

ICDRiA

**INTERNATIONAL CENTER FOR
DECISION AND RISK ANALYSIS**

Activity Report

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

THE UNIVERSITY OF TEXAS AT DALLAS
INTERNATIONAL CENTER FOR DECISION AND RISK ANALYSIS
P.O. BOX 830688 SM30 RICHARDSON, TEXAS 75083-0688
(972) 883-5970 FAX (972) 883-5850



ICDRiA Activity Report 2018

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 2017. 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 Collaborative Research Agreement between EREN Groupe S.A.: OSMOS and JSOM-ICDRiA

Alain Bensoussan (PI)
\$ 180,000 USD
November 29, 2017 – November 29, 2020

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 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.

We completed our work for EREN Development in the field of alternative energies. The group asked us to switch to a new company OSMOS. This company develops sensors to measure vibrations very accurately. These sensors are placed on infrastructures, mostly bridges, but also rails and buildings. Thanks to these sensors, one can accumulate a large quantity of data. The final objective is to use these data to build and calibrate degradation models for the status of the infrastructures. Thanks to these models, we intend to develop stochastic maintenance in this context. Stochastic maintenance is one of the most promising research areas of the application of machine learning methods.

Concerning NSF, we proceed with the grant on Mean Field Control Theory. This is done jointly with Dr. Jameson Graber as a co PI. Dr. Graber now has a position at Baylor University.

Research Program

FUTURE ACTIVITIES

Among the important evolutions of the research domains of the center, the area of machine learning is fast emerging. This is enhanced by the fact that at City U, there is a new school of Data Sciences, in which the position of Alain Bensoussan has been transferred. We have now organized a working group, including Hong Kong scholars, UTD scholars and Le Mans University scholars, with a professor from SMU to collaborate on this domain. We study in particular the connection between machine learning and control theory, which is quite promising. The connection is in both ways. On the one side, we investigate how machine-learning methods can help solving control problems, namely Dynamic Programming equation of large dimension. On the other side, we investigate how machine-learning methods can be reformulated as control problems. We also want to reconsider classical techniques of identification and Bayesian inference with the new vision of machine learning.

Within the framework of cooperation between IRA and ICDRiA, a workshop in “Machine Learning and Control Theory” has been organized on December 4th. It has been quite successful, and a follow up will be planned in 2020.

4. 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 “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 major effort is now devoted to the new class “Stochastic Dynamic Programming and applications to Operations Management and Finance” which started in fall 2015. Fall 2018, the class cross-listed

jointly by the Mathematics department and the Jindal School of Management.

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.

5. 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.

5.1. 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 Jindal School of Management. The center cooperates also with the Cyber-security Center of the School of Engineering And Computer Science, headed by Professor Bhavani Thuraisingham. Alain Bensoussan has been co-PI of several grants obtained by the center of cybersecurity.

We have 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. In a recent extension, we consider the possibility of random attacks, modelled as a compound Poisson process. We show the existence of a random steady state.

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.

5.2. 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. This domain leads to very interesting developments, in connection with inventory theory. If we can observe the past demands, basic results of inventory control can be extended. The problem is rather complex if we observe the sales instead of the demand.

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

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

design of the contract, the problem of the principal is to choose the time when he proposes the contract. This leads to problems of optimal stopping in inventory control with partial information, which is new and challenging. We have enhanced our previous results, by incorporating the possibility that the agent rejects the offer of the principal in which case the current arrangement is continued. Therefore, 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 has been 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 many possibilities.

Finally, we try to extend the Base stock and s,S policy to intermediary situations, in which the ordering cost is concave bilinear. We also try to introduce machine-learning methods.

5.3. RISKS IN FINANCIAL AND ECONOMIC SYSTEMS

In the third direction, we are considering several questions. Financial Engineering is a particularly challenging domain, and the 2008 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 former post-doc, Benoit Chevalier-Roignant, who holds a position at King’s College, 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 to 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.

Another quite interesting direction is the application of Mean field type control to risk management. In stochastic control, one optimizes always an average, therefore risk is not included. The average will never occur. A random cost will occur, and a risk appears when this random cost is far from its average. The natural idea is to introduce a variance in the cost function. The problem is no more classical and requires mean field type control techniques. We have applied the methodology to investment problems.

5.4. RISKS AND UNCERTAINTIES IN ALTERNATIVE ENERGIES

We have completed our 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.

5.5. 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 started a new direction, concerning stochastic maintenance. In view of the availability of big data, it is promising to model the degradation of infrastructures and structures, and therefore to develop a methodology of maintenance which is adapted to the random state of degradation. This investigation is at a preliminary stage.

6. PRESENT ACTIVITIES

6.1. ACTIVITIES IN THE INFORMATION SYSTEMS DOMAIN

6.1.1. 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. 2016. De-biasing the reporting bias in social media analytics. *Production and Operations Management*, 25(5) 849-865.

6.1.2 Can health information sharing reduce duplicate testing?

Participants: Sezgin Ayabka, Eric Zheng, Indranil Bardhan, Kirk Kirksey

Recent healthcare reform has focused on reducing excessive waste in the U.S. healthcare system, with duplicate testing being one of the main culprits. We explore the factors associated with duplicate tests when patients utilize healthcare services from multiple providers, and yet information sharing across these providers is fragmented. We hypothesize that implementation of health information sharing technologies will reduce the duplication rate more for radiology tests compared to laboratory tests, especially when health information sharing technologies are implemented across disparate provider organizations. We utilize a unique panel data set consisting of 39,600 patient visits from 2005 to 2012, across outpatient clinics of 68 hospitals, to test our hypotheses. We apply a quasi-experimental approach to investigate the impact of health information sharing technologies on the duplicate testing rate. Our results indicate that usage of information sharing technologies across health organizations is associated with lower duplication rates, and the extent of reduction in duplicate tests is more pronounced among radiology tests compared to laboratory tests. Our results support the need for implementation of health information exchanges as a potential solution to reduce the incidence of duplicate tests.

Ayabkan, S., Bardhan, I., Zheng, Z., Kirksey K. 2017. "Can health information sharing reduce duplicate testing? A longitudinal analysis of patient switching behavior across multiple hospitals". *MIS Quarterly*, 41 (4), 1083-1103.

6.1.3 Modeling multi-channel advertising attribution across competitors

Participants: Yiyi Li, Ying Xie and Eric Zheng

The bursts and multiplicity of Internet advertising have made multi-channel attribution an immediate challenge for marketing practitioners. Existing attribution models predominantly focus on analyzing consumers' conversion path with respect to one focal firm while largely overlooking the impact of their interactions with competing firms, leading to biased estimation of advertising effectiveness. We address this problem by developing an integrated individual-level choice model that considers consumers' online visit and purchase decisions across all competitors within one industry. We specifically analyze the effects of multi-channel advertising on: (1) consumer choice of entry site, (2) consumer search decisions concerning the remaining competing websites, and (3) subsequent purchase at one of the searched websites. We quantify the impact of different digital advertising channels on consumers' decisions at different purchase funnel stages based on individual-level click stream data for the online air ticket booking industry.

Li, Y., Xie, Y., Zheng Z. 2018. "Modeling Multi-Channel Advertising Attribution across Competitors", *MIS Quarterly* (Forthcoming)

6.1.4. Prescribing Response Strategies to Manage Customer Opinions: A Stochastic Differential Equation Approach

Participants: Mingwen Yang, Eric Zheng and Vijay Mookerjee

Today, the reputation of a firm is profoundly influenced by user opinions expressed in online consumer reviews. Managing these opinions is therefore critical for the success of firms. We study the problem of devising an appropriate opinion management strategy (or response strategy) for a firm to respond to online customer reviews. To unravel the underlying mechanics of the problem, we develop a stochastic differential equation model that describes the evolution of review ratings over time for a given response strategy employed by the firm. This model is validated using data on online customer reviews and firm responses from two of the world's largest online travel agents. When pitted against popular benchmark models such as ARMA, GARCH, Moving Average, Exponential Smoothing, and Naive Method, our approach not only achieves comparable (often better) predictive performance, but is also able to incorporate the response strategy into the data generation process underlying the review ratings.

Yang, M., Zheng, Z., Mookerjee, V. 2018. "Prescribing Response Strategies to Manage Customer Opinions: A Stochastic Differential Equation Approach", Information Systems Research, Forthcoming.

6.1.5. 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" *MIS Quarterly*, pp 963-981, 40(4) December 2016.

6.1.6. Privacy Preserving Techniques for Shared Distributed Transactional Databases.

Participants: Abhijeet Ghoshal, Jing Hao, 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. Hiding Sensitive Information When Sharing Distributed Transactional Data, Working Paper (under review).

6.1.7. 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)

6.1.8 Not Just a Fad: Optimal Sequencing in Mobile In-App Advertising

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

In this paper, we address the challenge faced by ad networks in managing the fading ads (or fads) shown to an end user during a session of a mobile application (app). A fad is an ad that disappears if the user does not interact with it for some length of time. The withdrawn ad could be replaced by another ad. The goal of the ad network is to determine the sequence of fads shown to the user in an ad space to maximize the expected revenue generated over the user's app session. Mobile in-app advertising is uniquely suited for the sequencing of fads because user sessions are typically longer (than web sessions), and a single ad is displayed at any given point in time. We consider two factors that affect the probability of a click on an ad during a session: (i) the sojourn effect, the influence of the passage of time, and (ii) the exposure effect, the influence of the number of prior exposures of the ad to the user during that session. We provide simple and optimal policies for the ad-sequencing problem when either of these two effects dominates. For the general case in which both effects are significant, we offer a provably near-optimal heuristic policy. The following two enhancements to the basic sequencing problem are also analyzed: (a) consideration of both click ads (which generate revenue for the ad network only through clicks) and display ads (which generate revenue only through exposures) and (b) the presence of a constraint imposed by the publisher (i.e., the owner of the app) that the expected revenue in each time slot exceeds a certain threshold.

Z. Sun, M. Dawande, G. Janakiraman and V. Mookerjee, (Accepted by Information Systems Research)

6.1.9 Procurement Policies for Mobile-Promotion Platforms

M. Aseri, M. Dawande, G. Janakiraman and V. Mookerjee

Mobile-promotion platforms enable advertisers (individual users or businesses) to directly launch their personalized mobile advertising campaigns. These platforms contract with advertisers to provide a certain number of impressions on mobile apps in their desired sets of geographic locations (usually cities or zip codes) within their desired time durations (for example, a month); the execution of each such a contract is referred to as a campaign. To fulfill the demands of the campaigns, the platform bids in real time at an ad exchange to win mobile impressions arising over the desired sets of locations of the campaigns and then allocates the acquired impressions among the ongoing campaigns. The core features that characterize this procurement problem—supply is uncertain, supply cannot be inventoried, and there are demand-side commitments to be met—are applicable to a variety of other business settings as well. Our analysis in this paper offers near-optimal policies for both a static model and a dynamic model of campaign arrivals. The static model represents a subscription-based setting, where customers provide information of their campaigns in advance to the platform. The dynamic model represents a setting where campaigns arrive randomly and the platform reacts to these arrivals in real time; for this model, our rolling-horizon policy periodically recomputes the platform's procurement (or bidding) and allocation decisions. We establish performance bounds on our policies for both models and demonstrate the attractiveness of these bounds on real data. By isolating important structural features of a given set of campaigns, we discuss practical implementation issues and offer procurement-policy recommendations for a variety of settings based on these features.

M. Aseri, M. Dawande, G. Janakiraman and V. Mookerjee (Accepted by Management Science)

6.2. Activities in the Supply Chain Domain

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

Participants: 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.

d) 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*, (3), 2017, 369-388.

e) 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

6.2.2 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.

6.2.3 Organization of Production

a) “Lessons from *Seru* Production on Manufacturing Competitively in a High Cost Environment,”

Participants: Yong Yin, Kathryn E. Stecke, Morgan Swink and Ikou Kaku, *Journal of Operations Management*, Vols. 49-51, pp. 67-76 (March 2017).

High capital and labor costs, coupled with high rates of technological and competitive change, present challenges for manufacturers in developed countries, often spurring them to offshore production to low cost sources. However, the electronics industry provides an exception to this trend, where dynamic, high cost conditions have given rise to a new production system – *seru* – a cellular assembly approach. *Seru* evolved as an alternative to lean systems approaches, manifesting important differentiated system design choices that appear to offer promise for manufacturing in dynamic, high-cost markets. This paper reports the results of in-depth, longitudinal case studies of two electronics giants who have implemented *seru*. The case studies describe *seru*'s fundamental extensions to, and departures from, lean production, agile production, and group technology-based cellular manufacturing. We explain how Sony and Canon have applied *seru* to improve productivity, quality, and flexibility in ways that have enabled them to remain competitive. In addition, our findings elaborate the theory of swift, even flow, with implications for future research of trade-offs related to production efficiency, responsiveness, and competitiveness in high-cost, technologically dynamic markets.

b) “The Evolution of Production Systems from Industry 2.0 through Industry 4.0”,

Participants: Yong Yin, Kathryn E. Stecke, and Dongni Li, *International Journal of Production Research*, forthcoming, 2018.

This paper discusses production systems with a focus on the relationships between product supply and customer demand in the context of Industry 2.0 - 4.0. One driver of production evolution is changes in customer demand over time, which is categorized into several dimensions. Major production systems – flow line, Toyota production system (TPS), job shop, cell, flexible manufacturing system, and *seru* – have been developed and applied to supplies to match different demand dimensions over time. For each production system, two questions are addressed: *what* and *how*. Comparisons between *seru* with TPS and cell are given. The possibilities of a future smart factory equipped with internet of things (IoT) are discussed. The demand dimensions of Industry 4.0, the product architecture change in the automobile industry, and the impact of 3D printing are elaborated. Potential applications of lean and *seru* principles for Industry 4.0 are presented.

c) “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*, Vol 25, Issue 6, , June 2016, 1073-1087

d) “Mitigating Disruptions in a Multi-echelon Supply Chain Using Adaptive Ordering”

Participants: 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, Vol 68, pp 185-198 (April 2017)

e) “Flow Shop Scheduling with Jobs Arriving at Different Times “

Participants: G Li, N Li, N Sambandam, SP Sethi, F Zhang

Flow shop scheduling is common in modern lean production systems. In practice, jobs in flow shops can arrive at irregular times. However, scheduling that considers such irregularity has not been adequately investigated in the literature. In this paper, we examine the scheduling of n -jobs in an m -machine permutation flow shop with an unlimited intermediate storage. The jobs in this shop are assumed to have deterministic and known occurrence times. The objective of this scheduling is to reduce the total completion time ($F_{\max}|\text{prmu}|\sum C_j$). To improve the quality of solution, we successively put each job in the current best position and reinsert certain jobs based on weight calculations. We then develop and compare the solutions obtained by our simple and constructive heuristic method against the optimal schedules or other simple heuristic solutions with and without jobs arriving at different times.

G Li, N Li, N Sambandam, SP Sethi, F Zhang (2018) “Flow shop scheduling with jobs arriving at different times” *International Journal of Production Economics* 206, 250-260

6.2.4 Transport Problems

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.(2018)

6.2.5 Innovation - Consumer Behavior

a). A Strategic Approach to Vendor Managed Inventory.

Participants: Özalp Özer, A. Bensoussan, B. Kadiyala

Abstract: This paper studies an inventory management problem faced by an upstream supplier who is in a collaborative agreement, such as vendor-management inventory (VMI), with a retailer. A VMI partnership provides the supplier an opportunity to manage inventory for the supply chain, in exchange for point-of-sales (POS) and inventory level information from the retailer. However, retailers typically possess superior local market information and, as has been the case in recent years, are able to capture and analyze customer purchasing behavior beyond the traditional POS data. Such analyses provide the retailer, access to market signals that are otherwise, hard to capture using POS information. We demonstrate and quantify the implication of the financial obligations of each party in VMI that renders communication of such important market signals as non-credible. To help institute a sound VMI collaboration, we propose learn-and-screen - a dynamic inventory mechanism- for the supplier to effectively 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 private demand information. Inventory decisions in the proposed mechanism serve a strategic purpose in addition to their classic role of satisfying customer demand. We show that our proposed dynamic mechanism significantly improves the supplier's expected profit and increases the efficiency of the overall supply chain operations under a VMI agreement. In addition, we determine the market conditions in which a strategic approach to VMI results in significant profit improvements for both firms, in particular, when the retailer has high market power (i.e., when the supplier highly depends on the retailer) and when the supplier has relatively less knowledge about the end customer/market compared to the retailer.

Kadiyala, B., Ö. Özer, A. Bensoussan A Strategic Approach to Vendor Managed Inventory. *Management Science*, Forthcoming.

b). Information Sharing, Advice Provision or Delegation: What Leads to Higher Trust and Trustworthiness?

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

Abstract: In many market settings, a customer often obtains assistance from a supplier (or service provider) 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 thus 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 no 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, Ö. U. Subramanian and Y. Wang. Information Sharing, Advice Provision or Delegation: What Leads to Higher Trust and Trustworthiness? (*Management Science*, 64(1) pp. 474-493, 2018.

c) Establishing Trust and Trustworthiness in Supply Chain Information Sharing.

Participants: Özalp Özer, K. Zheng

Abstract: 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.

Özer, Ö., K. Zheng. Establishing Trust and Trustworthiness in Supply Chain Information Sharing. *Handbook of Information Exchange in SCM* (Eds. A. Ha and C. Tang) pp. 287-312, 2017.

d) Characterizing the Structure of Optimal Stopping Policies.

Participants: Özalp Özer, S. Oh

Abstract: 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.

Özer, Ö. And Oh, S, Characterizing the Structure of Optimal Stopping Policies. (with S. Oh). *Production and Operations Management* 25 (11) pp. 1820-1838, 2016.

e). Knowledge 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.

Özer, Ö., A. Angelus, Knowledge You Can Act On: Optimal Policies for Assembly Systems with Expediting and Advance Demand Information. (with A. Angelus). *Operations Research* 64(6) pp. 1338-1371, 2016.

f) Dynamic Pricing and Timing of Upgrades

Participants: Metin Çakanyildirim, Ozalp Ozer, Xiao Zhang

Upgrading is a travel industry practice used to mitigate supply-demand mismatches among products of different quality levels. Such upgrades are usually implemented either at the booking time or at the check-in time. In this paper, we consider dynamically-offered upgrades between the booking and the check-in times by a firm that sells two types of products (premium and regular). The firm decides on the timing and quantity of upgrades. Customers who purchased the regular product may be offered upgrades via notifications containing a link to an upgrade website. A regular product purchaser either accepts or rejects the upgrade offer after clicking the link and observing the upgrade fee (price) dynamically determined by the firm. The upgrade is time limited. When the upgrade process is not profitable, the firm can stop it by deactivating the upgrade links. Formulating the firm's revenue maximization problem as a dynamic program, we show that the optimal upgrade policy is of a pulsing type. The firm either maintains zero or the maximum number of active links. Both the optimal number of active links and the optimal upgrade fee are monotone with respect to the leftover capacities. We then propose and analyze two model variations: one with a restricted upgrade fee choice set and one with upward stockout substitution, in which the firm can sell a premium product to an arriving regular customer at a discount if the regular product stocks out. Finally, through a systematic numerical study, we quantify the revenue improvement from industry-standard check-in fixed-price upgrades to dynamic pricing and timing of upgrades. We also identify the market environment, in which the revenue improvement is significant across various models.

Available at SSRN: <https://ssrn.com/abstract=3056060>

g) 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. *Production and Operations Management*. 25(11), 2016, 1866–1884

h) 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.

C. Liang, M. Çakanyıldırım and S.P. Sethi. Can Strategic Customer Behavior Speed up Product Innovation? *Production and Operations Management*. Vol.27, No.8, 2018: 1516-1533.

i) Harvesting Solar Power Fosters Prices in a Vicious Cycle: Breaking the cycle with price mechanisms

Participants: Fariba M. Farajbakhsh and Metin Çakanyildirim

Solar energy generation is growing in many markets, as a result of increasing efficiencies with decreasing costs and the presence of government regulations. The growth of residential solar energy in a market benefits the environment but not necessarily the (utility or transmission) firms in that market. It reduces the residential power demand and hence hinders the coverage of fixed generation and transmission costs with reasonable energy rates (prices). In real life, the firms tend to raise the retail rates and make electricity less affordable for their consumers. This adverse effect is even more pronounced for less privileged consumers that cannot afford to invest into solar power and remain as captured customers. Higher solar power penetration into markets, despite being an environmentally desirable outcome, paradoxically can be socially undesirable. Having both environmental and social accountabilities, market regulators face challenges with deciding on the structure and amount of rates. We provide a novel revenue maximization formulation for a regulated firm and analytically reveal the connection between rate increases and solar penetration. We also extend this formulation to take into account new rate structures that mitigate rate increases by allowing for the coverage of fixed costs in part or full.

j) 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

k) Coordinating Contracts for a Financially Constrained Supply Chain

Participants: Shuang Xiao, Suresh P. Sethi, Mengqi Liu, Shihua Ma

We consider a financially constrained supply chain in which a supplier (leader) sells products to a retailer (follower) who has no access to bank financing due to her low credit rating. However, the supplier can borrow from a bank and offer trade credit to the retailer to alleviate her financial constraint. Failure to pay off a bank loan or trade credit incurs a variable default cost. We analyze the centralized version of the supply chain to obtain new coordination requirements. We then examine whether revenue-sharing, buyback, and all-unit quantity discount contracts can coordinate our supply chain. We show that the all-unit quantity discount contract fails to coordinate. However, the revenue-sharing and buyback contracts can coordinate the supply chain, but only when the supply chain has a sufficient total working capital. Moreover, they cannot allocate profit flexibly unless the supplier has a large enough working capital. Finally, we design a generalized revenue-sharing contract that coordinates the supply chain with flexible profit allocation, and also show by numerical examples its superiority over the revenue-sharing and buyback contracts.

Liu, M., Xiao, S., Sethi, S.P., and Ma, S., “Coordinating Contracts for a Financially Constrained Supply Chain,” *Omega: The International Journal of Management Science*, 72, 2017, 71-86.

6-2-6 Game Problems

A Review of Dynamic Stackelberg Game Models

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)* 22(1), 2017 125-150

6.2.7 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*, 54(7), 2016, 1334-1357.

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) 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.

d) Capacity Investment with Demand Learning

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

We study a firm's optimal strategy to adjust its capacity using demand information. The capacity adjustment is costly and often subject to managerial hurdles which sometimes make it difficult to adjust capacity multiple times. In order to clearly analyze the impact of demand learning on the firm's decision, we study two scenarios. In the first scenario, the firm's capacity adjustment cost increases significantly with respect to the number of adjustments because of significant managerial hurdles, and resultantly the firm has a single opportunity to adjust capacity (*single adjustment scenario*). In the second scenario, the capacity adjustment cost does not change with respect to the number of adjustments because of little managerial hurdles, and therefore the firm has multiple opportunities to adjust capacity (*multiple adjustment scenario*). For both scenarios, we first formulate the problem as a stochastic dynamic program, and then characterize the firm's *optimal* policy: when to adjust and by how much. We show that the optimal decision on when and by how much to change the capacity is not monotone in the likelihood of high demand in the single adjustment scenario, while the optimal decision is monotone under mild conditions and the optimal policy is a control band policy in the multiple adjustment scenario. The sharp contrast reflects the impact of demand learning on the firm's optimal capacity decision. Since computing and implementing the optimal policy is not tractable for general problems, we develop a data-driven heuristic for each scenario. In the single adjustment scenario, we show that a two-step heuristic which explores demand for an appropriately chosen length of time and adjusts the capacity based on the observed demand is asymptotically optimal, and show the convergence rate. In the multiple adjustment scenario, we also show that a multi-step heuristic under which the firm adjusts its capacity at a predetermined set of periods with exponentially increasing gap between two consecutive decisions is asymptotically optimal and show its convergence rate. We finally apply our heuristics to a numerical study and demonstrate the performance and robustness of the heuristics.

Citation: Qi, A., Ahn, H.-S. and Sinha, A. (2017), Capacity Investment with Demand Learning. *Operations Research*, 65.1: 145-164.

e) Optimal Procurement Mechanisms for Assembly

Participants: Bin Hu, Anyan Qi

This paper investigates mechanisms by which a powerful OEM procures multiple inputs for assembly from suppliers with privately informed costs, either simultaneously or sequentially. The optimal mechanisms always lead to matching purchase quantities of the inputs. Thus, quantity-payment contracts that implement the optimal mechanisms are contingent across suppliers (i.e., each supplier's contract terms contain other suppliers' private costs as variables), making the implementation impractical. To address this issue, we propose alternative implementations of the optimal mechanisms by menus of two-part tariff contracts that are non-contingent. In addition, optimal simultaneous and sequential procurement mechanisms for assembly are shown to be revenue-equivalent for all parties, despite their different asymmetric information structures. Our findings suggest that procurement managers

need not strategize contracting sequences for assembly, but should rather focus on achieving the best pricing with each supplier and coordinating purchase quantities.

Citation: Hu, B. and Qi, A. (2017), Optimal Procurement Mechanisms for Assembly. *Manufacturing & Service Operations Management*, (forthcoming)

f) Supplier Centrality and Auditing Priority in Socially-Responsible Supply Chains

Participants: Jiayu Chen, Anyan Qi, Milind Dawande

Most supply networks are characterized by firms that source from multiple suppliers and suppliers that serve multiple firms, thus resulting in suppliers who differ in their *degree centrality*, i.e., the number of firms they supply to. In such networks, any negative publicity from suppliers' noncompliance of socially-responsible practices -- e.g., employment of child labor, unsafe working conditions, and excessive pollution -- can significantly damage the reputation of the buying firms. To mitigate this impact, firms preemptively audit suppliers, although resource and time considerations typically restrict the number of suppliers a firm can audit. Therefore, a key question is whether firms should prioritize the auditing of suppliers with low or high centrality, *ceteris paribus*. To investigate, we consider an assembly network consisting of two firms (buyers) and three suppliers -- each firm has one *independent supplier* who uniquely supplies to that firm and one *common supplier* who supplies to both. We use game-theoretic analysis. We find that downstream competition between the firms drives them away from auditing the supplier with higher centrality; i.e., the common supplier, in equilibrium, despite the fact that auditing this supplier is better for the aggregate profit of the firms. We show that this inefficiency is corrected when the firms cooperate (via a stable coalition) to *jointly audit* the suppliers and share the auditing cost in a fair manner. We also examine conditions under which the firms' auditing decisions are in sync with a social-planner's objective of minimizing harm to society via the identification of socially-irresponsible practices.

Citation: Chen, J., Qi, A. and Dawande, M. (2018), Supplier Centrality and Auditing Priority in Socially-Responsible Supply Chains. (*Working Paper*)

g) Optimal Incentive Contracts in Project Management

Participants: Milind Dawande, Ganesh Janakiraman, Anyan Qi, Qi Wu

Motivated by the ever-growing complexity of projects and the consistent trend of outsourcing of individual tasks or components, we study the contract-design problem faced by a firm (or organization) for executing a project consisting of multiple tasks, each of which is performed by an individual contractor whose efforts (work-rates) are not observable. While the contractors incur costs continuously during the course of their tasks, the firm realizes its reward or revenue only when the entire project is (i.e., *all* tasks are) completed. The firm's contract-design decisions and the contractors' effort-level decisions are all governed by the goals of maximizing the respective party's expected discounted profit. We adopt the framework in Kwon et al. (2010a) and Chen et al. (2015), and derive optimal contracts for both parallel projects (tasks can be performed in parallel) and sequential projects (tasks have to be performed sequentially). The simplicity of the contracts we obtain suggests that there is potential for designing profit-maximizing contracts without paying a price in terms of contract complexity.

Citation: Dawande, M., Janakiraman, G., Qi, A. and Wu, Q. (2018), Optimal Incentive Contracts in Project Management. (*Working Paper*)

h) Project Management under Risk-Sharing Contracts

Participants: Sina Shokoohyar, Anyan Qi, Elena Katok

We study the coordination problem in a setting with multiple contractors working on a project. Specifically, we analyze the risk-sharing contract in which the contractors are paid at the end of the project, after all the tasks have been completed. Although intuitively the contractors should try to complete their tasks early, because under the risk-sharing contract the risk of delay is shared between them and the OEM, we show that the contractors may fail to coordinate their efforts. For a project with parallel tasks, there exist multiple Pareto-ranked equilibria, where all contractors exert the same efforts, and the worst project delay is observed when the contractors play the secure equilibrium. To mitigate this coordination failure, we propose an information feedback policy, and show that the contractors' efforts in the secure equilibrium increase in the information feedback frequency. Therefore, the OEM may induce the contractors to increase their effort by providing information feedback with frequency that increases linearly in the number of contractors. To test our theoretical findings, we conducted a behavioral experiment that varied the availability of information feedback and the number of contractors. Our experiment confirms that absent feedback, coordination failure occurs, and information feedback is effective in improving the project progress.

Citation: Shokoohyar, S., Qi, A. and Katok, E. (2017), Project Management under Risk-Sharing Contracts. (*Working Paper*)

6.2.8 Methodology

a) Integral Policies in Deterministic and 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 (FTL) shipping is optimal if customer demand is in integral number of truckloads. In this paper, we investigate the integrality question in single-product, multi-echelon distribution systems and show that integrality holds under deterministic demand but fails to hold under stochastic demand. In distribution systems with stochastic demand, less-than-truckload (LTL) shipping can be significantly cheaper than the cost of the optimal FTL shipping policy, even in the presence of economies of scale. For instance, this occurs in settings where shipping costs are expected to increase in the future and/or inventories are more expensive to hold upstream than downstream. In such situations, our results highlight the importance of strategically positioning inventory: LTL shipments can offer a more balanced allocation of inventory across the distribution network, leading to benefits that can exceed the savings from FTL shipments due to economies of scale. However, when the cost parameters are fairly constant across time and inventory holding costs are not significantly higher upstream than downstream, then the difference between the costs of optimal FTL and optimal LTL shipping is provably marginal.

On Integral Policies in Deterministic and Stochastic Distribution Systems, 2017. *Operations Research*. 65:3:703-711

b) 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

c) 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)

6.2.9 Inventory Policies

a). Capacitated Multi-echelon Inventory Systems: Bounds

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

We study a periodically reviewed multiechelon serial inventory system with a capacity constraint on the order quantity at each stage. The cost criterion we use to evaluate inventory policies for this system is the sum of the expected long-run average holding and shortage costs. It is well known that for this problem, characterizing the structure of the optimal policy and computing it are very difficult. We consider the use of echelon base-stock policies for our system (even though they are known to be suboptimal) and propose algorithms for finding base-stock levels that are easy to understand and implement. We derive bounds on the ratios between the costs achieved by our algorithms and the optimal costs (over all policies). For light-tailed demand distributions, our algorithms are

shown to be asymptotically optimal in the sense that our bounds are close to one in high service-level environments. Our computational investigations reveal that our algorithms perform well even under modest service levels.

W.T. Huh, G. Janakiraman and M. Nagarajan, *Capacitated Multiechelon Inventory Systems: Policies and Bounds*. 2016 MSOM 18(4):570-584

b) 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.

Z. Sun, M. Dawande, G. Janakiraman and V. Mookerjee, 2016 MIS Quarterly, 40:3 pp 717-739

c) 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. Guda, M. Dawande, G. Janakiraman and K. Jung, 2016 POM 25:7:1194—1202

d) 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

G. Janakiraman and S. Seshadri MSON 26 (2) 2017, 203-210

e) Distressed Selling by Farmers: Model, Analysis and Use in Policy-Making (Accepted by POM)

Participants: S.Gupta, M.Dawande, G. Janakiraman and A. Sarkar,

Among the various governmental schemes that support agriculture, support prices have been adopted by many developing countries. A support price for an agricultural crop is a guaranteed price at which a governmental entity agrees to purchase that crop from farmers. Despite this surety, a surprising practice of “distressed” selling has been widely observed in practice: Farmers sell a significant portion of their crops to outside agents at prices much *lower* than the support price. We build a tractable stochastic dynamic programming model that captures the salient features of the ground realities—limited as well as uncertain procurement capacity, high holding costs for the farmers, and lack of affordable credit—that conspire to induce distressed selling and, consequently, a significant loss of welfare of the farmers. Using real data on procurement under a support-price program, we establish the accuracy of our model's prediction on the volume of distressed sales. Finally, we show how our model and its solution can serve as a simple and useful tool for policy-makers to assess the relative impact of the improvements in the main determinants of distressed sales. (2017)

f) Optimality of (s,S) Inventory Policies under Renewal Demand and General Cost Structures. (Accepted by POM)

Participants: S. Perera, G. Janakiraman and S.C.Niu,

We study a single-stage, continuous-time inventory model where unit-sized demands arrive according to a renewal process and show that an $(s;S)$ policy is optimal under minimal assumptions on the ordering/procurement and holding/backorder cost functions. To our knowledge, the derivation of almost all existing $(s;S)$ -optimality results for stochastic inventory models assume that the ordering cost is composed of a fixed setup cost and a proportional variable cost; in contrast, our formulation allows virtually any reasonable ordering-cost structure. Thus, our paper demonstrates that $(s;S)$ -optimality actually holds in an important, primitive stochastic setting for *all other* practically interesting ordering cost structures such as well-known quantity discount schemes (e.g., all-units, incremental and truckload), multiple setup costs, supplier-imposed size constraints (e.g., batch-ordering and minimum-order-quantity), arbitrary increasing and concave cost, as well as any variants of these. It is noteworthy that our proof only relies on elementary arguments. (2018)

g) Simple Policies for Managing Flexible Capacity. (Accepted by MSOM)

Participants: G. Janakiraman, M. Nagarajan and S. Veeraraghavan.

In many production scenarios, a fixed capacity is shared flexibly between multiple products. To manage such multi-product systems, firms need to make two sets of decisions. The first one requires setting an inventory target for each product and the second decision requires dynamically allocating the scarce capacity among the products. It is not known how to make these decisions optimally. In this paper, we propose easily implementable policies that have

both theoretical and practical appeal. We first suggest simple and intuitive allocation rules that determine how such scarce capacity is shared. Given such a rule, we calculate the optimal inventory target for each product. We demonstrate analytically that our policies are asymptotically optimal (as service levels approach one) for an important subclass of problems, and demonstrate numerically that they significantly outperform policies suggested previously over a wide range of problem parameters. In particular, the cost savings from our policies become more significant as the capacity gets more restrictive. (2018)

6.2.10 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) 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, 697-701.

d) 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 Inequalities’ 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 *Journal of Applied Analysis and Computation* ,8 (3) Jun 2018

e) Return Strategy and Pricing in a Dual-Channel Supply Chain

Participants: Guo Li, Suresh P. Sethi, Lin Li, and Xu Guan

This study investigates the strategic effect of return policies in a dual-channel supply chain, wherein a manufacturer can directly and indirectly sell products to end consumers and via independent retailers, respectively. The

manufacturer decides whether or not to implement a return policy in either direct or indirect channels or both with the cost of the returned products to be covered by receiving channels. We consider four possible strategies, namely, full refund in the direct channel only, full refund in the indirect channel only, full refund in both channels, and no refund in both channels. Given the equilibrium pricing strategies of firms, the preferences of firms over different strategies are determined by the comparisons between the anticipated return rate of consumers and their perceived value of the return policy. The manufacturer prefers the full-refund policy in both channels when the return rate of the consumer is low. Otherwise, the dominant strategy for the manufacturer is the no-refund policy in both channels. Furthermore, the retailer benefits more from the full-refund policy in the indirect channel alone when the return rate is low; otherwise, the retailer prefers the full-refund policy in the direct channel only.

Li, G., Sethi, S.P., Li, L., and Guan, X., "Return Strategy and Pricing in a Dual-Channel Supply Chain," *International Journal of Production Economics*, Jun 2017

6.2.11 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.), Dynamic Modeling and Econometrics in Economics and Finance, Springer International Publishing Switzerland, (22) 2016, 253-277

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,” *IISE Transactions*, 49(2) 2017, 223-237.

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,” *INFOR*, 55(2), 2017, 93-117.

6.2.12 Contracts

a) 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*, 47(6) 2016, 1150-1177

b) Inducing Environmental Disclosures: A Dynamic Mechanism Design Approach

Participants: Shouqiang Wang, Peng Sun and Francis de Véricourt, *Operations Research*, 64(2): 371-389, 2016.

This paper studies the design of voluntary disclosure regulations for a firm that faces a stochastic environmental hazard. The occurrence of such a hazard is known only to the firm. The regulator, if finding a hazard, collects a fine and mandates the firm to perform costly remediation that reduces the environmental damage. The regulator may inspect the firm at any time to uncover the hazard. However, because inspections are costly, the regulator also offers a reward to the firm for voluntarily disclosing the hazard. The reward corresponds to either a subsidy or a reduced fine, depending on whether it is positive or negative. Thus, the regulator needs to dynamically determine the reward and inspection policy that minimizes expected societal cost in the long run. We model this problem as a dynamic adverse selection problem with costly state verification in continuous time. Despite the complexity and generality of this setup, we show that the optimal regulation policy follows a very simple cyclic structure, which we fully characterize in closed form. Specifically, the regulator runs scheduled inspections periodically. After each inspection, the reward level decreases over time until a subsequent inspection takes place. If a hazard is not revealed, the reward level is reset to a high level, restarting the cycle. In contrast to the reward level, the mandated remediation level is constant over time. Nonetheless, when subsidies are not allowed in the industry, we show that the regulator should dynamically adjust this remediation level, which then acts as a substitute for a subsidy. Our analysis further reveals that optimal inspection frequency increases not only when the inspection accuracy decreases, but also when the penalty for not disclosing the hazard increases.

Shouqiang Wang, Peng Sun and Francis de Véricourt, *Operations Research*, 64(2): 371-389, 2016

c) **Resource Allocation under Demand Uncertainty and Private Information**

Participants: Alexandre Belloni, Giuseppe Lopomo and Shouqiang Wang

We study the effect of multilateral private information on the efficiency of markets where capacity-constrained upstream agents supply a resource to downstream entities facing uncertain end-demands. We analyze two models: a “pooling system,” in which a single downstream principal pools a resource from multiple upstream agents; and a “distribution system,” in which one upstream principal allocates a resource across multiple downstream agents. We show that the presence of multilateral private information does not hinder efficiency in the pooling system. In contrast, in the distribution system, the quantities allocated to downstream agents can exceed, as well as fall short of, their first-best levels. These results shed light on the recently improved performance of U.S. agricultural produce market, and the observed episodes of shortages/oversupplies in flu vaccine and other seasonal markets.

Alexandre Belloni, Giuseppe Lopomo and Shouqiang Wang, *Operations Research* 66(2), March-April 2018

d) **Signaling Product Quality through a Trial Period**

Participants: Shouqiang Wang and Gülru F. Özkan-Seely,

It has become a ubiquitous practice for firms that sell new products, such as software, to offer consumers time-locked product trial periods free of charge. We identify trial length as a nuanced signaling instrument, which, together with the price signal, a firm can use to communicate proprietary information about its product quality. We show that a high-quality firm offers a longer trial period and sets a higher price, and is rewarded with a higher profit, relative to its low-quality counterpart. Our finding extends to cases where the firm faces ex ante heterogeneous consumers or when the firm competes with an incumbent product.

Shouqiang Wang and Gülru F. Özkan-Seely, *Signaling Product Quality through a Trial Period*, *Operations Research* 66(2), March-April 2018, 301-596

e) Audit and Remediation Strategies in the Presence of Evasion Capabilities

Participants: Shouqiang Wang, Francis de Véricourt and Peng Sun, working paper, 2017.

In this paper, we provide managerial insights on how to uncover an adverse issue that may occur in organizations with the capability to evade detection. To that end, we formalize the problem of designing efficient auditing and remediation strategies as the optimal stochastic control of a piecewise deterministic Markov process. In this set-up, a principal seeks to uncover and remedy an issue that occurs to an agent at a random point in time, and which harms the principal if not addressed promptly. This occurrence is the agent's private information. Further, the agent can exert effort to render the principal's audits ineffective at discovering the issue. We fully characterize, in closed form, the corresponding optimal policy, which can be implemented as a dynamic remediation cost-sharing mechanism with cyclic audits. We show that the strength of the agent's evasion capability changes the nature of the audit policy. When the effort cost is high (i.e., the evasion capability is weak), the principal runs the audit according to a pre-determined schedule. However, when the effort cost is low (i.e. the evasion capability is strong), the audit schedule becomes random. Further, as the effort cost increases and the evasion capability becomes more limited, the principal audits the agent more frequently, which overall results in higher audit costs.

f) Procurement with Cost and Non-Cost Attributes: Cost-Sharing Mechanisms.

Participants: Shivam Gupta, Milind Dawande, Ganesh Janakiraman, and Shouqiang Wang, working paper, 2017. We study a class of auction-based "cost-sharing mechanisms" for a buyer (firm) who wishes to award a project to one among a set of contractors, in an environment with multi-dimensional asymmetric information. In the setting we analyze, the buyer faces information asymmetry along two dimensions: each contractor's cost and his estimate of an a priori uncertain non-cost attribute; the winning contractor's realization of his non-cost attribute is observed by the buyer and inflicts on her an associated disutility cost. A cost-sharing mechanism is described by a single parameter, namely the cost-sharing fraction, which is the percentage of the buyer's realized disutility cost that the winning contractor reimburses upon completion of the project. Cost-sharing mechanisms are practically appealing in that they solicit only a single bid from each contractor vying for the project and are straightforward to implement. We show that the class of cost-sharing mechanisms is also theoretically well-justified in that a mechanism with a carefully-chosen cost-sharing fraction delivers a near-optimal total cost for the buyer. Our analysis explains the essential tradeoff between allocative inefficiency and information rent that the buyer faces under this class of mechanisms, and also provides easy-to-understand recommendations on the choice of the cost-sharing fraction

g) Designing Sustainable Products under Co-Production Technology

Participants: Yen-Ting Lin, Haoying Sun, and Shouqiang Wang, working paper, 2017.

Motivated by the emerging business practices in various industries, we consider a firm that designs a green product utilizing a natural material with an exogenous distribution of vertically-differentiated quality grades (i.e., co-production technology). The market consists of a traditional segment, who only values a product's quality, and a green segment, who additionally values a product's material savings. We find that the firm may strategically abandon part of the traditional segment's demand. Perhaps unexpectedly, expansion of the green market may adversely result in higher resource consumption and waste.

h) A Stationary Infinite-Horizon Supply Contract under Asymmetric Inventory Information

Participants: Alain Bensoussan, Suresh Sethi, and Shouqiang Wang, working paper, 2017.

In studying the dynamic contracts between a supplier and a retailer who is privately informed about her inventory level in each period, Zhang et al. (2010) find, under certain circumstance, a stationary Batch Order Contract (BOC), which only supplies to retailer with zero inventory with a pre-specified order quantity and fixed payment, is optimal. In a general framework, we identify a necessary optimality condition within the class of stationary truth-telling contracts. Specializing it to the BOC, we obtain a more stringent parametric condition than Zhang et al.'s (2010), but without a tail condition on the value function assumed in therein. To obtain these results, we develop novel methodologies based on Gateaux derivatives, which are applicable to other settings.

6-2-13 General Supply Chain

a) Simultaneous Optimization of Contingent and Advance Purchase Orders with Fixed Ordering Costs

Participants: X Gan, SP Sethi, L Xu

We analyze a finite horizon periodic-review inventory model in the presence of advance purchase discount (APD). In addition to the opportunity to place a contingent order when required, the buyer can also commit to advance orders and receive discounts. Thus the buyer faces the following tradeoff: Contingent orders provide operational flexibility to respond to uncertain demands at a high purchase cost, whereas advance orders incur low purchase cost while sacrificing operational flexibility. We consider a simple and easy-to-implement APD scheme in which the buyer enjoys price discounts by committing at the outset to a fixed size of advanced order for each period along with contingent orders when required. We first show that for any given advance order size, an advance-order dependent (s, S) policy is optimal. We then find the advance order size together with the corresponding (s, S) policy that minimizes the buyer's total cost.

X Gan, SP Sethi, L Xu "Simultaneous Optimization of Contingent and Advance Purchase Orders with Fixed Ordering Costs - *Omega*, (2018)

b) A Survey on Control Theory Applications to Operational Systems, Supply Chain Management and Industry 4.0

Participants: D Ivanov, S Sethi, A Dolgui, B Sokolov

Modern production and logistics systems, supply chains, and Industry 4.0 networks are challenged by increased uncertainty and risks, multiple feedback cycles, and dynamics. Control theory is an interesting research avenue which contributes to further insights concerning the management of the given challenges in operations and supply chain management. In this paper, the applicability of control theory to engineering and management problems in supply chain operations is investigated. Our analysis bridges the fundamentals of control and systems theory to supply chain and operations management. This study extends our previous survey in the Annual Reviews in Control (Ivanov et al. 2012) by including new literature published in 2012–2018, identifying two new directions of control theory applications (i.e., ripple effect analysis in the supply chains and scheduling in Industry 4.0) and analysis towards the digital technology use in control theoretic models. It describes important issues and perspectives that delineate dynamics in supply chains, operations, and Industry 4.0 networks and identifies and systemizes different streams in the application of control theory to operations and supply chain management and engineering in the period from 1960–2018. It updates the existing applications and classifications, performs a critical analysis, and discusses further research avenues. Further development of interdisciplinary approaches to supply chain optimization is argued. An extended cooperation between control engineers and supply chain experts may have the potential to introduce more realism to dynamic planning and models, and improve performance in production and logistics systems, supply chains, and Industry 4.0 networks. Finally, we analyze the trends towards the intellectualization of control and its development towards supply chain control analytics.

D Ivanov, S Sethi, A Dolgui, B Sokolov, "A survey on control theory applications to operational systems, supply chain management, and Industry 4.0" *Annual Reviews in Control* (2018)

c) Inducing Downstream Information Sharing via Manufacturer Information Acquisition and Retailer Subsidy

Participants: G Li, H Zheng, SP Sethi, X Guan

We investigate a manufacturer's information acquisition and subsidization strategies in a supply chain featuring two competing retailers who sell substitutable products and have private demand information. The manufacturer can decide whether to acquire demand information at a cost and further decide whether to offer subsidies simultaneously to retailers to induce their sharing of private demand information. We demonstrate that subsidizing retailers is always in the manufacturer's interest, but direct information acquisition is profitable only if its cost is low. Information acquisition helps the manufacturer gain superior demand information and leverages the retailer's information advantage, thereby reducing the expenditure of subsidization. Compared with the simultaneous subsidy provision scheme, we further investigate the sequential and partial subsidy schemes and find that the simultaneous and sequential subsidy schemes result in an identical equilibrium outcome that dominates the equilibrium outcome in the partial subsidy scheme when three subsidy provision schemes are all feasible. Although the outcomes are the same, we show that the simultaneous subsidy scheme can be applied in a broader range than the sequential subsidy scheme can. Otherwise, if complete information sharing cannot be achieved, the partial subsidy scheme may be the optimal choice for the manufacturer.

G Li, H Zheng, SP Sethi, X Guan; (2018) "Inducing Downstream Information Sharing via Manufacturer Information Acquisition and Retailer Subsidy" *Decision Sciences*

d) Can Strategic Customer Behavior Speed Up Product Innovation?

Participants: C Liang, M Çakanyildirim, SP Sethi

We study a monopolistic firm which introduces two product versions sequentially in two periods. We analyze and compare the firm's decisions on 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 analytical 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.

C Liang, M Çakanyildirim, SP Sethi; (2018) "Can Strategic Customer Behavior Speed Up Product Innovation?" *Production and Operations Management* 27 (8), 1516-1533

e) Dynamic Cooperative Advertising Under Manufacturer and Retailer Level Competition

Participants: A Chutani, SP Sethi

We study dynamic cooperative advertising decisions in a market that consists of a finite number of independent manufacturers and retailers. Each manufacturer sells its product through all retailers and can offer different levels of advertising support to the retailers. Each retailer sells every manufacturer's product and may choose to carry out a different amount of local advertising effort to promote the products. A manufacturer may offer to subsidize a fraction of the local advertising expense carried out by a retailer for its product, and this fraction is termed as that manufacturer's subsidy rate for that retailer. We model a Stackelberg differential game with manufacturers as leaders and retailers as followers. A Nash game between the manufacturers determines their subsidy rates for the retailers and another Nash game between the retailers determines their optimal advertising efforts for the products they sell in response to manufacturers' decisions. We obtain optimal policies in feedback form. In some special cases, we explicitly write the incentives for coop advertising as functions of different model parameters including the number of manufacturers and retailers, and study the impact of the competition at the manufacturer and the retailer levels. We analyze the profits of the players and find the model parameters under which a manufacturer benefits from a coop advertising program. Furthermore, in the case of two manufacturers and two retailers, we study the effect of various model parameters on all four subsidy rates. We also extend our model to include national level advertising by the manufacturer.

A Chutani, SP Sethi; "Dynamic cooperative advertising under manufacturer and retailer level competition." *European Journal of Operational Research* (2018).

f) Relationship-specific investment and hold-up problems in supply chains: theory and experiments

Participants: E Haruvy, E Katok, Z Ma, S Sethi

Supply chains today routinely use third parties for many strategic activities, such as manufacturing, R&D, or software development. These activities often include relationship-specific investment on the part of the vendor, while final outcomes can be uncertain. Therefore, writing complete contracts for such arrangements is often not feasible, but incomplete contracts, especially when relationship-specific investment is required, may leave the supplier vulnerable to a version of the "hold-up problem," which is known to result in sub-optimal levels of investment. We model the phenomenon as a sequential move game with asymmetric information. Absent behavioral considerations, the unique Perfect Bayesian Equilibrium implies zero investment. However, with social preferences, the hold-up problem may be mitigated. We propose a model that incorporates social preferences and random errors, and solve for the equilibrium. In addition, we look at reputation and find it to be effective for increasing investment. We conduct laboratory experiments with human subjects and find that a model with social preferences and random errors organizes our data well.

E Haruvy, E Katok, Z Ma, S Sethi; (2018) "Relationship-specific investment and hold-up problems in supply chains: theory and experiments" *Business Research*, 1-30

g) Optimal abatement and emission permit trading policies in a dynamic transboundary pollution game

Participants: S Chang, SP Sethi, X Wang

We obtain optimal emission levels and abatement expenditures in a finite-horizon transboundary pollution game with emission trading between two regions. We show that emission trading has significant impact on the optimal strategies and profits of the two regions. We find that cooperation between the regions leads to increased abatement and lower emissions, resulting in a lower pollution stock. We also provide a stochastic extension in which the pollution stock and the emission trading price are diffusion processes and solve it numerically.

Chang, S., Sethi, S.P. & Wang, X. (2018) "Optimal abatement and emission permit trading policies in a dynamic transboundary pollution game" *Dynamic Games and Applications*, 1-31

h) Scheduling in production, supply chain and Industry 4.0 systems by optimal control: fundamentals, state-of-the-art and applications

Participants: A Dolgui, D Ivanov, SP Sethi, B Sokolov

This paper presents a survey on the applications of optimal control to scheduling in production, supply chain and Industry 4.0 systems with a focus on the deterministic maximum principle. The first objective is to derive major contributions, application areas, limitations, as well as research and application recommendations for the future research. The second objective is to explain control engineering models in terms of industrial engineering and production management. To achieve these objectives, optimal control models, qualitative methods of performance analysis and computational methods for optimal control are considered. We provide a brief historic overview and clarify major mathematical fundamentals whereby the control engineering terms are brought into correspondence with industrial engineering and management. The survey allows the grouping of models with only terminal constraints with application to master production scheduling, models with hybrid terminal–logical constraints with applications to short term job and flow shop scheduling, and hybrid structural–terminal–logical constraints with applications to customized assembly systems such as Industry 4.0. Computational algorithms in state, control and adjoin variable spaces are discussed.

Alexandre Dolgui, Dmitry Ivanov, Suresh P. Sethi & Boris Sokolov (2018) “Scheduling in production, supply chain and Industry 4.0 systems by optimal control: fundamentals, state-of-the-art and applications”, *International Journal of Production Research*

i) A Three-layer Chromosome Genetic Algorithm for Multi-Cell Scheduling with Flexible Routes and Machine Sharing

Participants: Y Feng, G Li, SP Sethi

Alternative machines assignment, machine sharing, and inter-cell movements are very common yet difficult to be solved integratedly in modern dynamic Cellular Manufacturing Systems (CMS). In this paper, we incorporate these issues and consider a dynamic cellular scheduling problem with flexible routes and machine sharing. We employ a mixed integer programming scheduling model to minimize both the makespan and the total workload. To solve this new model, we propose a three-layer chromosome genetic algorithm (TCGA). We first compare the performances of the proposed TCGA with the optimal solution obtained by CPLEX. Computational results show that the TCGA performs well within a reasonable amount of time. We further compare our proposed TCGA with the classic genetic algorithm (GA) and the shortest processing time (SPT) rule through numerical experiments. The results reveal that the TCGA significantly improves the performance and effectively balances the workload of machines.

Y Feng, G Li, SP Sethi (2018) “A three-layer chromosome genetic algorithm for multi-cell scheduling with flexible routes and machine sharing”, *International Journal of Production Economics* 196, 269-283

j) Creative Delinquency or Destructive Selfishness?

Participants: H Yu, SP Sethi, X Shan

We study two competing firms with different production costs and moral standards making decisions to sell their products in the market by choosing their optimal production quantities and degrees of disobedience of a guiding rule imposed by a regulatory authority such as the government. We model this problem as a Cournot–Nash game in which. We introduce rules unfairness as a behavioral factor at work. We answer the questions of why firms disobey rules and to what degree and what are the effects of such actions. Our results show that firms disobey the rules for self-interest and harm other incentives. The case when the firms' disobediences can improve the total surplus (sum of their profits) is referred to as creative delinquency, whereas destructive selfishness refers to situation in which one's behavior only benefits self and leads to a decreased total surplus. Our results indicate that rules unfairness could be beneficial in some cases. Finally, our derivation of the optimal decision rules allows a regulatory authority to put into effect a coordinated punishment strategies that can benefit one firm or both firms.

Haihong Yu, Suresh P. Sethi & Xi Shan (2018) Creative delinquency or destructive selfishness? *International Journal of Production Research*, 56:1-2, 783-794 2018

k) Control Theory Applications to Operations Systems Supply Chain Management and Industry 4.0 Networks.

Participants: A Dolgui, D Ivanov, S Sethi, B Sokolov

Uncertainty, feedback cycles and dynamics are major challenges in production and logistics systems, supply chains, and Industry 4.0 networks. From this perspective, control theory is an important research avenue in operations and supply chain management. We briefly survey the applications of control theory to engineering and management problems in supply chains and operations areas during the period 1960-2017. Our analysis is based on bridging the fundamentals of control and systems theory to supply chains and operations management. Although operations and supply chain systems resemble control systems, they have some peculiarities which do not allow a direct application of control theoretic methods. The required modifications and possible limitations are discussed. In this setting, further development of interdisciplinary approaches to supply chain optimization is argued.

A Dolgui, D Ivanov, S Sethi, B Sokolov; (2018) "CONTROL THEORY APPLICATIONS TO OPERATIONS SYSTEMS, SUPPLY CHAIN MANAGEMENT AND INDUSTRY 4.0 NETWORKS", *IFAC-PapersOnLine 51 (11)*, 1536-1541

l) Impact of Power Structures in a Subcontracting Assembly System

Participants: G Li, L Li, M Liu, SP Sethi

We investigate the impact of power structures on the production and pricing strategies in a decentralized subcontracting assembly system consisting of two suppliers (key supplier and subcontractor) and one manufacturer (assembler). The key supplier, who is also the general contractor, negotiates with the manufacturer and assigns partial component production to the subcontractor. We first identify a single power regime (SPR), in which either the key supplier or the manufacturer determines the wholesale price or the order/production quantity. Under SPR, we consider three power structures, namely, KSA, KAS, and SKA. We find that the assembly system will substantially benefit under KAS. Results show that the subcontracting mechanism between the two suppliers can increase each firm's profit and disperse the bargaining power. Such a decentralization of powers can weaken the horizontal decentralization between the suppliers and improve the system's performance, thereby achieving a win–win situation. Furthermore, we extend our analysis to a dual power regime (DPR), in which the key supplier or the manufacturer decides on price and quantity. We show that the proposed assembly system performs optimally under DPR. Moreover, the system will benefit if the firm that is substantially near the end market makes the centralization decision. Compared with the classical pull and push contract model, the proposed assembly system provides the best performance under DPR.

G Li, L Li, M Liu, SP Sethi; (2018) "Impact of power structures in a subcontracting assembly system", *Annals of Operations Research*, 1-24

m) Advance Selling in the Presence of Market Power and Risk-Averse Consumers

Participants: S Ma, G Li, SP Sethi, X Zhao

We consider a manufacturer who procures raw material through a long-term contract as well as in a spot market to produce goods for selling to consumers, a fraction of whom are risk averse. We assume that the manufacturer has the market power to influence the spot market price of raw material. To increase consumer demand and obtain demand information, the manufacturer may implement an advance selling program that depends on his market power and consumer risk aversion. We investigate whether the manufacturer should offer the advance selling program and how his decision and performance are influenced by the program. We find that the advance selling program should be offered when consumer risk aversion is low, or when it is high, and the manufacturer has high and low market power. By contrast, the advance selling program should not be offered when consumer risk aversion is high and the market power is medium. Our results also reveal that even with no promotion cost of the advance selling program, the manufacturer may not always offer it. Finally, the manufacturer benefits more from advance selling when consumers are myopic and/or risk neutral.

Ma, S., Li, G., Sethi, S. P. and Zhao, X. (2018), "Advance Selling in the Presence of Market Power and Risk-Averse Consumers." *Decision Sciences*.

6.3. Activities in Finance and Economics

6.3.1. 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., C. Hoe. Real Options Games - Stackelberg Competition vs. Pre-emption in Complete and Incomplete Markets"

Bensoussan, A., C. Hoe, Z. Yang, and G. Yin. (2017) Real Options with Competition and Regime Switching *Mathematical Finance*,), 27(1), 224-250.

Hoe, C., Yan, Z., Bensoussan, A. (2018) Technical Note: The Impact of Competitive Advantage on the Investment Timing in the Stackelberg Leader-Follower Game. *Engineering Economist* , 63(3), 236-249.

6.3. 2 Real Options with Mean Field Games and Mean Field Type Control

Participants: Alain Bensoussan, Celine Hoe, ZhongFeng Yan

Expanding the game models studied in previous works, 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 mean-field game model, the uncertainty is related to the product price. In the framework, a firm's profit flow depends on the mean of market price due to the dependence of wage and the product market price. We solve a firm's optimal physical capital investment decision under uncertainty through mean-field type control methods.

Bensoussan, A., Hoe, C., Yan, Z. Mean-Variance Approach to Capital Investment Optimization

Bensoussan, A., Hoe, C., Yan, Z. Capital Accumulation with Constraint: A Mean Field Type Control Framework

6.3. 3 Risk Management and Mean Field Control

Participants: Alain Bensoussan, Celine Hoe, Joohyun Kim, ZhongFeng Yan

Risk Management can be viewed as an extension of stochastic control in which one is not just concerned by optimizing the average of a random payoff, consisting of a run off cost (or profit) and a final cost (or profit). The risk lies in the fact that the real cost can be far from its mean. A traditional way to handle this issue is to introduce an exponential of the cost function. This approach has merits, but lacks flexibility. A better way is to notice that Mean field type control is the right theory to extend stochastic control to include many aspects of risk management. We provide the general formalism. Applications can be numerous. We present here the risk management version of the classical investment-consumption problem known as Merton's problem in the finance literature. The interesting feature is that we can solve the problem completely. The methodology can be adapted to all kinds of investment decisions, or operations decisions.

Bensoussan, A., Hoe, C., Kim, J., Yan, Z. Risk Management and Mean Field Control

6-3-3 Real Options and Growth of Firms

Participants: 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.

6-3-4 Corporate 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)

c) Extension of 'Dividend Policy, Growth, and the Valuation of Shares' by Miller and Modigliani (1961) to Allow for Share Repurchases

Participants: Suresh P. Sethi

Miller and Modigliani (1961) consider valuation of infinite horizon firms that may not engage in purchasing their own shares. While their fundamental valuation approach also applies to firms that purchase their own shares, their stream of dividends approach does not apply to these firms if they do not distribute “sufficient” cash via dividends and share repurchases, as characterized by a necessary and sufficient condition. Also presented is a modified stream of dividends approach that provides an equivalent valuation of every firm that can be valued by the fundamental approach.

Sethi, S.P., “Extension of the Miller and Modigliani Theory to Allow for Share Repurchases,” *Mathematical Finance Letters*, Vol 2017 (2017), Article ID 3.

6-3-5 Mean Field Theory

a) Sobolev regularity for first order Mean Field Games

Participants: P. Jameson Graber (with Alpar Meszaros)

In this paper we obtain Sobolev estimates for weak solutions of first order variational Mean Field Game systems with coupling terms that are local functions of the density variable. Under some coercivity conditions on the coupling, we obtain first order Sobolev estimates for the density variable, while under a similar coercivity condition on the Hamiltonian we obtain second order Sobolev estimates for the value function. These results are valid both for stationary and time-dependent problems. In the latter case the estimates are fully global in time, thus we resolve a

question which was left open in a paper by Prosinski and Santambrogio. Our methods apply to a large class of Hamiltonians and coupling functions.

P. J. Graber and A. Meszaros, "Sobolev regularity for first order Mean Field Games," submitted. arXiv:1708.06190

b) Variational mean field games for market competition

Participants: P. Jameson Graber (with Charafeddine Mouzouni)

In this paper, we explore Bertrand and Cournot Mean Field Games models for market competition with reflection boundary conditions. We prove existence, uniqueness and regularity of solutions to the system of equations, and show that this system can be written as an optimality condition of a convex minimization problem. We also provide a short proof of uniqueness to the system addressed in [Graber, P. and Bensoussan, A., *Existence and uniqueness of solutions for Bertrand and Cournot mean field games*, Applied Mathematics & Optimization (2016)], where uniqueness was only proved for small parameters ϵ . Finally, we prove existence and uniqueness of a weak solutions to the corresponding first order system at the deterministic limit.

P. J. Graber and C. Mouzouni, "Variational mean field games for market competition," (proceedings article, to appear in Springer INdAM Series). arXiv:1707.07853

c) Discontinuous solutions of Hamilton-Jacobi equations on networks

Participants: P. Jameson Graber (with Cristopher Hermosilla, Hasnaa Zidani)

This paper studies optimal control problems on networks without controllability assumptions at the junctions. The Value Function associated with the control problem is characterized as the solution to a system of Hamilton-Jacobi equations with appropriate junction conditions. The novel feature of the result lies in that the controllability conditions are not needed and the characterization remains valid even when the Value Function is not continuous.

P. J. Graber and C. Hermosilla and H. Zidani, "Discontinuous solutions of Hamilton-Jacobi equations on networks," to appear in Journal of Differential Equations. hal-01363628

d) Linear Quadratic Mean Field Type Control and Mean Field Games with Common Noise, with Application to Production of an Exhaustible Resource

Participants: P. Jameson Graber

We study a general linear quadratic mean field type control problem and connect it to mean field games of a similar type. The solution is given both in terms of a forward/backward system of stochastic differential equations and by a pair of Riccati equations. In certain cases, the solution to the mean field type control is also the equilibrium strategy for a class of mean field games. We use this fact to study an economic model of production of exhaustible resources.

P. J. Graber, "Linear Quadratic Mean Field Type Control and Mean Field Games with Common Noise, with Application to Production of an Exhaustible Resource," Applied Mathematics and Optimization Vol. 74, No. 3 (special issue, Dec. 2016) pp. 459-486. arXiv:1607.02130

e) Existence and uniqueness of solutions for Bertrand and Cournot mean field games

Participants: P. Jameson Graber and Alain Bensoussan

We study a system of partial differential equations used to describe Bertrand and Cournot competition among a continuum of producers of an exhaustible resource. By deriving new a priori estimates, we prove the existence of classical solutions under general assumptions on the data. Moreover, under an additional hypothesis we prove uniqueness.

P. J. Graber and A. Bensoussan, "Existence and uniqueness of solutions for Bertrand and Cournot mean field games," to appear in Applied Mathematics and Optimization. arXiv:1508.05408

6-3-6 Financial Contracts

a) Robust Contracts in Continuous Time

Participants: Jianjun Miao (Boston University) and Alejandro Rivera(UT-Dallas)

Abstract: We study a continuous-time contracting problem under hidden action, where the principal has ambiguous beliefs about the project cash flows. The principal designs a robust contract that maximizes his utility under the worst-case scenario subject to the agent's incentive and participation constraints. Robustness generates endogenous belief heterogeneity and induces a tradeoff between incentives and ambiguity sharing so that the incentive constraint does not always bind. We implement the optimal contract by cash reserves, debt, and equity. In addition to receiving ordinary dividends when cash reserves reach a threshold, outside equity holders also receive special dividends or inject cash in the cash reserves to hedge against model uncertainty and smooth dividends. The equity premium and the credit yield spread generated by ambiguity aversion are state dependent and high for distressed firms with low cash reserves. Published in Econometrica (2016)

b) Dynamic Moral Hazard, Risk-Shifting, and Optimal Capital Structure

Participants: Alejandro Rivera (UT-Dallas)

Abstract: I develop an analytically tractable model that integrates the risk-shifting problem between bondholders and shareholders with the moral hazard problem between shareholders and the manager. The presence of managerial moral hazard exacerbates the risk-shifting problem. An optimal contract binds shareholders and the manager. The flexibility of this contract allows shareholders to relax the incentive constraint of the manager when a good profitability shock is drawn. Hence, the optimal contract amplifies the upside thereby increasing shareholder appetite for risk-shifting. Moreover, some empirical studies find a positive relation between risk-shifting and leverage, while others studies find a negative relation. The model predicts a non-monotonic relation between risk-shifting and leverage and has the potential to reconcile this empirical evidence. Implications for capital structure, business cycles and executive compensation are also considered.

c) Optimal Shorttermism

Participants: Dirk Hareckbarth (Boston University), Alejandro Rivera (UT-Dallas), and Tak Wong (SUFU)

Abstract:

This paper develops a framework of multi-tasking and optimal contracting between shareholders and a manager of a levered firm that faces both permanent and transitory cash flow shocks. The manager selects long-term and short-term efforts, while shareholders choose initially optimal leverage and ex-post optimal default policies. There are three results. First, underinvestment in long-term effort results from risky debt, but optimal short-termism for shareholders results from attenuating underinvestment by short-term effort that delays default at the expense of augmenting the firm's growth rate via long-term effort. Second, the endogenous default threshold rises with the substitutability of tasks and, for a positive correlation of shocks, the endogenous default threshold is hump-shaped in the volatility of permanent shocks, but increases monotonically with the volatility of transitory shocks. Third, we quantify agency costs of short-term and long-term effort, cost of short-termism, effects of investor time horizons and industry growth rates, pay-performance sensitivities for short-term and long-term efforts, credit spreads, and risk-

shifting.

6.4. Activities in Alternative Energies

6.4.1 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*, 2016, 19(7) 1355-1365

A. Bensoussan, A. Brouste, *Marginal Weibull Diffusion Model for Wind Speed Modeling and Forecasting*, to appear in *Renewable Energy: Forecasting and Risk* (ed. P. Drobinski, M. Mougeot, D. Picard, R. Plougonven, P. Tankov), Springer.

6-4-2 Fractional Gaussian Processes

Participants: A. Brouste

Brouste, A., Istas, J. and Lambert-Lacroix, S., *Conditional fractional Gaussian Fields with the Package*, FieldSim R, Journal 8 (1) 2016, 38-47

Brouste, A. and Fukasawa, F., *Local Asymptotic normality property for fractional Gaussian noise under high-frequency observations*, The Annals of Statistics, 2018, 46(5), 2045-2061.

A. Brouste and H. Masuda (2018) *Efficient estimation of stable Lévy process with symmetric jumps*, Statistical Inference for Stochastic Processes, 2018, 21, 289-307

6.5. Activities in Risks on Technical Systems

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

a) Participants: Alain Bensoussan, Laurent Mertz

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

method (Stochastic Stability of Differential Equations, Sijthoff and Noordhof, 1980) leads to the study of degenerate Dirichlet problems with partial differential equations and nonlocal boundary conditions.

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

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

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

Bensoussan A., Mertz L., Yam P., Nonlocal problems related to an elasto-plastic oscillator excited by a filtered noise, SIAM J. Math. Anal. 48-4 (2016), pp. 2783-2805.

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

Several works related to this domain are collected here:

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

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

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

6.5.3 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.

6.5.4 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.

6.5.5 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.

6.5.6 Stochastic control of non-smooth stochastic systems

Participants M. Lauriere, Z. Li, L. Mertz, J. Wylie and S. Zuo

We consider the optimal stopping and optimal control problems related to stochastic variational inequalities modeling elasto-plastic oscillators subject to random forcing. We formally derive the corresponding free boundary value problems and Hamilton-Jacobi-Bellman equations which belong to a class of nonlinear partial of differential equations with nonlocal Dirichlet boundary conditions. Then, we focus on solving numerically these equations by employing a combination of Howard's algorithm and the numerical approach [A backward Kolmogorov equation approach to compute means, moments and correlations of non-smooth stochastic dynamical systems; Mertz, Stadler, Wylie; 2017] for this type of boundary conditions. Numerical experiments are given and further research directions are commented concerning risk analysis of failure and the problem of critical excitation in earthquake engineering.

M. Laurière, Z. Li, L. Mertz and J. Wylie, Free boundary value problems and HJB equations for the stochastic optimal control of elasto-plastic oscillators, submitted.

2018 PUBLICATIONS

Parabolic Equations with Quadratic Growth in \mathbb{R}^n

A. Bensoussan, Jens Frehse, Shige Peng, Sheung Chi Phillip Yam

*Book Chapter In: **Contributions to Partial Differential Equations and Applications*** eds Chetverushkin, B.N., Fitzgibbon, W., Kuznetsov, Y.A., Neittaanmäki, P. Periaux, J., Pironneau, O. Springer International Publishing, (2019)

Control Problem on Space of Random Variables and Master Equation

A. Bensoussan, Sheung Chi Phillip Yam

ESIAM: Control, Optimization and Calculus of Variations

Accepted - to be published

Sequential Capacity Expansion Options

A. Bensoussan, Benoît Chevalier-Roignant

INFORMS, Operations Research, Articles in Advance, Oct 9, 2018, 1-26

[2](#)

Optimal Inventory Control with Jump Diffusion and Nonlinear Dynamics in the Demand

Jingzhen Liu, Ka Fai Cedric Yiu, Alain Bensoussan

SIAM J. Control Optimization (2018) **56** (1), 53-74

Bellman Systems with Mean Field Dependent Dynamics

A. Bensoussan, Miroslav Bulíček, Jens Frehse
Chinese Annals of Mathematics, Series B **39(3)**, 2018 461-486

Backward Stochastic Dynamics with a Sub Differential Operator and Non-local Parabolic Variational Inequalities

A. Bensoussan, Y. Li, S. C. P. Yam
Stochastic Processes and their Applications, (online June, 2017) Elsevier (2018)

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

P. Jameson Graber, Alain Bensoussan
Applied Math Optimization, (2018) **77**, pp47-71

Inventory Control with Fixed Cost and Price Optimization in Continuous Time

A. Bensoussan, Sonny Skaaning, Janos Turi
Journal of Applied Analysis and Computation, **8 (3)**, June 2018, 805-835

Parabolic Bellman Equations with Risk Control

Alain Bensoussan, Dominic Breit, Jens Frehse
Siam Journal on Control & Optimization **56 (2)**, January 2018, 1535-1549

The Impact of Competitive Advantage on the Investment Timing in Stackelberg Leader-Follower Game

SingRu Hoe, Zhongfeng Yan, Alain Bensoussan
Engineering Economist **63 (3)**, January 2018, 236-240

SPEAKER INVITATION

Risk Management and Mean Field Control Theory

Mean Field Games, Energy, Environment
Alan Turing Institute, London
February 12-14, 2018

Scientific and Industrial Council

Technopôle de l'Arbois
Aix en Provence
March 29- 31, 2018

Risk Foundation

Scientific Board
Paris, France
May 28, 2018

Systems of Quasilinear Parabolic Equations in R^n and Systems of Quadratic BSDE

Symposium: New Trends in Theory of Stochastic Control
14th Viennese Conference on Optimal Control and Dynamic Games
Vienna, Austria

July 2 – 4, 2018

Machine Learning and Control Theory

Huawei Forum: Vision for Mathematics

Paris, France

July 5, 2018

Machine Learning and Control Theory

Mathematics Department

Southern Methodist University

Dallas, Texas

November 2, 2018

Real Options and Performance Sensitive Debt

Informs 2017 Meeting

Phoenix, Arizona

Nov 4 – 7, 2018

Mean Field Games and Mean-Field Type Control

Advanced Networking Colloquium

Hybrid Networks Center (HyNet)

University of Maryland College Park

Nov 13 – 16, 2018

2017

Ergodic Control for a Mean Reverting Inventory Model

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

Journal of Industrial and Management Optimization, (2017)

Optimal Inventory Control with Jump Diffusion and Nonlinear Dynamics Demands

Jingzhen Liu, Ka Fai Cedric Yiu, Alain Bensoussan

SIAM Control and Optimizations (2017)

Linear-Quadratic Mean Field Stackelberg Games with State and Control Delays

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

SIAM Journal on Control and Optimization **55** (4) (July 5, 2017) 2748-2781

Editorial: SECOND ISSUE ON MEAN FIELD GAMES, *Applied Mathematics & Optimization*, **1-3**, (Springer, June, 29, 2017), A. Bensoussan & François Delarue, June 29, 2017, Springer Science+Business Media, LLC 2017, DOI 10.1007/s00245-01709436-y

A Prediction Model Guided Jaya Algorithm for the PV System Maximum Power Point Tracking

Chao Huang, Long Wang, Ryan Shun-cheung Yeung, Zijun Zhang, Henry Shu-hung Chung, A. Bensoussan

IEEE Transactions on Sustainable Energy, **PP** (99) (June 2017)

Optimal Security Investments in a Prevention and Detection Game

C. Barreto, A. Cardenas, A. Bensoussan

ACM Proceedings: Hot Topics in Science and Security Symposium, Hanover, MS, ACM, (April 4-5, 2017) New York, 24-34, NY ISBN: 978-1-4503-5272-1

Base Stock List Price Policy in Continuous Time

A. Bensoussan, Sonny Skaaning

Discrete and Continuous Dynamical Systems Series **22 (1)** (January 2017) 1-28

Real Options with Competition and Regime Switching

A. Bensoussan, SingRu Hoe, Zhong Fenb Yan, George Yin

Mathematical Finance, **27 (1)**, January, 2017 224-250

Optimality of (s,S) Policies with Nonlinear Processes

A. Bensoussan, Jingzhen Liu, Ka Fai Cedric Yiu

Discrete and Continuous – Dynamic Systems Series B **22, (1)**, January 2017 161-185

Backward Stochastic Dynamics with a Sub Differential Operator and Non-local Parabolic Variational Inequalities*

A. Bensoussan, Yiqun Li, Sheung Chi Phillip Yam

Stochastic Processes and their Applications, June 7, 2017

SPEAKER INVITATIONS

Should We Be Concerned by Risk Management?

Café des Sciences

French-American Chamber of Commerce

October 27, 2017

Scientific and Industrial Council

Technopôle de l'Arbois

Aix-en-Provence, France

April 1, 2017

Mean Field and Principal Agent Contracts

University of Maine Workshop

University of Maine, France

March 28, 2017

Team Indus: Mission to the Moon

Chairman of the International Jury

Bangalore, India

March 13 – 15, 2017

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 Noise

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

