating supply uncertainty, we show that they are not necessarily substitutes. The relationship between these two strategies depends on two adverse effects caused by supply uncertainty: the lost-revenue effect and the lost-goodwill effect. More specifically, when the lost-revenue effect dominates the lost-goodwill effect, these two strategies are complements; otherwise, they are substitutes. Furthermore, we examine the impact of market size, price sensitivity, supplier reliability, and failure rebate on the interplay between these two strategies, and discuss the implications of our results. Finally, we extend our analysis to the case with two unreliable suppliers and show that most of the insights continue to hold.

Li, T. Sethi, S.P. and Zhang, J., "Mitigating Supply Uncertainty: The Interplay between Diversification and Pricing," *Production and Operations Management*, 2016, forthcoming.

g) 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

5-2-2 Combination of Products

a) "The Impact of Limited Supply on a Firm's Bundling Decision"

Participants: Kathryn Stecke, Qingning Cao, Jun Zhang

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.

Kathryn Stecke, Qingning Cao and Jun Zhang *Production and Operations Management*, Vol. 24, Issue 12, pp. 1931-1944 (December 2016)

b) "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.

5-2-3 Organization of Production

a) "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.

Kathryn Stecke, Xuying Zhao and Zhan Pang, *Production and Operations Management*, forthcoming, 2016.

b). "Mitigating Disruptions in a Multi-echelon Supply Chain Using Adaptive Ordering"

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<u>Participants:</u> Thomas Schmitt, Sanjay Kumar, Kathryn E. Stecke, Fred Glover and Mark A.Ehlen,

Supply chains often experience significant economic losses from disruptions such as facility breakdowns, transportation mishaps, natural calamities, and intentional attacks. To help respond and recover from a disruption, we investigate adjustments in order activity across four echelons including assembly. Simulation experiments reveal that the impact of a disruption depends on its location, with costlier and longer lasting impacts occurring from disruptions at echelons close to ultimate consumption. Cost functions based on system inventory and service can be quite ill-behaved in these complex problem settings. Expediting, an adaptive ordering approach often used to mitigate disruptions, can trigger unintended bullwhip effects, and hurt rather than help overall performance. As an alternative to expediting interventions, dynamic order-up-to policies show promise as an adaptive mitigation tool. We also find benefits in the dynamic policies from incorporating a metaheuristic parameter search over multiple echelons, yielding significantly better solution quality than embedded unimodal search.

Omega, forthcoming, 2017.

c) "An Implementation Framework for *Seru* Production"

<u>Participants:</u> ChenGuang Liu, Kathryn E. Stecke, Jie Lian, and Yong Yin

Seru production, which merges the flexibility of job shops, efficiency of mass production, and environment friendly characteristics of sustainable manufacturing, largely for electronics assembly, is the latest manufacturing mode developed in Japan. It is receiving attention from Japanese practitioners and researchers. However, some attempts to implement *seru* production are unsuccessful, especially outside Japan. This is because of lack of knowledge of the specific means to implement *seru* production. The purpose of this paper is to provide a general framework and some basic principles that should be followed while implementing *seru* production for practitioners from a practical perspective. This work is based on a systematic analysis of many implementation experiences of *seru* production in Japanese manufacturing factories as well as a broad investigation of the popular literature information. The proposed framework can serve as a concise guide to help implement *seru* production in the manufacturing industry. In addition, constructive information is provided for researchers who would like to know and study the advanced manufacturing mode of *seru* production but do not understand the Japanese language.

International Transactions in Operational Research, Vol. 21, No. 1, pp. 1-19 (January 2014).

5-2-4 Transport Problems

a) Optimal Transshipments and Reassignments under Periodic or Cyclic Holding Cost Accounting

<u>Participants:</u> K. Stecke, Nagihan Çömez, 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.

b) Transshipment Price negotiation and Coordination of Two Independent Retailers

Participants: Metin Çakanyildirim, Kathryn Stecke, Nagihan Comez

Transshipments among two retailers ordering from a manufacturer at the beginning of a season are studied. Retailers consider sending transshipments one-by-one in each period, but also compete for demand as an unsatisfied customer at a retailer may visit another retailer. We prove that retailers can maximize their profits without making any transshipment before a stockout. For each period and inventory level, we construct a transshipment price interval, all of whose members coordinate transshipment decisions. We map this price characterization to a threshold-based transshipment policy for ease of implementation. We also illustrate a negotiation mechanism that leads to a unique equilibrium price in the interval. Resulting transshipment prices can be static or dynamic depending on retailer powers, although the interval is always dynamic. To coordinate retailer orders, we provide a simple and transparent purchase cost sharing mechanism, which eliminates independent retailers' incentives to overstock by appropriately increasing the unit purchase cost. We show how this mechanism can be made Pareto-improving for retailers and illustrate profit improvements obtained by coordinating the orders in addition to transshipments. To our knowledge, this paper is the first to dynamically study independent retailers' transshipment price negotiations or to hierarchically address the coordination of transshipments and orders.

5-2-5 Innovation- Consumer Behavior

a) 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*

b) 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.

c) 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.
Gupta,V. and M. Çakanyildirim. A WTP-Choice Model: Empirical Validation, Competitive and Centralized Pricing. To appear in *Production and Operations Management.*

d) 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.

e) 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

5-2-6   Game Problems

a).   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.), International Series in Operations Reseaarch & Management Science, Vol. 198, Springer, New York, 2014, 3-15.

b)   Feedback Stackelberg Games in Operations Management

Participants: Suresh P. Sethi and Tao Li

Dynamic Stackelberg game models have been used to study sequential decision making in noncooperative games in various fields. In this chapter we give relevant dynamic Stackelberg game models, and review their applications to operations management and marketing channels. A common feature of these applications is the specification of the game structure: a decentralized channel consists of a manufacturer and independent retailers, and a sequential decision process with a state dynamics. In operations management, Stackelberg games have been used to study inventory issues, such as wholesale and retail pricing strategies, outsourcing, and learning effects. in dynamic environments. The underlying demand typically has a growing trend or seasonal variation. In marketing, dynamic Stackelberg games have been used to model cooperative advertising programs, store brand and national brand advertising strategies, shelf space allocation, and pricing and advertising decisions. The demand dynamics are usually extensions of the classic advertising capital models or sales-advertising response models. We begin each section by introducing the relevant dynamic Stackelberg game formulation along with the definition of the equilibrium used, and then review the models and results appearing in the literature.

Sethi, S.P. and Li, T., "A Review of Dynamic Stackelberg Game Models," *Discrete and Continuous Dynamical Systems - Series B (DCDS-B)*, 2017, forthcoming.

c)   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.

d) 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.

5-2-7 Decentralized Supply Chain

a) The Implication of Vendor Inventory Liability Period in a Decentralized Assembly System

Participants: X. Guan and Suresh P. Sethi

This paper investigates a decentralized assembly system that consists of one manufacturer and multiple suppliers who produce the complementary components. In a single selling season, the manufacturer initially sets a vendor inventory liability period (VILP) to control the suppliers' delivery times, and the suppliers simultaneously determine when to deliver their components. Given the firms' equilibrium strategies, we find that it is not wise for the manufacturer to set an overly long VILP, since having no inventory is not always beneficial to the manufacturer. A supplier may choose to postpone his delivery when the length of the VILP increases or the other suppliers' deliveries are delayed, and either of these conditions is detrimental to the supplier's profitability. We also examine the impact of VILP under different situations and find that having VILPs customized for different suppliers can reduce the manufacturer's cost as well as improve the supply chain's overall efficiency.

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.

b) 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 behavior 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*, 54(5), 2016, 1334-1357

c) 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*, May 2015.

d) 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*, 240(2), 2016, 617-640.

e) Investing in a Shared Supplier in a Competitive Market: Stochastic Capacity Case

Participants: Anyan Qi, Hyun-Soo Ahn, Amitabh Sinha

 When firms invest in a shared supplier, one key concern is whether the invested capacity will be used for a competitor. In practice, this concern is addressed by restricting the use of the capacity. We consider what happens when two competing firms invest in a shared supplier. We consider two scenarios that differ in how capacity is used: exclusive capacity and first-priority capacity. We model firms' investment and production decisions, and analyze the equilibrium outcomes in terms of the number of investing firms and capacity levels for each scenario; realized capacity is a stochastic function of investment levels. We also identify conditions under which the spillover effect occurs, where one firm taps into the other firm's invested capacity. Although the spillover supposedly intensifies competition, it actually discourages firms' investment. We also characterize the firms' and supplier's preference about the capacity type. While the non-investing firm always prefers spillovers from the first-priority capacity, the investing firm does not always want to shut off the other firm's access to its leftover capacity, especially when allowing spillover induces the other firm not to invest. The supplier's preference depends on the trade-off between over-investment and flexibility.

Citation: Qi, A., Ahn, H.-S. and Sinha, A. (2015), Investing in a Shared Supplier in a Competitive Market: Stochastic Capacity Case. *Production and Operations Management*, 24: 1537–1551.

5-2-8 Methodology

a)   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**

b) 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 $L^\natural$-convex, we propose a pseudo-polynomial time approximation scheme that solves this problem to within an arbitrary pre-specified additive error of $\varepsilon > 0$. 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 $L^\natural$-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, (I)**, 81-103.

c)   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)

d)   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, 2016, *Production and Operations Management*. 25:4:684-700

d) **You Can Act On: Optimal Policies for Assembly Systems with Expediting and Advance Demand Information**.

Participants: Özalp Özer, A. Angelus

We consider a nonstationary, stochastic, multi-stage supply system with a general assembly structure, in which customers can place orders in advance of their future demand requirements. This advance demand information is now recognized in both theory and practice as an important strategy for managing the mismatch between supply and demand. In conjunction, we allow expediting of components and partially completed subassemblies in the system in order to provide the supply chain with the means to manage the stock out risk and significantly enhance cost savings realized through advance demand information. To solve the resulting assembly system, we develop a new method based on identifying local properties of optimal decisions. This new method allows us to solve assembly systems with multiple product flows. We derive the structure of the optimal policy, which represents a double-tiered echelon base stock policy whose base stock levels depend on the state of advance demand information. This form of the optimal policy allows us to: (i) provide actionable policies for firms to manage large-scale assembly systems with expediting and advance demand information; (ii) prove that advance demand information and expediting of stock both reduce the amount of inventory optimally held in the system; and (iii) numerically solve such assembly systems, and quantify the savings realized. In contrast to the conventional wisdom, we discover that advance demand information and expediting of stock are complementary under short demand information horizons. They are substitutes only under longer information horizons.

Özalp Özer, A. Angelus, Operations Research;   Forthcoming

e) **Characterizing the Structure of Optimal Stopping Policies.**

Participants: Özalp Özer, S. Oh

This paper studies a stochastic model of optimal stopping processes that arise frequently in operational problems (e.g., when a manager needs to determine an optimal epoch to stop a process). For such problems, we propose an effective method that characterizes the structure of the optimal stopping policy for the class of discrete-time optimal stopping problems. Using the method, we also provide a set of metatheorems that characterize when a *threshold* or *control-band* type stopping policy is optimal. We show that our proposed method can characterize the structure of the optimal policy for some stopping problems for which conventional methods fail to do so. Our method also simplifies the analysis of some existing results. In addition, the metatheorems help identify sufficient conditions that yield simple optimal policies when such policies are not generally optimal. We show the aforementioned benefits of our method by applying it to several optimal stopping problems frequently encountered, for example, in operations, marketing, finance and economics literature. We remark that structural results make an optimal-stopping policy easier to follow, describe, compute and hence implement. They also help understand how a stopping policy should respond to changes in the operational environment. In addition, structural results are critical for the development of efficient algorithms to solve optimal stopping problems numerically.

Özalp Özer, S. Oh, Production and Operations Management; Forthcoming

5-2-9 Inventory Policies

a) **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**

b)   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**

c).   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 polices 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 (Forthcoming in *Manufacturing and Service Operations Management*.)

d) 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, 2015 *Production and Operations Management*. 24:12:1955-1965

e) 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*)

f) The Making of a Good Impression: Information Hiding in Ad Exchanges

Participants: Z. Sun, M. Dawande, G. Janakiraman and V. Mookerjee

In this paper, we examine information revelation designs and policies in ad exchanges that use a second-price auction mechanism. Two auction designs are studied: one-call and two-call. Under the one-call design, the ad exchange makes one call to all bidders at the beginning of an auction. Under the two-call design, in addition to the call to all bidders at the beginning of the auction, the exchange calls out the winning bidder at the end of the auction; this second call enables the winning bidder to match the right advertiser for the impression. Thus, the two-call design requires a higher level of technical sophistication but offers to the auction site the choice of the timing and the extent of information released to bidders about an impression.

While valuations are private to bidders, there are two possibilities as far as the information available to the ad exchange on these bidder valuations is concerned: One, the ad exchange has no reliable knowledge about bidder valuations. For this situation, we develop simple information revelation policies that do not use any knowledge of the valuations and establish their performance guarantees. Two, the ad exchange has distributional knowledge about bidder valuations. For this situation, we develop an informed heuristic that exploits this information. While the heuristic continues to offer the same performance guarantee as that of the simple policies, we show that its performance on a comprehensive test bed is near-optimal. The welfare implications of the information revelation policy of the ad exchange on other stakeholders of the ecosystem are also analyzed.

g) Optimal Policy for a Stochastic Scheduling Problem with Applications to Surgical Scheduling

Participants: H. Guda, M. Dawande, G. Janakiraman and K. Jung,

We consider the stochastic, single-machine earliness/tardiness problem (SET), with the sequence of processing of the jobs and their due-dates as decisions and the objective of minimizing the sum of the expected earliness and tardiness costs over all the jobs. In a recent paper, Baker (**2014**) shows the optimality of the Shortest-Variance-First (SVF) rule under the following two assumptions: (a) the processing duration of each job follows a normal distribution. (b) The earliness and tardiness cost parameters are the same for all the jobs. In this study, we consider problem SET under assumption (b). We generalize Baker's result by establishing the optimality of the SVF rule for more general distributions of the processing durations and a more general objective function. Specifically, we show that the SVF rule is optimal under the assumption of *dilation ordering* of the processing durations. Since *convex ordering* implies dilation ordering (under finite means), the SVF sequence is also optimal under convex ordering of the processing durations. We also study the effect of variability of the processing durations of the jobs on the optimal cost. An application of problem SET in surgical scheduling is discussed.

h) Dual Sourcing Inventory Systems: Optimal Policies and the Value of Costless Returns

Participants: G. Janakiraman and S. Seshadri

We study dual sourcing inventory systems with backordering and with stationary, stochastic demands. The two supply sources differ in their unit prices and lead times. We focus on the option of making costless returns to the cheaper, longer-lead time supplier. We show that the value of this option is zero. Our analysis leading to this result includes the derivation of several structural properties of the optimal policies for dual sourcing systems with and without the return option

i) Optimal Batch Ordering over a Finite Horizon

Participants: Abdullah O. Alsuwinea, 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).

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

5-2-10 Competition-Pricing-Learning

a) 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.

b) 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.

c) Supply Diversification with Iseolastic 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.

d) 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.

e) On the Optimality Conditions of a Price-Setting Newsvendor Problem

Participants: Sirong Luo, Suresh P. Sethi, and Ruixia Shi

We analyze a price-setting newsvendor problem with an additive–multiplicative demand. We show that the unimodality of the newsvendor profit function holds when the underlying random term has an increasing failure rate and the demand functions satisfy certain concavity conditions. Furthermore, we show that the optimal price decreases in the order quantity. Finally, we compare our optimality conditions with those existing in the literature.

Luo, S., Sethi, S.P. and Shi, R., "On the Optimality Conditions of a Price-Setting Newsvendor Problem," *OR Letters*, 2016, forthcoming.

f) Inventory Control with Pricing Optimization in Continuous Time

Participants: Bensoussan A., Skaaning S.

We study the continuous time extension to the inventory control problem considered by A. Federgruen and A. Herching in *"Combined Pricing and Inventory Control under Uncertainty"* where the no fixed cost case is studied.

By use of Quasi-Variational Inequalities we show the solution to the inventory control problem can be found by solving the associated two-point boundary value problem on a semi-infinity domain. We show theoretically the solution exist and is unique by use of an epsilon problem. We show the optimal strategy follows a Base-Stock List Price policy, which in the discrete case was shown to be optimal by A. Federgruen and A. Herching.

Providing continuous time equivalence to the discrete time case provides a benchmark of the highest attainable profit. The whole policy relies on the knowledge of the value of the Base-Stock *"S"* since both the inventory as well as the pricing feedback is dependent on it. We therefore develop a searching algorithm, which finds the value of *"S"* by solving the associated two-point boundary value problem. The MATLAB solver bvp5c was used to achieve these findings.

We next study the case where fixed cost is incorporated. Here we extend the findings by X. Chen and D. Simchi-Levi in *"Coordinating Inventory Control and Pricing Strategies with Random Demand and Fixed Ordering Cost: The Infinite Horizon Case."* We again use the power of Quasi-Variational Inequalies to provide us with the associated two-point boundary value problem. We show the optimal strategy is of a *(s,S,p)*-format, as was shown by X. Chen and D. Simchi-Levi for the discrete case. Again no deterministic formula to find *(s,S)* can be attained theoretically, and we therefore develop a new searching algorithm that incorporates the different conditions needed to find the value of *(s,S)*. In our numerical studies we show for the case where the fixed cost is zero we have *s=S.*

Bensoussan, A., Skaaning, S. (2016) Base-Stock List Price in Continuous Time (Accepted by Discrete and Continuous Dynamical Systems – Series B (DCDS – B), anticipated publication in 2017)

Bensoussan, A., Skaaning, S. (2016) Inventory Control with Fixed Cost and Price Optimization in Continuous Time (Working paper)

5-2-11 Logistics

a) **Organizational Nimbleness and Operational Policies: The Case of Optimal Control of Maintenance Under Uncertainty**

Participants: Ali Dogramaci and Suresh P. Sethi

The speed with which an organization takes action against unplanned failure and scrapping of its capital equipment is used as a measure of organizational nimbleness. Operational decisions at the plant level are studied in terms of the optimal control model of Kamien and Schwarz for maintenance policy. In this context it is shown how the form of optimal policies at the lower operational levels change, as the degree of nimbleness in decision making at higher echelons of the organization is increased.

Dogramaci, A. and Sethi, S.P., "Organizational Nimbleness and Operational Policies: The Case of Optimal Control of Maintenance under Uncertainty," *Dynamic Perspectives on Managerial Decision Making, Essays In Honor of Richard F. Hartl*, in Series: Dynamic Modeling and Econometrics in Economics and Finance, W. Semmler and S. Mittnik (Eds.), Springer, 2016 forthcoming.

b) **Optimizing Logistics Operations in a Country's Currency Supply Network**

Participants: Yiwei Huang, H. Neil Geismar, Divakar Rajamani, Suresh P. Sethi, Chelliah Sriskandarajah, and Marcelo Carlos

We optimize a large country's currency supply network for its central bank. The central bank provides currency to all branches (who in turn serve consumers and commerce) through its network of big vaults, regional vaults, and retail vaults. The central bank intends to reduce its total transportation cost by enlarging a few retail vaults to regional vaults. It seeks further reductions by optimizing the sourcing in the updated currency network. We develop an optimization model to select the retail vaults to upgrade so that the total cost is minimized. Optimally

choosing which retail vaults to upgrade is strongly NP-hard, so we develop an efficient heuristic that provides solutions whose costs average less than 3% above the optimum for realistic problem instances. An implementation of our methodology for a particular state has generated a total cost reduction of approximately 57% (equivalently, $2 million). To optimize the sourcing, we propose an alternative delivery process that further reduces the transportation cost by over 31% for the actual collected data, and by over 38% for randomly-generated data. This alternative optimizes the sourcing within the new currency network and requires significantly less computational effort.

Huang, Y., Geismar, H.N., Rajamani, D., Sethi, S.P., Sriskandarajah, C., Carlos, M., "Optimizing Logistics Operations in a Country's Currency Supply Network," *IIE Transactions*, 2016, forthcoming.

c) Needle Exchange for Controlling HIV Spread under Endogenous Infectivity

Participants: Yonghua Ji and Suresh P. Sethi

Losses due to HIV infections among injection drug users are substantial. Among HIV prevention programs targeting IDUs, needle and syringe programs are relatively easy to administrate and cost-effective. We study the problem of optimally allocating prevention effort over a finite time horizon in a needle and syringe program by balancing the benefit of infections averted with prevention costs. To maximize the system value, one needs to consider the timing and amount of prevention effort carefully. A key finding of our work is that extreme treatment policies from previous literature are not optimal. Instead, a period of moderate prevention effort is crucial in an optimal policy. We also find that as the time horizon increases, a policy of initial extreme treatment becomes more attractive and such treatment duration grows. Another interesting finding is the non-linear impact of control effectiveness on the amount of prevention effort: when prevention effort is highly effective, the amount of effort decreases with the effectiveness, contrary to what one might expect. Through policy comparison, optimal policies are found to be most beneficial when the budget is less constrained.

Ji, Yonghua and Sethi, S.P., "Needle Exchange for Controlling HIV Spread Under Endogenous Infectivity," *Information Systems and Operational Research*, 2016, forthcoming.

5-2-12 Contracts

a) Buyback Contracts with Price-Dependent Demands: Effects of Demand Uncertainty

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

b) Push and Pull Contracts in Local Supply Chains with an Outside Market

Participants: Qinglong Guo, Jinfeng Yue, Suresh P. Sethi, and Juan Zhang

Wholesale price contracts are widely studied in a single supplier-single retailer supply chain. However, this consideration ignores the existence of an outside market, where the supplier may sell if he gets a high enough price. The retailer, on the other hand, may also purchase from this outside market if the price is low enough. Motivated by these considerations, we study push and pull contracts in a local supplier-retailer supply chain in the presence of an outside market. Taking the local supplier's maximum production capacity into account, we demonstrate that a supplier can use a push contract to improve the supply chain's performance. Further analysis of the Pareto set of push or pull contracts reveals that: (i) an export barrier in the local market and the supplier's production capacity influence the supplier's export strategy; (ii) a low import (resp., export) barrier in the local market can improve the local supply chain's efficiency by use of push (resp., pull) contract; and (iii) a high import (resp., export) barrier in the local market encourages the supplier (resp., retailer) to bear more inventory risk.

Gou, Q., Sethi, S.P., Yue, J., and Zhang, J., "Push and Pull Contracts in Local Supply Chains with an Outside Market," *Decision Sciences*, 2016, forthcoming.

c) 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*

d) 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

e) 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*

f) Establishing Trust and Trustworthiness in Supply Chain Information

Participants: Özalp Özer, K. Zheng

In this chapter, we discuss when, how and why trust and trustworthiness arise to support credible information sharing and cooperation in a supply chain. Synthesizing our learning, we identify the four building blocks of trust and trustworthiness as personal values and norms, market environment, business infrastructure, and business process design. We elaborate on these building blocks and offer tangible insights into how to establish more trusting and cooperative supply chain relationships.

Özalp Özer, K. Zheng, Handbook of Information Exchange in SCm (Eds A. Ha and C. Tang) Forthcoming.

g) Information Sharing, Advice Provision or Delegation; What Leads to Higher Trust and Trustworthiness?

Participants: Özer Özalp, U. Subramanian, Y. Wang

In many market settings, a customer often obtains assistance from a supplier (or service provider) in order to make better-informed decisions regarding the supplier's product (or service). Because the two parties often have conflicting pecuniary incentives, customer trust and supplier trustworthiness play important roles in the success of these interactions. We investigate whether and how the process through which assistance is provided can foster trust and trustworthiness and facilitate better cooperation. We compare three prevalent assistance processes: information sharing, advice provision, and delegation. We propose that, even if the pecuniary incentives of both parties do not vary from one assistance process to another, the assistance process itself impacts the customer's and supplier's non-pecuniary motives that give rise to trust and trustworthiness. Consequently, the assistance process affects the level of cooperation and payoffs. We test our behavioral predictions through laboratory experiments based on a retail distribution setting. We quantify the impact of different assistance processes on trust, trustworthiness and channel performance, and identify the underlying drivers of those impacts. Our results offer insight into the role of the assistance process in managing supplier assistance effectively, and why certain assistance processes may lead to more successful outcomes than others even if the pecuniary incentives remain unaltered.

Özer Özalp, U. Subramanian, Y. Wang   Management Sciences   Forthcoming

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. 2 Real Options with Mean Field Games and Mean Field Type Control

<u>Participants:</u> **Alain Bensoussan, Celine Hoe, ZhongFeng Yan**

Expanding the game models studied in previous works, we explore the 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 men-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 methods.

5-3-3 Real Options and Growth of Firms

<u>Participants:</u> **Alain Bensoussan, Benoit Chevalier-Roignant**

We consider a continuous-time setup where a firm can repeatedly invest and raise capital incurring fixed costs as well as costs proportional to the lump-sum capital investment. We follow the methodology of impulse controls: We obtain a new type of quasi-variational inequality, derive general properties, and solve in some particular cases. Our model generalizes and unifies the theory of investment under uncertainty by allowing both fixed and variable costs. In contrast to existing models of capital accumulation, we obtain that the firm does not raise capital incrementally but by lump-sums. The setting involving incremental capital investments obtains as a degenerate case.

5.3.3 Stochastic Optimization

a)   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, March 2015.

b) 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.

Bensoussan A., Jang Bong-Gyu, Park Seyoung,

Unemployment Risks and Optimal Retirement in an Incomplete Market, *Operations* Research **64** (**4**)*, (*March, 2016)

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

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

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.

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.

5-4-3 Forecasting based on Diffusion Processes

Participants: A. Bensoussan, A. Brouste
We use diffusion type approaches to model wind energy in the short term. We then apply this model for forecasting, and make comparison with more standard approaches

A. Bensoussan, A. Brouste , Cox-Ingersoll-Ross Model for Wind Speed Modeling and Forecasting
John Wiley & Sons, Wind Energy, (August 27, 2015)

5.5. Activities in Risks on Technical Systems

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

a) <u>Participants</u>: 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

b) <u>Participants:</u> 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., Nonlocal problems related to an elasto-plastic oscillator excited by a filtered noise, SIAM J. Math. Anal. 48-4 (2016), pp. 2783-2805.

5.5.2. New Results on the Long Time Behavior of Elastic-Plastic Systems

Several works related to this domain are collected here:

<u>Participants:</u> 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 goes to 0. Then, numerical experiments on the convergence reveal, on the one hand, that the rate of convergence behaves as A exp(− B) 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 ∞. 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   Failure of Mechanical Structures

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. Submitted to Asymptotic Analysis, in revision

Participants   L. Mertz, G. Stadler and J. Wylie

The purpose of this paper is to present a computational alternative to probabilistic simulations for path-dependent stochastic dynamical systems that are prevalent in engineering mechanics. As examples we target (a) stochastic elasto-plasticity (involving transitions between elastic and plastic states) and (b) obstacle problems with noise (involving discrete impulses due to collisions with an obstacle). We focus on solving Backward Kolmogorov Equations (BKEs) originating from elasto-plastic and obstacle oscillators. The main challenge in solving each of these BKEs corresponding to these problems is to deal with the nonlocal boundary conditions which describe the behavior of the underlying process on the boundary.

L. Mertz, G. Stadler and J. Wylie, A numerical alternative to probabilistic simulations for path-dependent stochastic dynamical systems, preprint.

7. Publications

2016

PAPERS

The Optimal Mean Variance Problem with Inflation
Jingzhen Liu, Ka Fai Cedric Yiu, A. Bensoussan
Discrete and Continuous Dynamical Systems Series **21** (**1**) (January 2016) 185-203

Managing Inventory with Cash Register Information
A. Bensoussan, Metin Çakanyildirim, Meng Li, Suresh P. Sethi
Production and Operations Management POMS, **25** (**1**) (January, 2016) 9-21

Evaluating Long-Term Service Performance Under Short-Term Forecast Updates
A. Bensoussan, Qi Feng, Sirong Luo, Suresh P. Sethi
International Journal of Production Research, (March 5, 2016)

Unemployment Risks and Optimal Retirement in an Incomplete Market
A. Bensoussan, Bong-Gyu Jang, Seyoung Park
Operations Research **64** (**4**)*, (*March, 2016) 1015-1032

NonLocal Boundary Value Problems of a Stochastic Variational Inequality Modeling an Elasto-Plastic Oscillator Excited by a Filtered Nose
A. Bensoussan, L. Mertz, S.C.P. Yam
SIAM Journal on Mathematical Analysis, (April 15, 2016)

Optimal Cable Laying Across an Earthquake Fault line Considering Elliptical Failures
Cong Cao, Zengfu Wang, Moshe Zukerman, Jonathan H. Manton, Alain Bensoussan
IEEE Transactions in Reliability (2016)

Improvement in Artificial Neural Network-Based Estimation of Grid Connected Photovoltaic Power Output
Chao Huang, A. Bensoussan, Michael Edesess, Kwok L. Tsui
Elsevier Renewable Energy **97** (2016) 838-848

Performance Analysis of a Grid-Connected Upgraded Metallurgical Grade Silicon Photovoltaic System
Chao Huang, Michael Edesess, A. Bensoussan, Kwok L. Tsui
Energies **9** (**5**) 342 (May 5, 2016)

On the Interpretation of the Master Equation
Alain Bensoussan, J. Frehse, S.C.P. Yam
Stochastic Processes and their Applications (October 8, 2016), (in publication)

SPEAKER INVITATIONS

Master Equation in Mean Field Control Theory
University of Houston, Department of Mathematics
International Workshop on Applied and Computational Mathematics Honoring Prof. O. Pironneau
February 26-27, 2016

Capital Accumulation and Real Options
Shandong University, Qilu Securities Institute for Financial Studies
Polytechnic University and Shandong University Workshop
June 7-8, 2016

Wind Energy Forecasting
International Conference on Interface between Statistics and Engineering
Palermo, June 20-23, 2016

Master Equation on Mean Field Control Theory
First Joint Meeting Brazil Italy of Mathematics
Rio de Janeiro, August 29 – Sept 2, 2016

Introduction to Backward Stochastic Differential Equations and Parabolic P.D.E. in the Whole Space
Cornell University CAM Colloquium
Ithaca, New York   Nov 8, 2016

2015

BOOK EDITED

Future Perspectives in Risk Models and Finance eds; A. Bensoussan, Dominique

Guegan, Charles S. Tapiero
Springer, Heidelberg, New York, Dordrecht, London, Springer, (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)

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 70th Birthday Part I,
V13**, (3**), (2015) 623-639

PAPERS

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 on-line, (July 2, 2015)

Mean Field Stackelberg Games: Aggregation of Delayed Instructions
A. Bensoussan, M.H. M Chau, S.C.P. Yam
SIAM, J. Control Optimization **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 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)*

The Maximum Principle for Global Solutions of Stochastic Stackelberg Differential Games
A. Bensoussan, Shaokuan Chen, S.P. Sethi
SIAM Control & Optimizations, Springer, **53** (**4**) *(*September, 2015) 1956-1981

Well-Posedness of Mean-Field Type Forward-Backward Stochastic Differential Equations
A. Bensoussan, S.C.P Yam, Z. Zhang
 *Stochastic Processes and Their Applications 1*2**5** (**9**) (September, 2015) 3327-3354
A. Bensoussan, S.C.P. Yam, Z. Zhang

 Linear-Quadratic Mean Field Games
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Mean-Field Game Model for Botnet Defense in Cyber-Security
V.N. Kolokoltsov and A. Bensoussan
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SPEAKER INVITATIONS

Dynamic Programming in Mathematical Finance
National University of Singapore, China
Model Uncertainty and Stochastic Control in Financial Risk Management Workshop
February 3 - 5, 2015)

 Techno Pole de l'Environement
Aix en Provence, France
Conseil Scientifique et Industriel – Scientifique Board (March 18 – 21, 2015)

On the Interpretation of the Master Equation in Mean Field Control Theory
Vienna, Austria
Mean-Field Models and Control of Multi-Agent Systems 13th Viennese Workshop
On Optimal Control and Dynamic Games (May 8 – May 16, 2015)

On the Interpretation of the Master Equation in Mean Field Control Theory
Institut Henri Poincare, Paris, France
Workshop Mean Field Games and Related Topics Workshop (June 6 – 10, 2015)

On the Master Equation Interpretation
Paris, France

SIAM Conference on Control and Its Applications (CT15) (July 8 – 10, 2015)

Base Stock List Price Policy in Continuous Time
University of Texas at Dallas
JSOM - Operations Management Seminar Series (Sept 4, 2015)

Application of Control Theory to Cyber-Security
Imperial College, England – 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 Interpretation of the Master Equation
University of Texas, Austin
Western Conference in Mathematical Finance - WCMF (October 31 – 31)

Dynamic Programming in Mathematical Finance
Philadelphia, Pennsylvania
INFORMS Annual Meeting (Nov 1 – 4, 2015)

On the Interpretation of the Master Equation
Shanghai, China
NYU Shanghai & NYU ECNU Institute of Mathematical Science (Nov 21 – 26, 2015)

2014

PAPERS

Optimal Control of Hidden Markov Models w/ Binary Observations
A. Bensoussan, Arash Komaee
 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,
A. Bensoussan, Hua-Ming Song, Hui Yang, Ding Zhang
Computers & Operations Research, **41** (January, 2014) 200-308

A Trust-Score-Based Access Control in Assured Information Sharing Systems: An Application of Financial Credit Risk Score Models
A. Bensoussan, Celine Hoe, Murat. Kantarcioglu
Risk and Decision Analysis, **5, 2-3** (January 1, 2014), 129-138

Confidence Intervals for Annual Wind Power Production

A. 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)

An Analytical Approach for the Growth Rate of the Variance of the Deformation Related to an Elasto-Plastic Oscillator Excited by a White Noise
A. Bensoussan, Laurent Mertz, Sheung Chi, Phillip Yam
Applied Mathematics Research, (**4**) (October 20, 2014) 30

The Master Equation in Mean Field Theory
A. Bensoussan, J. Frehse, S. C. P. Yam
Journal de Mathématiques Pures et Appliquées (Nov 5, 2014)

Degenerate Dirichlet Problems Related to the Ergodic Property of the Elasto-Plastic Oscillator Excited by a Filtered White Noise
A. Bensoussan, Laurent Mertz
IMA Journal of Applied Mathematics (Dec 2, 2014) 1-46

Real Options with Competition and Regime Switching
A. Bensoussan, SingRu Hoe, ZhongFeng Yan, G. Yin
Mathematical Finance, (announced 2014)

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 Quardighi, Konstantin Kogan
Springer (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

Control and Nash Games with Mean Field Effect
A. Bensoussan, Jens Frehse
Partial Differential Equations: Theory, Control and Approximation
Springer (2014) 161-192

Inventory Management with Overlapping Shrinkages and Demands
A. Bensoussan, Metin Çakanyildirim, Meng Li, Suresh P. Sethi

Risk and Decision Analysis
IOS Press (2014) 189-210

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

Entrepreneurial Decisions on Effort and Project with a Non-Concave Objective Function
Alain Bensoussan, A. Cadenillas, H.K. Koo   Presenter: A. Cadenillas
20th Conference of the International Federation of Operational Research Society (IFORS)
Barcelona, Spain, July 13 – 18, 2014   www.ifors.org/web/

Entrepreneurial Decisions on Effort and Project with a Non-Concave Objective Function
Alain Bensoussan, A. Cadenillas, H.K. Koo   Presenter: A. Cadenillas
Stochastic Calculus, Martingales and Financial Modeling
Pushkin, St. Petersburg, Russia June 29 – July 6 , 2014   *http://smf.hse.ru/*

SPEAKER INVITATIONS

Mean Field Games and Mean Field Type Control
King Abdullah University of Science and Technology
Saudi Arabia (February 25, 2014)

The Master Equation in Mean Field Theory
Sino-French Conference on Computational & Applied Mathematics
Xiamen, China (June 2, 2014)

An Overview of Risk Management
7th International Symposium on BSDE, Shandong University
Weihai, China (June 22-24, 2014)

W.T. and Idalia Reid SIAM Award Lecture
SIAM 2014 Annual Conference
Chicago, Illinois (July 7-11, 2014)

Uncertainties and Competition
Association of Korean Financial Engineering
Pusan, Korea (August 19-23, 2014)

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

Dynamic Programming in Mathematical Finance
Tofler Chair Lecture, New York University School of Engineering
New York, New York (October 7, 2014)

Big Data, How to Meet Expectations
ERCIM 25th Anniversary,
Pisa, Italy (October 23, 2014)

Gestion des Risques: Une Science en Construction
INRIA, Alumni
Paris, France   (November 25, 2014)

Dynamic Programming in Mathematical Finance
The Chinese University of Hong Kong
Hong Kong, China (December 22-23, 2014)