EWG STOCHMOD STOCHASTIC MODELLING

# Book of Abstracts
# StochMod18


13 - 15 June 2018

Lancaster University
Management School

UCL
SCHOOL OF
MANAGEMENT

www.lancaster.ac.uk/staff/jacko/stochmod2018/

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Tweet us @StochMod2018

# Foreword

Dear StochMod18 participant,

It is our pleasure to welcome you to the seventh edition of the EURO Working Group on Stochastic Modelling! This year's meeting is taking place in Lancaster, home to the renowned Lancaster University Management School, which is hosting the event, and a gateway to the UK's largest national park, the Lake District.

Lancaster University is currently ranked in the top 10 across all national league tables of UK universities. It was awarded University of the Year by The Times and Sunday Times Good University Guide (2018), and it holds its highest ever institutional ranking of 6th place within the guide's national table. Lancaster is a research-intensive university, as evidenced by the 2014 Research Excellence Framework (REF) where 83% of its research was rated as either internationally excellent or world leading. Its Management School was ranked as the top business school in the UK for 'research power'.

This year's meeting brings together researchers who are interested in the development and use of probabilistic models for the design, evaluation, improvement, and optimisation of systems that involve random phenomena. StochMod18 has a record number of scheduled talks, as well as keynote talks by Margaret Brandeau (Stanford University), Kevin Glazebrook (Lancaster University) and Kalyan Talluri (Imperial College London), and a tutorial by Warren B. Powell (Princeton University).

We would also like to acknowledge the support of all the partners that have made this event possible: the Association of European Operational Research Societies (EURO), Lancaster University Management School (LUMS), and the University College London (UCL) School of Management.

Finally, thank you for your participation in this event! We hope that you will spend three rewarding days filled with interesting sessions, discussions, and fun moments.

Rouba Ibrahim and Peter Jacko

(Co-chairs)

# Committees

**Organising Committee**

- *Meeting Coordinator:* Lindsay Newby (Lancaster University Management School, UK)
- *Co-chairs:* Rouba Ibrahim (University College London School of Management, UK) and Peter Jacko (Lancaster University Management School, UK)
- *Student Helpers:* Jake Clarkson, Stephen Ford, Lucy Morgan and Faye Williamson (STOR-i Centre for Doctoral Training, Lancaster University, UK)

**Steering Committee**

- Apostolos Burnetas (University of Athens, Greece)
- Philippe Chevalier (Université catholique de Louvain, Belgium)
- Oualid Jouini (CentraleSupélec, France)
- Fikri Karaesmen (Koç University, Turkey)
- Ger Koole (VU Amsterdam, Netherlands)
- Raik Stolletz (University of Mannheim, Germany)
- Nico Vandaele (KU Leuven, Belgium)

# Practical Information

## 1 Upon Arrival

### Getting to Campus from Lancaster Railway Station

*(i) By Bus*

- There is a bus stop opposite the railway station. From here, you can take the U3R bus directly to Lancaster University which operates every 30 minutes during the daytime.
- Alternatively, you can take a 6 minute walk to the bus stop at Common Garden Street (see city map in section 4) where buses to campus are more regular. Buses U2, U3, U3R and U4 all leave from here to the University every 5-10 minutes on weekdays (the bus direction is "University", not "Morecambe" or "Heysham").
- All buses drop off and collect passengers in the underpass which is situated underneath Alexandra Square in the centre of campus. Please note that only **cash** is accepted on all buses (exact change not required).
- For timetables and further information, visit the Stagecoach website (`https://www.stagecoachbus.com/`) or call Traveline on +44 (0)871 200 22 33.

*(ii) By Taxi*

- Local taxi services can be contacted on: +44 (0)1524 32090; +44 (0)1524 35666 and +44 (0)1524 848848. You will also find a taxi rank outside the railway station.

### Car Parking

- Please note that only guests of the Lancaster House Hotel may use their car park. For all other participants **not** staying in Lancaster House Hotel, please park in the allocated parking zones (zones H, I and F) or Alexandra Park. These parking zones are located close to the Conference Centre, see `http://www.lancaster.ac.uk/media/lancaster-university/content-assets/documents/facilities/car-parking-policy/ParkingZonesMap-updated13.10.17.pdf` for their precise location. Participants staying in Guest Rooms on campus will also be given a parking permit valid near their accommodation.

## 2 Meeting Venue

**The Conference Centre**

- StochMod18 will take place in The Conference Centre, which is located on campus opposite the Lancaster University Management School (LUMS) and can be accessed either directly from Lancaster House Hotel or from campus itself.
- For directions, please refer to the Lancaster University campus map in section 4; The Conference Centre is labelled.
- Registration and refreshment breaks will take place in the Foyer & Lounge/Conference Suite 1. All sessions will take place in Conference Suites 2 and 3, with keynote talks in Conference Suite 2. See the Floor Plan on the next page.
- For enquires related to The Conference Centre, tel: +44 (0)1524 592444 or e-mail: lancasterconferences@lancaster.ac.uk.

**Registration**

- Please pick up your badge from our registration desk at the Conference Centre on **Wednesday 13 June from 8:15 to 8:45**.

**Session Chairs**

- The last speaker in every session is assigned as the session chair. The session chair's role is simply to introduce the talks and keep track of timing.

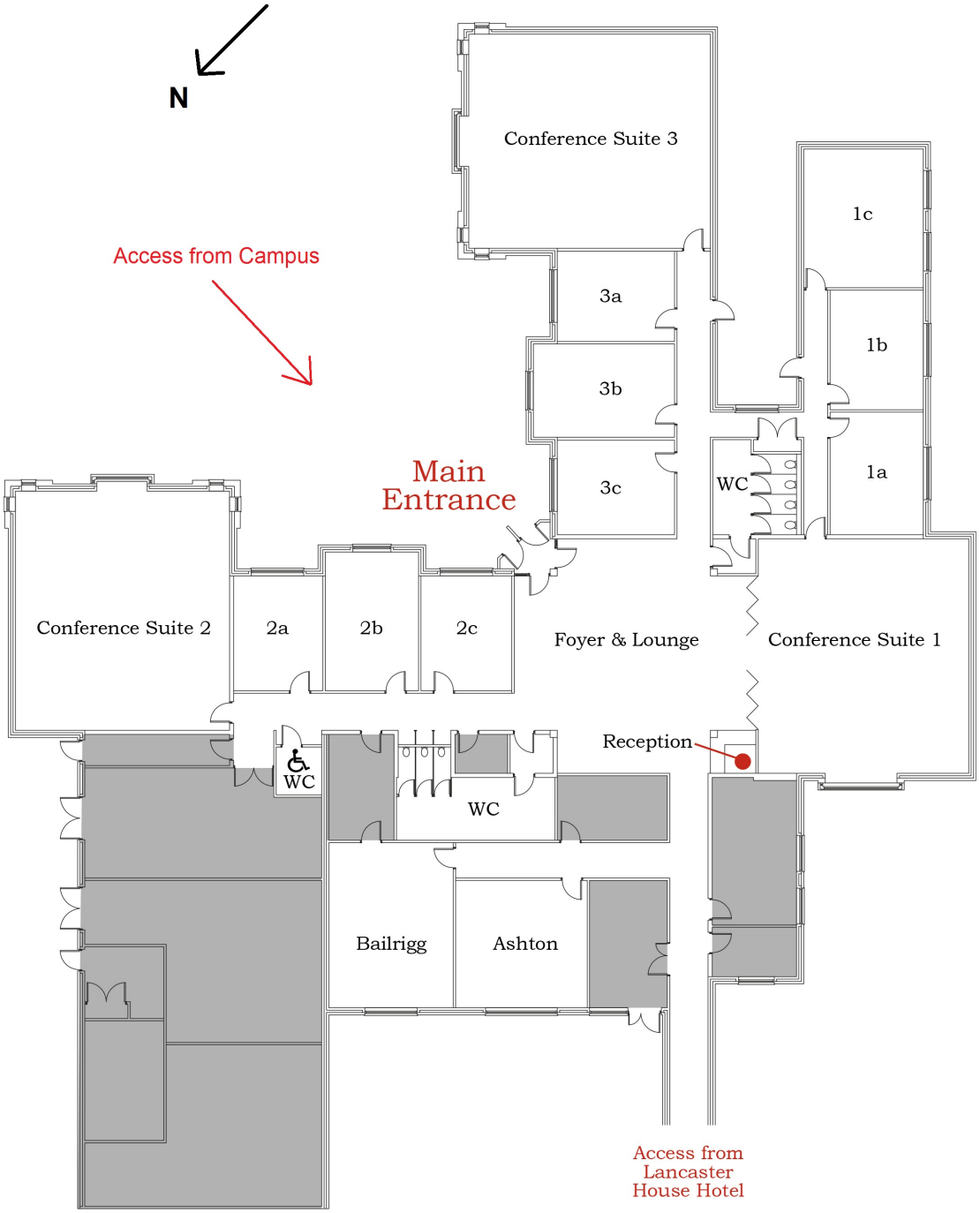
**Reminder to Speakers**

- Please remember to transfer your presentation (in PDF format) from your USB stick to the laptop provided **before** your session. Note that a clicker will be available to use.
- Your presentation will be allocated a **20 minute** slot.

**Wi-Fi**

- Eduroam is available in the Conference Centre and on campus. However, if you are not able to access this, please ask and we will be able to provide you with a visitor username and password for the duration of the StochMod18 meeting. Please note that Eduroam is not be available in the Lancaster House Hotel. Hotel guests will be provided with Wi-Fi login details when they check in. Non-hotel guests can also request Wi-Fi login details from the reception.

# Floor Plan


N
Access from Campus
Conference Suite 3
1c
3a
1b
3b
3c
WC
1a
Main Entrance
Conference Suite 2
2a
2b
2c
Foyer & Lounge
Conference Suite 1
Reception
WC
WC
Bailrigg
Ashton
Access from Lancaster House Hotel

## 3 Social Programme

**Welcome**

- We warmly invite you to join us for an informal welcome drink at The Sandeman's Bar in Lancaster House Hotel on **Tuesday 12 June** from 18:00. Please note that main meals are only available from the bar until 18:00, but light snacks continue until 21:30. The hotel restaurant next to the bar (The Foodworks) serves main meals until 21:00. This event is not a formal part of the meeting and is not covered by the registration fee.

**Casual Student Dinner**

- All **students** attending the conference are invited to join our PhD student helpers (Jake, Stephen, Lucy and Faye) for an informal dinner at The Borough Pub, situated in Lancaster city centre (Dalton Square), on **Wednesday 13 June** from 19:00. The pub is shown on the city map in section 4, yet we will meet outside the main entrance of the conference building after the last talk of the day to catch the bus as a group. This event is not a formal part of the meeting and is not covered by the registration fee, yet it will be a great opportunity to venture off campus for an evening and get to know each other in a more relaxed setting.

**Conference Dinner**

- The conference dinner will be held on **Thursday 14 June** between 19:00 - 22:00, and will take place in Ashton Hall - a 14th-century mansion recorded in the National Heritage List for England and now the Club House of Lancaster Golf Club - located three miles from campus.
- There will be two coaches provided which are due to leave Lancaster University Management School at 18:45 and will return from Ashton Hall at approximately 23:15.

## 4 Lancaster University and Around

**What's on Campus?**

- Some of our favourite cafés include: Café 21 (serves great vegetarian, vegan and gluten-free food as well as sustainable fish), The Deli Café (serves brunch, Atkinson's coffee, homemade soups, deli salads, roasted meats, freshly baked tartlets, plus a range of delicious cakes) and Pizzetta Republic (serves fast food such as pizza, burgers, wraps etc. and arguably the best coffee on campus!).
- The campus also has Subway, Greggs, Spar, County Diner, Ketcap, The Sultan Indian Restaurant, Wok Inn, GoBurrito, Costa, Wong's Chinese Restaurant, Juicafe, Wibbly Wobbly Burger Bar and even an ice cream shop!
- For more information about some of the cafés and restaurants on campus, including the nine college bars, visit `http://www.lancaster.ac.uk/eat/index.php#cafes`.
- The campus map on the next page may also be helpful.
- Note that **health services**, including an NHS doctor's surgery, a pharmacy and a private dentist, are also available on the campus, in addition to a post office, sports centre and two banks (several ATM machines can be found in Alexandra Square).
- Look out for the Woodland Walk and Trim Trail which provides a beautiful route through 2.6 miles of woodland canopy around campus (route provided on the campus map on the next page).

# Campus Map

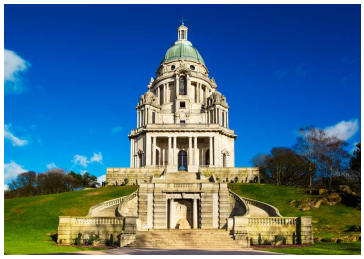
Lancaster University


1. Refuel
   County College
2. The Lounge
   County South
3. The Northern Oak
   County College
4. The Trough of Bowland
   Bowland College
5. The Deli
   Off Alexandra Square
6. Trevor
   Furness College
7. The Mill
   Fylde College
8. The Hub
   Management School
9. Grizedale Café Bar
   Grizedale College
10. The Pendle Rooms
    Pendle College
11. Café 21
    Infolab
12. The Red Lion
    Lonsdale College
13. The Herdwick
    Graduate College
14. The Winning Post
    Cartmel College
15. Refuel
    Barker House Farm

For more information, find us at: facebook.com/LancasterCampusLife @LUCampusLife

**About Lancaster City**

- Often described as the cultural centre of Lancashire, Lancaster is dominated by its medieval castle and the River Lune that runs through the city. The narrow, Georgian streets surrounding the castle contain a surprising wealth of museums. As one of England's Heritage Cities, there is history around every corner, from the conviction of the Lancaster Witches in 1612 to Charles Dickens' hotel room!
- The City centre boasts lots of open green spaces, from canal-side walks, the River Lune footpath and several parks. Stunning views over Lancaster across to Morecambe Bay and the distant hills of the Lake District are available from Ashton Memorial, which is set in the beautiful Williamson Park.
- The included city map highlights many of Lancaster's attractions. For more information on any of the attractions in Lancaster and nearby areas, visit the Lancaster University website: `http://www.lancaster.ac.uk/study/life-at-lancaster/city/` or the Tourist Information Office (located on Castle Hill) which can be contacted on +44(0)152432878.
- Alternatively, please feel free to ask any of our student helpers who will be more than happy to assist.


**Suggested canal-side walk from campus to city**

- On campus, head towards North West Drive where you will join the cycle path. Walk along the cycle path and continue along Bailrigg Lane which will join Scotforth Road (the main road that heads from campus into the city). Continue along Scotforth Road until you reach Booths supermarket (on your right). At this point, turn left down Ashford Road and continue walking. When you reach Caspian Way, take a left turn and walk down a slight decline (on the bus and cycle only road) until you join Ashton Road. Here, take a left turn and walk about 150m until you reach a wooden gate on the right hand side of the road. You have then reached the canal!
- From here, you can walk all the way along the scenic canal-side path for approximately 30 minutes until you reach the city centre. You will see The Water Witch pub (see city map) on the opposite side of the canal - if it's a sunny day, we recommend you cross over the bridge and reward yourself with a well-earned drink here! This walk is 3.6 miles in total and takes approximately 1h 10 minutes (according to Google maps).

**Travel from Lancaster**

*(i) By Rail*

– There are direct, regular rail links between Lancaster and many of the UK's major cities, including: Glasgow (2 hours), Edinburgh (2.5 hours), London (2.5 hours), Manchester (1 hour), Preston (15 mins), Leeds (2 hours - see the scenic Bentham Line, one of the earliest railway lines in Britain), Morecambe (9 mins) and The Lake District (from 15 mins). For the latest train times, visit National Rail Enquiries (`http://www.nationalrail.co.uk/`).

*(ii) By Coach*

– There are daily scheduled coach services from the underpass on campus to various destinations across the UK. These are operated by Megabus and National Express.

# Lancaster

Lancaster Visitor Information Centre
The Storey, Meeting House Lane, Lancaster LA1 1TH
T: 01524 582394 E: lancastervic@lancaster.gov.uk W: visitlancaster.co.uk


Design: The Drawing Room
graham@drawing.demon.co.uk

# Timetable

| Wednesday 13th June | Thursday 14th June | Friday 15th June |
|---|---|---|
| **8:15 Registration** | | |
| **8:45 Opening Remarks** | | |
| **9:00 Tutorial**<br>Warren B. Powell<br>(Suite 2) | **9:00 Resource Allocation**<br>(Suite 2)<br>**9:00 Logistics and Transportation 2**<br>(Suite 3) | **9:00 Markov Decision Processes 1**<br>(Suite 2)<br>**9:00 Stochastic Processes**<br>(Suite 3) |
| **10:30 Break**<br>(pastries/pretzels/ fruit/tea/coffee) | **10:30 Break**<br>(pastries/pretzels/ fruit/tea/coffee) | **10:30 Break**<br>(pastries/pretzels/ fruit/tea/coffee) |
| **11:00 Queueing Theory 1**<br>(Suite 2)<br>**11:00 Finance and Risk**<br>(Suite 3) | **11:00 Heuristics**<br>(Suite 2)<br>**11:00 Inventory Management**<br>(Suite 3) | **11:00 Markov Decision Processes 2**<br>(Suite 2)<br>**11:00 Computing and Communications**<br>(Suite 3) |
| **12:30 Break**<br>(lunch/fruit/juice) | **12:30 Break**<br>(lunch/fruit/juice) | **12:30 Break**<br>(lunch/fruit/juice/tea/coffee) |
| **13:30 Keynote**<br>Margaret Brandeau<br>(Suite 2) | **13:30 Keynote**<br>Kevin Glazebrook<br>(Suite 2) | **13:30 Keynote**<br>Kalyan Talluri<br>(Suite 2) |
| **14:30 Break**<br>(fruit/tea/coffee) | **14:30 Break**<br>(fruit/tea/coffee) | **14:30 Open Discussion about Teaching**<br>chaired by Ger Koole<br>(Suite 2) |
| **14:45 Queueing Theory 2**<br>(Suite 2)<br>**14:45 Logistics and Transportation 1**<br>(Suite 3) | **14:45 Healthcare**<br>(Suite 2)<br>**14:45 Networks**<br>(Suite 3) | **15:45 Closing Remarks** |
| **15:50 Break**<br>(biscuits/fruit/ juice/tea/coffee) | **15:50 Break**<br>(doughnuts/fruit/ juice/tea/coffee) | **15:50 Break**<br>(doughnuts/fruit/ juice/tea/coffee) |
| **16:20 Queueing Theory 3**<br>(Suite 2)<br>**16:20 Game Theory and Behaviour Theory**<br>(Suite 3) | **16:20 Simulation**<br>(Suite 2)<br>**16:20 Machine Learning and Data Science**<br>(Suite 3) | **16:00 End** |
| **17:50 End** | **17:25 End** | |
| | **18:45 Bus to Social Dinner** | |

# Invited Speakers

**Professor Warren B. Powell:** Warren Powell is a faculty member in the Department of Operations Research and Financial Engineering at Princeton University where he has taught since 1981. In 1990, he founded CASTLE Laboratory which spans research in computational stochastic optimization with applications initially in transportation and logistics. In 2011, he founded the Princeton laboratory for ENergy Systems Analysis (PENSA) to tackle the rich array of problems in energy systems analysis. In 2013, this morphed into "CASTLE Labs", focusing on computational stochastic optimization and learning.

**Professor Margaret Brandeau:** Margaret Brandeau is Coleman F. Fung Professor of Engineering and Professor of Medicine (by Courtesy) at Stanford University. Her research focuses on the development of applied mathematical and economic models to support health policy decisions. Recently she has examined HIV and drug abuse prevention and treatment programs, programs to control the spread of hepatitis B virus, and preparedness plans for public health emergencies. She is a Fellow of INFORMS. From INFORMS, she has received the Philip McCord Morse Lectureship Award, the President's Award, the Pierskalla Prize, and the Award for the Advancement of Women in Operations Research and the Management Sciences.

# Invited Speakers

**Professor Kevin Glazebrook:** Kevin is Distinguished Professor of Operational Research (OR) in the Department of Management Science at Lancaster University where he also chairs the Centre for Doctoral Training in Statistics and OR in partnership with industry (STOR-i). He chairs the Research Panel of the UK OR Society. He has co-authored two books and around 150 papers in peer-reviewed journals. His primary research concerns the development of exact and heuristic methods for dynamic resource allocation. Recent work has focussed on models and methods for optimal patrol, search and surveillance, the collection and analysis of intelligence data and the effective use of airport capacity. He is a Beale medallist (the OR Society) and an INFORMS Fellow.

**Professor Kalyan Talluri:** Kalyan Talluri is a Professor of Operations Management in the Department of Management. He obtained his PhD in Operations Research from MIT, a Masters in Industrial Engineering from Purdue University and a B.Tech in Mechanical Engineering from Osmania University, Hyderabad. He had previously taught at Kellogg Graduate School of Management, Northwestern University and the Dept. of Economics at the Universitat Pompeu Fabra, Barcelona. He also worked at US Airways for three years prior to that. He has held visiting positions at the Indian School of Business, New York University, INSEAD and Dartmouth College. Professor Talluri's research interestes are in network and service design, data analytics, revenue management and pricing.

# Abstracts

## Wednesday 13th June

### 9:00-10:30 - Invited Tutorial (Suite 2)



### 11:00-12:30 - Queueing Theory 1 (Suite 2)



### 11:00-12:30 - Finance and Risk (Suite 3)



### 13:30-14:30 - Invited Keynote (Suite 2)



### 14:45-15:50 - Queueing Theory 2 (Suite 2)

## 14:45-15:50 - Logistics and Transportation 1 (Suite 3)



## 16:20-17:50 - Queueing Theory 3 (Suite 2)



## 16:20-17:50 - Game Theory and Behaviour Theory (Suite 3)

# Thursday 14th June

## 9:00-10:30 - Resource Allocation (Suite 2)



## 9:00-10:30 - Logistics and Transportation 2 (Suite 3)



## 11:00-12:30 - Heuristics (Suite 2)



## 11:00-12:30 - Inventory Management (Suite 3)

## 13:30-14:30 - Invited Keynote (Suite 2)



## 14:45-15:50 - Healthcare (Suite 2)



## 14:45-15:50 - Networks (Suite 3)



## 16:20-17:25 - Simulation (Suite 2)



## 16:20-17:25 - Machine Learning and Data Science (Suite 3)

# Friday 15th June

## 9:00-10:30 - Markov Decision Processes 1 (Suite 2)



## 9:00-10:30 - Stochastic Processes (Suite 3)



## 11:00-12:30 - Markov Decision Processes (Suite 2)



## 11:00-12:30 - Computing and Communications (Suite 3)

## 13:30-14:30 - Invited Keynote (Suite 2)



## 14:30-15:45 - Open Discussion about Teaching (Suite 2)

# Wednesday 13th June

## 9:00-10:30 - Invited Tutorial (Suite 2)

### A Unified Framework for Optimisation under Uncertainty

**Invited Speaker:** Warren B. Powell

Princeton University, USA

Stochastic optimisation is a fragmented field comprised of multiple communities from within operations research (stochastic programming, Markov decision processes, simulation optimisation, decision analysis), computer science (reinforcement learning, multi-armed bandit problems), engineering and economics (stochastic optimal control, optimal stopping), statistics (ranking and selection), probability (multi-armed bandit problems), and applied mathematics (stochastic search). In this talk, I will begin by presenting a much-needed canonical framework for stochastic optimisation that matches the widely used setting for math programming. I will then identify the major dimensions of this rich class of problems, spanning static to fully sequential problems, offline and online learning, derivative-free and derivative-based algorithms, with special attention given to problems with expensive function evaluations. We divide solution strategies for sequential problems ("dynamic programs") between policy search (searching within a class of functions) and policies based on approximating the impact of a decision now on the future. We further divide each of these two fundamental solution approaches into two subclasses, producing four classes of policies for approaching sequential stochastic optimisation problems that covers all the solution strategies that have been used in any of the fields (including whatever is currently being used in practice). We demonstrate that each of these four classes may work best, as well as opening the door to a range of hybrid policies. The goal is to create a single, elegant framework for modelling optimisation problems under uncertainty, and a general tool box for designing and testing effective policies in both offline (simulated) and online (real world) settings. Every problem class, as well as the solution strategies, will be illustrated using actual applications.

## 11:00-12:30 - Queueing Theory 1 (Suite 2)

# Stochastic Footprints for Infinite-Server Queueing Models

Dave Worthington[1] and Martin Utley[2]

[1] Lancaster University, UK
[2] University College London, UK

Existing theory for infinite-server queues, whether in discrete time or continuous time, uses the idea that customers travel independently through an infinite-server system (which can consist of one or more nodes) to argue that the presence of any previous arrival in any state of interest ($s$) at time $t$ is an independent Bernoulli random variable. This leads to well-known results that for random arrivals the number in state $s$ at time $t$ is Poisson distributed, and for many cases of arrivals in discrete time the distribution of the number in state $s$ at time $t$ is based on convolutions of mixtures of Binomial distributions.

The key concept in these results is that for an individual arrival at time $u$ there is a set of probabilities $\{p_s(u,t) : s \in S, t \geq u\}$, where $S$ are our states of interest. We refer to these probabilities as a 'stochastic footprint', and note that independent arrivals create independent footprints, which in turn ensure the existing results.

However if arrivals are coordinated in some way, e.g. arrivals on different days are dependent, or arrivals of different types on the same day are dependent, then the stochastic footprints of individuals will no longer be independent, and the existing results do not apply. To deal with this issue we extend the stochastic footprint concept to groups of arrivals, which can be dependent within groups, as long as the groups are independent.

This talk will elaborate on these initial ideas, as well as asking the question as to whether there is already a theory of stochastic footprints that we ought to be aware of.

# The Call-Back Option in the ”Sensitive” Markovian Queueing System

Baris Balcioglu[1] and Odysseas Kanavetas[2]

[1] Sabanci University, Turkey
[2] Koç University, Turkey

We study a multi-server system with two queues: the phone line and the call-back queue. Customers place calls according to a Poisson process with state-dependent rates. Moreover, the rates of the exponential service times and times-to-abandonment of the queued customers can also change whenever the system size, namely the number of customers being served or waiting to be served in the phone line, changes. Customers finding all servers busy or those waiting in the phone line whose patience expires may request to be called back. The rate of customers choosing the call-back option can also vary with the system size. Since the rates of the underlying exponential random variables can change with the change in system size, we refer to the analysed system as the ”sensitive” Markovian queue. In this system, when the number of customers in the call-back queue surpasses a threshold, the next customer to serve is the longest waiting customer in the call-back queue. When the number of busy servers falls to a specified value, remaining call-back customers are served as well. We conduct an exact analysis of this system and obtain its steady-state performance measures. The steady-state system size distribution of the phone line and the queue length distribution in the call-back queue are obtained via a birth-death process. The times spent in the phone line by a customer is represented as the time until absorption in a continuous-time Markov chain and follows a Phase-type distribution with which the queueing time distribution and its moments are obtained. We also explore if this model can be employed to approximately estimate the performance measures if service times and customer patience times follow general distributions.

# On the Price of Anarchy in a Single-Server Queue with Heterogeneous Service Valuations Induced by Travel Costs

Irit Nowik[1], Refael Hassin[2] and Yair Shaki[1]

[1] Lev Academic Center (JCT), Israel
[2] Tel Aviv University, Israel

This work presents a strategic observable model where customer heterogeneity is induced by the customers' locations and travel costs. The arrival of customers with distances less than $x$ is assumed to be Poisson with rate equal to the integral from 0 to $x$, of a non-negative intensity function $h$. In a loss system M/G/1/1 we define the threshold Nash equilibrium strategy $x_e$ and the socially-optimal threshold strategy $x^*$. We investigate the dependence of the price of anarchy (PoA) on the parameter $x_e$ and the intensity function. For example, if the potential arrival rate is bounded then PoA is bounded and converges to 1 when $x_e$ goes to infinity. On the other hand, if the potential arrival rate is unbounded, we prove that $x^*/x_e$ always goes to 0, when $x_e$ goes to infinity and yet, in some cases PoA is bounded and even converges to 1; if $h$ converges to a positive constant then PoA converges to 2; if $h$ increases then the limit of PoA is at least 2, whereas if $h$ decreases then PoA is bounded and the limit of PoA is at most 2. In a system with a queue we prove that PoA may be unbounded already in the simplest case of uniform arrival.

# Does the Future Matter? Optimisation of Time-Dependent Service Systems

Jannik Vogel and Raik Stolletz

University of Mannheim, Germany

A service provider of complex services can adjust the time spent with a customer due to subjective completion criteria. Physicians for example can increase the rate of serving patients by reducing the time spent with questioning the patient or by refraining from additional tests. Working at a high service rate decreases the quality provided to the customers but reduces the congestion in the service system. Furthermore, many service systems are faced by time-dependent demand changes.

Even though the trade-off between quality and speed has been extensively studied in the literature, no publication considers time-dependent demand. We present models to optimise time-dependent service rates based on forecasted demand patterns that minimise quality costs and waiting costs. An integrated optimisation model is developed that approximates the time-dependent performance with a deterministic fluid approach or a stochastic stationary-backlog carryover (SBC) approach.

We present analytical and numerical results for the optimal service rate under stationary and time-dependent assumptions. Insight on the anticipation of demand changes in deterministic and stochastic systems are presented.

## 11:00-12:30 - Finance and Risk (Suite 3)

# Dynamic Cash Management Models with Loan Opportunities

Zimian Zhang and Christopher Kirkbride

Lancaster University, UK

Classical cash management models concern how an organisation should maintain their (liquid) cash balances in order to meet cash demands over time. In these models the balance can be increased or decreased to offset penalties for not being able to meet a cash demand or the opportunity cost of holding too much cash, respectively. The external source from which this money comes from or is sent to is not explicitly modelled but is assumed to be available at all times. In our work we seek to contribute to this problem by explicitly modelling this external source by the inclusion of a second asset. This asset will generate an income which we allow to be either deposited directly to the cash account or contributes to the asset account's volume. We model this version of the cash management problem, in which credits and debits from/to the cash balance are to/from the asset account and incur transaction costs for these movements, as a Markov decision process. The optimal policy is shown to be of a dynamic threshold type that extends the classical (L,l,u,U) type polices to this setting. The impact of the parameter settings on the optimal policy are studied in a large numerical study. We also extend this model to include the opportunity for the organisation to take out a loan to supplement their cash balance. The decision of whether to take out a loan or not makes the solution of this extended cash management problem computationally expensive. We propose a novel heuristic for the cash management with loans problem based on one-step policy improvement which is shown to perform strongly in our experiments.

# Data-Driven Consumer Debt Collection via Machine Learning and Approximate Dynamic Programming

Ruben van de Geer[1], Qingchen Wang[2] and Sandjai Bhulai[1]

[1] Vrije Universiteit Amsterdam, Netherlands
[2] University of Amsterdam, Netherlands

In this work a framework is presented that allows for data-driven optimisation of the scheduling of outbound calls made by debt collectors. More precisely, this paper considers the problem of deciding throughout time which debtors to call next, provided that the debt collector is constrained in the number of phone calls that its agents can make. We approach this problem by formulating a Markov Decision Process and, given its intractability, approximate the value function based on historical data through the use of state-of-the-art machine learning techniques. Specifically, we predict the likelihood with which a debtor in a particular state is going to settle the debt and use this as a proxy for the value function, allowing us to optimise the schedule by marginalising the value of making additional phone calls to a particular debtor. In doing so, the framework schedules phone calls based on all available relevant data that may affect payment behaviour. We find that in a holdout sample our machine learning technique achieves 0.689 AUC for repayment predictions, and that following the optimal policy prescribed by our framework could potentially lead to a ten-fold improvement in marginal gain per outbound call as compared to the incumbent policy. The improvement comes mostly from selecting debtors that have been in the collection process longer, have not been contacted recently, and have previously answered calls or contacted the debt collector themselves. Preliminary results from a controlled field experiment will be presented.

# Optimal Investment and Deferred Annuity Choice with Inflation and Labour Income Risks

Andrew Clare, Chul Jang and Iqbal Owadally

City, University of London, UK

We construct an optimal investment portfolio model with nominal-fixed and inflation-protected deferred annuities for an individual investor saving for retirement. The objective function consists of power utility in terms of secured retirement income from the deferred annuity purchases, as well as bequest from remaining wealth invested in equity, nominal bond, inflation-linked bond, and cash funds. The asset universe is governed by a vector autoregressive model incorporating the Nelson-Siegel term structure. We use multi-stage stochastic programming to solve the optimisation problem numerically with an efficient non-linear solver (MOSEK). Scenario trees are generated by an improved method based on a moment-matching method. Our model focuses on the accumulation phase, rather than the payout phase. Our numerical results show that the availability of deferred annuity purchases changes significantly the portfolio of the investor's saving for retirement. The optimally secured retirement income is increasing smoothly on average. The investment strategy fully utilizes timing and hedging price changes in deferred annuities. They are consistent with previous studies, but also provide novel support for deferred annuities as a major source of retirement income.

# Regress-Later Monte Carlo for Optimal Control of Markov Processes

Alessandro Balata and Jan Palczewski

University of Leeds, UK

We develop two Regression Monte Carlo algorithms (value and performance iteration) to solve general problems of optimal stochastic control of discrete-time Markov processes. We formulate our method within an innovative framework that allow us to prove the speed of convergence of our numerical schemes. We rely on the Regress Later approach unlike other attempts which employ the Regress Now technique. We exploit error bounds obtained in our proofs, along with numerical experiments, to investigate differences between the value and performance iteration approaches. Introduced in Tsitsiklis and VanRoy [2001] and Longstaff and Schwartz [2001] respectively, their characteristics have gone largely unnoticed in the literature; we show however that their differences are paramount in practical solution of stochastic control problems. We also exploit out theoretical bounds to provide some guidelines for the tuning of our algorithms. Finally we present two numerical examples that display the practical implications of remarks and guidelines given throughout the paper: (a) the control of batteries and generating units in a microgrid system and (b) a portfolio liquidation problem in a partially observable financial market.

## 13:30-14:30 - Invited Keynote (Suite 2)

# How Much Detail is Enough? Examining Stochastic Elements in Models to Support Disease Control Policy

**Invited Speaker:** Margaret Brandeau

Stanford University, USA

Many potential public health policies for disease control are evaluated using epidemic models, instantiated using the best available data. Such models attempt to capture, in a stylised way, the complex stochastic interactions of individuals in a population that lead to the spread of communicable diseases. Because of data uncertainty, typical policy studies perform extensive sensitivity analysis on input parameter values. However, structural assumptions in such models, such as the choice of model type and the determination of which stochastic elements to include, might affect model predictions as much as or more than the choice of input parameters. This talk explores the potential implications of structural assumptions on epidemic model predictions and policy conclusions. We present a case study of the effects of a hypothetical HIV vaccine in multiple population subgroups over eight related transmission models, which we sequentially modify to vary over two dimensions: parameter complexity (e.g. the inclusion of age and hepatitis C virus comorbidity) and contact/simulation complexity (e.g. aggregated compartmental vs. individual/disaggregated compartmental vs. network models). We describe the findings of the case study and suggest some guidelines for future model selection. Our qualitative findings are illustrative of broader phenomena and can provide insight for modellers as they consider the appropriate balance of simplicity versus complexity in model structure.

## 14:45-15:50 - Queueing Theory 2 (Suite 2)

# Queueing Models with State-Dependent Parameters: New Results and Applications to Next Generation Communication Networks

Ioannis Dimitriou

University of Patras, Greece

Motivated by design and performance challenges stemming from emerging applications in random-access networks and cloud computing, we focus on the development of novel queueing models with state-dependent parameters. Our work is composed of two parts. In the first part, we focus on slotted-time systems and consider an interference-limited random-access network of two users under a state-dependent transmission policy. Each user has an infinite capacity buffer for storing arriving packets. At the beginning of each slot, each user transmits a packet with a probability that depends on the number of stored packets at both user queues. If both stations transmit at the same slot a collision occurs, and both packets must be retransmitted in a later slot. In such a network of interacting queues, when a user transmits a packet, it causes interference to the nearby user and decreases its rate of communication. Each user is aware of the status of the network, and accordingly reconfigures its transmission parameters to improve the network performance. Generating functions for the steady-state distribution are obtained by solving a finite system of linear equations and a functional equation with the aid of the theory of Riemann-Hilbert boundary value problems. In the second part, we focus on the stationary analysis of the continuous-time join-the-shortest-queue (JSQ) problem with coupled processors. In such model, each processor adapts its service speed according to the state of the other. For this model, we apply three different methods for computing the steady-state joint queue length distribution. First, we show that this distribution is written as an infinite sum of product form solutions, and then, we use the power series method. Finally, the generating function of the stationary joint queue-length distribution is also derived using the theory of boundary value problems. Numerical examples are obtained to provide insights in the systems performance.

# M/G/1 Queue with Event-Dependent Arrival Rates

Benjamin Legros

Ecole Centrale Paris, France

Motivated by experiments on customers' behaviour in service systems, we consider a queueing model with event-dependent arrival rates. Customers' arrival rates depend on the last event which may either be a service departure or an arrival. We derive explicitly the performance measures and analyse the impact of the event-dependency. In particular, we show that this queueing model, in which a service completion generates a higher arrival rate than an arrival, performs better than a system in which customers are insensitive to the last event. Moreover, contrary to the M/G/1 queue, we show that the coefficient of variation of the service does not necessarily deteriorate the system performance. Next, we show that this queueing model may be the result of customer's, strategic behaviour when only the last event is known. Finally, we investigate the historical admission control problem. We show that under certain conditions a deterministic policy with two thresholds may be optimal. This new policy is easy to implement and provides an improvement compared to the classical one-threshold policy.

# An M/M/1/N Queuing Model with Self-Regulatory Servers and Retention of Impatient Customers

Rakesh Kumar

Shri Mata Vaishno Devi University, India

In this paper, we consider a finite capacity single server Markovian queuing system with self-regulatory servers and retention of reneging customers. The transient as well as steady-state analyses of the model are performed. It has been observed that the self-regulatory queuing system performs better than the one without self-regulatory servers.

## 14:45-15:50 - Logistics and Transportation 1 (Suite 3)

# The Benefits of Preprocessing the Stochastic Container Relocation Problem

Bernard Zweers[1], Sandjai Bhulai[2] and Rob van der Mei[1]

[1] Centrum Wiskunde en Informatica (CWI), Netherlands
[2] Vrije Universiteit Amsterdam, Netherlands

At a container terminal, containers are stacked on top of each other in multiple stacks. When a container needs to be retrieved and it has other containers on top of it, this blocking container should be replaced. We need to decide to which stack the blocking container should be relocated. This relocation move is a useless move. Thus, the number of relocation moves should be minimised.

In this so-called container relocation problem, the exact order in which the containers are retrieved is known. This assumption is relaxed in the stochastic container relocation problem. In the stochastic container relocation problem, it is only known that a certain batch of containers is retrieved before another batch. Inside a batch, the retrieval order of containers is assumed to be a uniform permutation. When a truck arrives to pick up a container, only then we get the information which container should be retrieved.

We extend the stochastic container problem by looking at preprocessing the containers. In this new problem, when the crane is idle it could do some preprocessing moves in order to reduce the expected number of relocation moves. These preprocessing moves are less harmful to the terminal operations than the relocation moves as there is no truck waiting and the crane is not doing anything otherwise. However, we still need to make a trade-off between the number of preprocessing and relocation moves.

We study two different situations, one in which the number of possible preprocessing steps is known beforehand and one in which it is uncertain. Besides the expected number of relocation moves, we also look at the worst-case number of relocation moves. As for the stochastic relocation problem, optimal solutions can only be calculated for small instances, we solve this extended problem using a new developed local search heuristic.

# Heterogeneous Strategic Customers in a Transportation Station

Athanasia Manou, Pelin Canbolat and Fikri Karaesmen

Koç University, Turkey

We consider a transportation station, where customers arrive according to Poisson process. A transportation facility with unlimited capacity visits the station according to a renewal process and serves all present customers at each visit. We assume that the arriving customers decide strategically to use the transportation facility or not. A customer who chooses to use the facility earns a reward upon service completion, pays a service fee, and incurs a waiting cost. Customers are heterogeneous in their sensitivity in delays and reward from service. The strategic choice is modelled as a game among the customers. We study this game under different levels of information provided to the customers upon arrival. We obtain the equilibrium customer behaviour and the utilities of the customers and the administrator of the system under equilibrium. We explore the effects of pricing policies by the administrator and finally, we look into the effect of heterogeneity on customer behaviour and the utilities of the customers and the administrator.

# ADP Strategies for Resource Allocation at Congested Airports

Rob Shone, Kevin Glazebrook and Konstantinos Zografos

Lancaster University, UK

In modern transportation systems there exists a need to develop fast, responsive and easily adaptable methods for computing optimal (or near-optimal) solutions to problems in which resources must be allocated dynamically in order to satisfy time-varying demands from multiple sources. In this talk we consider the case of a single airport which, in response to a pre-determined schedule of arrivals and departures, must use its runway capacity efficiently in order to minimise an objective function based on weighted second moments of aircraft queue lengths.

In keeping with a well-established convention in the literature, we model departures and arrivals as independent stochastic queues with time-varying arrival and service rates. Service times are assumed to follow Erlang distributions, whereas for the arrival distributions we consider two possible cases: non-homogeneous Poisson processes and pre-scheduled arrivals with random deviations. We discuss how to formulate the problem of optimising airport capacity usage as a Markov decision process (MDP), and introduce a "surrogate problem" which closely resembles our original problem during periods of heavy demand. We then show that, in our surrogate problem, the MDP value function can be represented as a quadratic function of the state variables, and use this principle to develop ADP strategies for optimising capacity utilisation.

## 16:20-17:50 - Queueing Theory 3 (Suite 2)

### Discrete-Time Queues with Disasters

Mustafa Demircioglu, Herwig Bruneel and Sabine Wittevrongel

Ghent University, Belgium

We study the behaviour of a discrete-time queueing system in the presence of disasters. Upon occurrence of such a disaster, all the customers in the system are removed at once, so the system becomes empty instantaneously. The concept of a disaster can be used for instance to model a virus infection or a server reset in a computer or communication system, destroying all the jobs or information present in the system. Disasters are also referred to as catastrophes, queue flushing, stochastic clearing or mass exodus in the literature. In our work, we extend the literature on discrete-time queues with disasters to the case of a queueing model with both general independent arrivals and general independent service times. More specifically, the numbers of customer arrivals in the system during different slots have a general distribution and are independent from slot to slot. The customer service times have a general distribution and are independent from customer to customer. Disasters are assumed to occur independently from slot to slot according to a Bernoulli arrival process. In our analysis, we make use of the supplementary random variable technique and introduce a suitable two-dimensional Markovian state description. As results, expressions are obtained for the probability generating functions of both the system content at the beginning of a slot and the sojourn time of an arbitrary customer in steady state, as well as for the mean values and variances of these quantities. By means of numerical examples we illustrate the impact of several model parameters, such as the disaster probability or the customer arrival characteristics, on the queueing behaviour.

# A Novel Way of Treating the Finite-Buffer Queue GI/M/c/N Using Roots

James Kim[1] and Mohan Chaudhry[2]

[1] Royal Canadian Air Force, Canada
[2] Royal Military College of Canada, Canada

We present a new way of solving the model GI/M/c/N using roots. By deriving and then solving the model's characteristic equation we are able to achieve this. The roots of the characteristic equation are quickly found and the solution is computed efficiently since it is entirely in terms of roots. The method presented embarks on the first application of the roots method in the finite-buffer multi-server queues and it remains robust even if the inter-arrival times follow heavy-tailed distributions. Some numerical results are provided.

# Structural Properties of Time-Dependent Flow Production Systems

Justus Arne Schwarz and Raik Stolletz

University of Mannheim, Germany

Flow lines process workpieces sequentially on multiple stations. The processing times are often stochastic, hence buffers are installed to decouple the stations. For these systems, structural properties characterise the relationship between design variables such as buffer capacities and the performance measures expected throughput and expected work in process inventory. The identification of structural properties is important because of their algorithmic consequences for flow line design approaches. We review structural properties of flow lines with constant processing rates that have been proven or are numerically observed under steady-state conditions. Moreover, new monotonicity results for systems with time-dependent processing rates are introduced. These properties are based on sample-path arguments for the case of exponentially distributed processing times and supported by numerical evidence for general distributions.

# Queueing and Markov Chain Decomposition Approach for Perishability Models: The (S,s) Control Policy with Lead Time

Yonit Barron[1] and Opher Baron[2]

[1] Ariel University, Israel
[2] Toronto University, Canada

We consider cost minimisation for an (S,s) continuous-review perishable inventory system with random lead times and times to perishability, and a state-dependent Poisson demand. We derive the stationary distributions for the inventory level using the Queueing and Markov Chain Decomposition (QMCD) methodology. Applying QMCD, we develop an intuitive approach to characterising the distribution of the residual time for the next event in different states of the system. We provide comprehensive analysis of two main models. The first model assumes a general random lifetime and an exponential distributed lead time. The second model assumes an exponential distributed lifetime and a general lead time. Each model is analysed under both backordering and lost sales assumptions. We consider a fixed cost for each order, a purchase cost, a holding cost, a cost for perished items, and a penalty cost in the case of shortage. We also derive the models' characteristics by using an analytic approach based on the supplementary variables method. Numerical examples are provided and show that variability of lead time is more costly than that of perishability time. Therefore, after reducing lead time and increasing perishability time, managers should focus on reducing variability of lead time.

## 16:20-17:50 - Game Theory and Behaviour Theory (Suite 3)

# An Appointment Game with Unobservable Schedules

Dieter Fiems, Matthias Deceuninck and Stijn De Vuyst

Ghent University, Belgium

Motivated by patient scheduling in health care, we consider a service provider which serves customers on appointment. A typical application would be a doctor's practice in which patients call in to make an appointment. To receive service, customers make the appointment in advance, and then come to the provider at their designated time. The present setting assumes that customers have some freedom in selecting the appointment block in which they will get service, but they cannot choose their appointment time within the appointed block. The consecutive slots within each block are allocated in the order in which the customers make their appointments. We study the trade-off between waiting for an appointment and waiting at the appointed time. Making the assumption that being scheduled later in a consultation block implies one has to wait longer on average for service, it may be beneficial to choose a consultation block further away in the future. We study the trade-off when (i) new appointments are made in accordance with a Poisson arrival process, (ii) the customer service times (consultation times) are independent and identically distributed random variables, and (iii) the customers have no information on how many customers are already scheduled in future consultation blocks. We compare the rational choice with the socially optimal schedule by some numerical examples.

# Stochastic Scheduling of Vessels' Arrivals at Ports to Reduce Emissions in Maritime Shipping

Afshin Mansouri[1] and Özlem Ergun[2]

[1] Brunel University, UK
[2] Northeastern University, USA

Maritime shipping is responsible for about 2.2% of the global greenhouse gas emissions. Given the cubic relationship between a vessel's speed and her fuel consumption, slow steaming has been adopted as a business norm by shipping companies. This practice is violated in many cases by vessels to make up for delays and to avoid penalties imposed by contractual agreements with customers. This problem is exacerbated at ports with uncertain service times that admit vessels using the first-come-first-served (FCFS) discipline. Although fuel consumption is one of the main operational costs of shipping companies, they consider in their speeding decisions the total costs including waiting costs at ports and delay penalties in addition to the fuel costs.

In this paper, we provide a modelling approach for the optimal arrival of vessels to a port to minimise their social welfare which requires a central planner. The social welfare consists of three components: (i) sailing cost (a function of vessels' speeds), (ii) waiting cost (mostly the energy consumption for electricity generation whilst waiting in the queue), and (iii) delay penalties. In doing so, we model the optimal arrival of vessels at ports as a dynamic stochastic single-machine scheduling problem with earliness-tardiness penalties in which port service times are stochastic. The first two components constitute the earliness cost whilst the last element is the tardiness cost. We provide initial results for problems with two vessels that constitute the majority of instances of competitions between vessels for port slots. We also discuss future steps for analysing the competition between the vessels in a decentralised system as a game. Comparing the Nash equilibrium of the game with socially optimal solution will determine the room for reducing fuel emission through collaboration between the shipping companies and/or command-and-control mechanisms such as emission tax, speed charges, and speed control zones.

# Group Purchasing with Demand and Technology Level Uncertainty

Philippe Chevalier[1], Gilles Merckx[2], Wenli Peng[1] and Aadhaar Chaturvedi[2]

[1] Université catholique de Louvain, Belgium
[2] University of Namur, Belgium

While group purchasing across rival OEMs enables these to obtain rebates from the supplier, it also requires regular interactions between the OEMs, which often result in private information leakage. In industries where both the market demand and the product technology are uncertain from period to period, the OEMs might prefer individual purchasing to conceal their private information about those types of uncertainty. This paper investigates how this information sharing dimension affects OEMs' motivations towards group purchasing, specifically in industries characterised by market demand and technology level uncertainties. Under Cournot competition, we find that, if product technology strongly affects market shares, group purchasing is always preferred, whereas for a lower influence of the product technology, group purchasing can be preferred depending on product substitutability, market demand variability and supplier rebate. We further obtain that group purchasing can benefit simultaneously both the OEMs and the consumers.

# Self, Social and Monopoly Optimisation in Observable Queues

Ran Snitkovsky and Refael Hassin

Tel Aviv University, Israel

Naor's (1969) celebrated paper studies customer decisions in an observable M/M/1 queue where the expected utility of a customer who joins the queue is a decreasing linear function of the joining position in the queue. Naor derives the optimal threshold strategies for the individuals, social planner and monopoly, and proves that the optimal threshold imposed by a monopoly is not greater than the socially optimal threshold, which is not greater than the individually optimal threshold. Studies show that this triangular relation holds in different set-ups where the arrival rate is not necessarily Poisson, or when the utility decreases not linearly but concavely. We point out these common features that imply the aforementioned result in Naor's model and its extensions. We suggest several model applications for our findings. In one of these models customers choose join or balk where the possibility of exogenous abandonment determines their utility function, and this function is convex in the observed queue length. We further show how our formulation in the general set-up gives strictly stronger results than these currently appearing in the literature, and, we give a simple example where the inequality does not hold

# Thursday 14th June

## 9:00-10:30 - Resource Allocation (Suite 2)

### Front-Office Multitasking Between Service Encounters and Back-Office Tasks

Oualid Jouini[1], Benjamin Legros[2], Zeynep Aksin[3] and Ger Koole[4]

[1] CentraleSupelec, France
[2] Ecole de Management de Normandie, France
[3] Koç University, Turkey
[4] Vrije Universiteit Amsterdam, Netherlands

We model the work of a front-line service worker, who interacts with customers in a multi-stage process. Some stages of this service encounter require an interaction between server and customer, while other stages are performed by the customer as a self service task or with the help of another resource. In addition to customer interactions, the server needs to deal with back-office tasks, or tasks that do not require interaction with the customer. The latter tasks are of lower priority. The server's work is represented by a queue with high priority tasks, and an infinitely backlogged amount of low priority tasks. The server needs a switching time when switching between the two types of tasks. The server can treat back-office tasks during the interludes of a service encounter or between successive encounters. The objective is to maximise the expected proportion of time spent on low priority tasks subject to a constraint on the high priority task waiting time. Hence, a good trade-off has to be found between two conflicting performance measures in a context where switching times may discourage frequent changes. Under certain parameter values, working on the back-office tasks during interludes is shown to be valuable. We find that switching times between tasks are best controlled by a queue length dependent threshold type policy during breaks, and by a static service probability during interludes.

# When to Switch? An Index Policy Approach to Resource Scheduling in Emergency Response

Dong Li[1], Li Ding[2] and Stephen Connor[3]

[1] Loughborough University, UK
[2] Durham University, UK
[3] York University, UK

This paper considers the scheduling of limited resources to a large number of jobs (e.g., medical treatment) with uncertain lifetimes and service times, in the aftermath of a mass casualty incident. Jobs are subject to triage at time zero, and placed into a number of classes. Our goal is to maximise the expected number of job completions. We propose an effective yet simple index policy based on Whittle's restless bandits approach. The problem concerned features a finite and uncertain time horizon that is dependent upon the service policy, which also determines the decision epochs. To the best of our knowledge, this is the first application of Whittle's index policies to such problems. Two versions of Lagrangian relaxation have been proposed to decompose the problem. The first one is a direct extension of the standard Whittle's restless bandits approach; while in the second one the total number of job classes still competing for service is taken into account. We show that the latter generalises the former. We prove the indexability of all job classes in the Markovian case, and develop closed-form indices. Extensive numerical experiments show that the second proposal has much stronger and more consistent performance over the first one and the other heuristics in the literature, even in the non-Markovian settings.

# Dynamic Resource Allocation for a Project with Uncertain Progress

Riccardo Mogre[1] and Luca Bertazzi[2]

[1] Durham University, UK
[2] University of Brescia, Italy

A manager is in charge of a project with clearly defined tasks, some sequential and others parallel, all required to finish the project. The project progress is random because of disruptions and productivity problems. At each time, the manager reviews the project progress and decides the resource allocation for each task. More resources allocated correspond to higher cost and higher expected progress. Her problem is to identify resource allocation policies to minimise her expected cost, given by two types of costs in trade-off with each other: 1) the cost of the resources used and 2) a penalty cost that depends on the project completion time.

Previous literature mostly consider static resource allocation in the planning phase of projects. We contribute to the literature on dynamic resource allocation in both the planning and execution phases of projects, which is limited because of the complexity of such optimisation problem.

In our research, we formulate this problem using infinite-horizon stochastic dynamic programming. The state enumeration for the problem is far from trivial. For this reason, we devise an algorithm to identify all the states of the problem. Researchers commonly employ value iteration, policy iteration and linear programming to solve infinite-horizon dynamic programming problems. However, the complexity of this problem makes the use of traditional infinite-horizon dynamic programming algorithms impractical or impossible. For this reason, we devise a computationally efficient algorithm to solve this problem. We complement our analytical results with a computational study that shows the optimal cost-to-go and corresponding policy not only for various parameters, but also for various networks.

# Efficient Rollout Algorithms for the Pharmaceutical R&D Pipeline Scheduling Problem

Xin Fei, Juergen Branke and Nalan Gulpinar

University of Warwick, UK

In this paper, we consider a pharmaceutical R&D pipeline scheduling problem with resource-dependent activity durations and uncertain activity outcomes formulated as a Markov decision process. As the underlying optimisation model is "weakly coupled" (i.e. several drug developments are only linked by resources constraints), we utilise this structural property to develop an optimistic scheduling policy that maximises the total expected net present value. We then employ this policy as a default policy in the rollout algorithm to approximate the downstream value function. Moreover, we tailor the rollout algorithm by developing several selection heuristics that determine potentially promising actions for Monte Carlo estimation. In addition, we implement a multi-armed bandit strategy to balance exploration and exploitation while selecting the best solution among a set of promising ones. The preliminary computational results show that the proposed extensions are able to obtain competitive solutions in reasonable computational time.

## 9:00-10:30 - Logistics and Transportation 2 (Suite 3)

# Generalised Gap Acceptance Models for Unsignalised Intersections

Abhishek Abhishek[1], Michel Mandjes[1] and Marko Boon[2]

[1] University of Amsterdam, Netherlands
[2] Eindhoven University of Technology, Netherlands

In this talk, we discuss the modelling and analysis of unsignalised intersections. In classical gap acceptance models, vehicles on the minor road accept any gap greater than the critical gap, and reject gaps below this threshold, where the gap is the time between two subsequent vehicles on the major road. The main focus of the talk is to present a series of generalisations of existing models, thus increasing the model's practical applicability significantly. First, we incorporate driver impatience behaviour while allowing for a realistic merging behaviour; we do so by distinguishing between the critical gap and the merging time, thus allowing multiple vehicles to use a sufficiently large gap. Incorporating this feature is particularly challenging in models with driver impatience. Secondly, we allow for multiple classes of gap acceptance behaviour, enabling us to distinguish between different driver types and/or different vehicle types. Thirdly, we use a queueing model in which vehicles arriving in an empty queue on the minor road have a different service-time distribution than the queueing vehicles (where 'service time' refers to the time required to find a sufficiently large gap). This set-up facilitates the analysis of the service-time distribution of an arbitrary vehicle on the minor road and of the queue length on the minor road. In particular, we can compute the mean service time, thus enabling the evaluation of the capacity for the minor road vehicles.

# Predicting Bicycle Parking Behaviour using a Discrete Modelling Approach

Jullian van Kampen[1], Rob van der Mei[1] and Elenna Dugundji[2]

[1] Centrum Wiskunde en Informatica (CWI), Netherlands
[2] Vrije Universiteit Amsterdam, Netherlands

In urban cities people often use a bicycle to travel towards their destination. A bicycle has several advantages over public transport or a car including, low costs, choice of departure/arrival time, and choice of parking. Especially this last advantage is important in Amsterdam, since demand for indoor parking facilities exceeds the capacity. This makes it hard to estimate demand for these parking facilities, and forces people to park their bicycle outdoor in a rack. Consequently, outdoor parking facilities increases which results in capacity not meeting demand for the outdoor parking facilities. Result is that instead of searching for a legal parking spot people choose to park their bicycle illegally. Illegally parked bicycles are removed and stored at the bike depot where the owner can recollect their bicycle for a fee.

To prevent illegal bicycle parking several parking policies have been introduced. Examples of these parking policies range from restricting parking duration, increasing parking regulations and increasing parking capacity. However, it remains unknown at which locations these policies should be applied and at what location the demand for parking facilities are the highest. In this paper an attempt is made to predict the parking demand of on-street parking in Amsterdam. Data of on-street parking was made available about the capacity, utilisation and environmental characteristics. Based on this data a prediction is made concerning the utilisation of these facilities and whether more should be installed. With the aid of a discrete modelling approach, an attempt is made to predict bicycle parking behaviour. With these insights an impression is gained about the bicycle parking demand in Amsterdam, and where we should improve parking facilities.

# Dynamic Vehicle Routing Problem with New York City Taxi Data

Jacky Li and Sandjai Bhulai

Vrije Universiteit Amsterdam, Netherlands

This paper develops a model to determine the optimal number of taxis in the city by examining the trade-off between the overall profitability for the taxi service versus the customer satisfaction. We provide a data analytic investigation of taxi trips in New York City. We model the taxi service strategy by a fleet management model that can handle random arrivals and deterministic travel times. Under this model, we examine the number of taxis in a particular period of time and measure the maximum profit in the overall system and the minimum number of rejected customer requests. We observe that the maximum profit of the overall system can be approximately 12% higher than the historical data in different time periods during the day. These data may have important implications in the field of self-driving vehicles.

# Early Detection of Highway Congestion from Probe Car Data

Emiliano Heyns

Vrije Universiteit Amsterdam, Netherlands

Highway congestion is an increasingly pressing societal problem, both in terms of cost (many productive hours lost) and safety (highway congestion increases the risk of accidents). While there is a plethora of research on detecting and predicting traffic flow state from floating car data from data generators such as in-car navigation systems, little research has been done on how more detailed vehicle-generated data such as available on the vehicle CAN-bus (breaking, steering, etc.) could be translated into earlier or better quantification of the traffic flow state. The hypothesis underlying my research is that the the data generated by participating cars can be modelled as a complex system of which the spatio-temporal complexity can be quantified; that a rise in the spatio-temporal complexity could be an early indicator of perturbed traffic flow; and that the aggregate patterns of multiple participating cars on a given road segment could in turn be modelled as such a system where the rise in spatio-temporal complexity is a good measure of the congestion-proneness of the traffic condition. This information could be fused with historical data on congestion probabilities to provide better congestion prediction with applications towards cooperative (cooperative adaptive speed control) or externally managed (variable message signs) traffic management strategies.

## 11:00-12:30 - Heuristics (Suite 2)

# Efficient Employment of Adaptive Sensors

Enver Yucesan[1], Roberto Szechtman[2] and Moshe Kress[2]

[1] INSEAD, France
[2] Naval Postgraduate School, USA

We consider a sensor which is subject to false-positive and false-negative errors. The sensor searches for objects of interest such as ship wrecks or survival craft. The objects are located in a certain area of interest, which is divided into area-cells. The area-cells are defined such that each one of them may contain at most one object. The task of the sensor is to determine whether an area-cell contains an object, and the objective of the searcher is to maximise the number of correctly determined area-cells. Since definitive identification of an object and subsequent handling of that object are done by a limited number of available resources, the correct determination of an area-cell is crucial for better allocating and directing these scarce resources. We develop an algorithm, rooted in the theory of large deviations and stochastic approximation theory, that provably leads to the optimal allocation of search effort (i.e. allocation that maximises the expected number of correctly determined area-cells) as the search budget becomes large.

# Heuristics for Call-Centre-Based Scheduling of Field Visits

Yanlu Zhao and Felix Papier

ESSEC Business School, France

Motivated by the sales-force-operations of a B2B services company in Belgium, we develop a model for scheduling customer appointments for a team of sales agents. The appointments are made by an outbound call centre and are subject to uncertain customer approval. The objective of the model is to maximise the number of sales appointments per agent by minimising the travel and idle times between appointments. We formulate the model as a Markov Decision Process, show the existence of an optimal policy, develop an upper bound on the optimal performance, and analytically derive sensitivity properties with regard to several design parameters such as the length of the planning horizon, the capacity of the call centre, and the size of the client database. Since the problem is too complex to be solved optimally, even for small instances, we develop a simple heuristic policy which dynamically decides which clients to call and which time slots to propose to each client. We perform numerical experiments based on a real data set to show that the optimality gap is small and to derive further managerial insights. We find that the appointment scheduling policy is an effective mean to achieve a trade-off between sales force effectiveness, efficiency, and reactivity that best fits the company's sales operations strategy.

# Dynamic Allocation of Assets Subject to Failure and Replenishment

Stephen Ford, Kevin Glazebrook and Peter Jacko

Lancaster University, UK

Allocation of assets to tasks is a common real-life problem, and a much-studied one. However, the simple expedient of allowing the assets to fail and require repair renders simple allocation problems difficult, and more complex problems nearly unsolvable.

The problem discussed arose from naval search problems, with the 'assets' being drones and the 'tasks' being search areas. Our problem falls within the broad area of routing and scheduling, and as formulated in this talk, is in many ways a prototypical stochastic optimisation problem.

We formulate an approximative open-system model (with assets arriving at some constant rate) for this problem in a restless bandit framework and derive the corresponding Whittle index policy. In addition to proving indexability (an important technical condition), we also present two informative formulae for the Whittle indices.

Extensive numerical simulations of the original problem indicate that two policies are effective: the Whittle index policy obtained from the approximate model, and a simple 'myopic' or 'greedy' policy. In circumstances where there are many assets relative to the number of the tasks, or where failure rates are the same across all tasks, the greedy policy performs best. For more difficult cases, especially when the failure-rates and reward-rates are correlated, the Whittle index policy performs best.

We also briefly look at possible extensions, particularly those with the tasks 'linked' in some way, so that the rewards gained depend on the overall state of the system, not merely on the assets assigned to each task.

# A New Method for Obtaining Closed-Form Approximations for Threshold-Based Optimal Policies for Markov Decision Processes using Symbolic Regression

Rob van der Mei[1], Asparuh Hristov[1], Joost Bosman[1] and Sandjai Bhulai[2]

[1] Centrum Wiskunde en Informatica (CWI), Netherlands
[2] Vrije Universiteit Amsterdam, Netherlands

In this talk, we introduce a novel approach in optimising the control of systems that can be modelled as Markov decision processes (MDPs) with a threshold-based optimal policy. Our method is based on a specific type of genetic program known as symbolic regression (SR). We present how the performance of this program can be greatly improved by taking into account the corresponding MDP framework in which we apply it.

The proposed method has two main advantages: (1) it results in near-optimal decision policies, and (2) in contrast to other algorithms, it generates closed-form approximations. Obtaining an exact expression for the decision policy gives the opportunity to conduct sensitivity analysis, and allows instant calculation of a new threshold function for any change in the parameters. We emphasise that the introduced technique is highly generic and applicable to any MDP that has a threshold-based policy. Extensive numerical experimentation demonstrates the usefulness of the method.

## 11:00-12:30 - Inventory Management (Suite 3)

# Optimal Battery Charging in Smart Grids with Price Forecasts

Sven van der Kooij[1], Pia Kempker[2], Hans van den Berg[2] and Sandjai Bhulai[1]

[1] Vrije Universiteit Amsterdam, Netherlands
[2] TNO, Netherlands

We consider a residential cluster in which some of the households own home batteries. The battery owners have forecasts of future prices for optimally utilising the long-term flexibility of the battery. These forecasts become increasingly uncertain the further we look into the future.

The home batteries are individually too small to influence prices; collectively, however, they have enough capacity to have an influence. We study three possible scenarios: (i) Each household controls its own battery to maximise its own profits; (ii) The battery owners coordinate their strategies to maximise the collective battery profits; (iii) The battery owners coordinate their strategies to maximise the overall cluster profits. For (i) we formulate an algorithm for a single price taker battery based on Stochastic Dynamic Programming. Through simulation with realistic data, we find that this solution performs well for one isolated home battery and remains stable when used by every battery in the cluster. Additionally, we formulate an algorithm based on Stochastic Dynamic Programming for scenarios (ii) and (iii). Using simulation with realistic data, we find that scenarios (ii) and (iii) outperform scenario (i) and that from a cluster perspective, scenario (iii) is more beneficial than scenario (ii). We conclude that incentives have to be put in place to promote the right use of storage in the future grid.

# Dynamic Location-Inventory Optimisation for Inland Container Fleet Management with Uncertain Demand

Mehdi Amiri-Aref[1], Jingxin Dong[2] and Kamran Sarmadi[2]

[1] Kedge Business School, France
[2] Newcastle University, UK

This paper tackles an inland container distribution network design problem, which is characterised by a set of potential depot locations and multi-period decisions for transporting empty and laden containers over the planning horizon, while demand at customer locations is uncertain. This paper is motivated by developing the seminal work of Crainic et al. (1993), in which the operational decisions had been optimised in a two-stage stochastic programming model. Amiri-Aref et al. (2018) has shown that strategic decisions have a significant impact on the tactical decisions and that the hierarchical structure between these decisions has to be taken into account when modelling a distribution network problem.

# Adaptive Ordering Policies for Two Products with Demand Substitution

Apostolos Burnetas[1] and Odysseas Kanavetas[2]

[1] National and Kapodistrian University of Athens
[2] Koç University, Turkey

We consider the problem of ordering for two products with stochastic demand and partial demand substitution. Successive demands arrive according to independent Poisson processes, thus the timing of arrivals affects the ending inventory and/or shortages. We consider the case of unknown arrival rates and substitution probabilities. The problem of parameter estimation in this context is not straightforward. Indeed, if, for example, only sales and not actual demand is observed and at the end of a period one of the two products is out of stock, this may be due to a high demand rate of this product or alternatively of a high demand rate and a high substitution probability of the other product or both. We propose an efficient estimation method combined with adaptive ordering policies to minimise the average cost over a large horizon.

# On the Hardness of Inventory Management with Censored Demand Data

Gabor Lugosi, Mihalis Markakis and Gergely Neu

Universitat Pompeu Fabra, Spain

We consider a repeated newsvendor problem where the inventory manager has no prior information about the demand, and can access only censored/sales data. In analogy to multi-armed bandit problems, the manager needs to simultaneously "explore" and "exploit" with her inventory decisions, in order to minimise the cumulative cost. We make no probabilistic assumptions - importantly, independence or time stationarity - regarding the mechanism that creates the demand sequence. Our goal is to shed light on the hardness of the problem, and to develop policies that perform well with respect to the regret criterion, that is, the difference between the cumulative cost of a policy and that of the best fixed action/static inventory decision in hindsight, uniformly over all feasible demand sequences. We show that a simple randomised policy, termed the Exponentially Weighted Forecaster, combined with a carefully designed cost estimator, achieves optimal scaling of the expected regret (up to logarithmic factors) with respect to all three key primitives: the number of time periods, the number of inventory decisions available, and the demand support. Through this result, we derive an important insight: the benefit from "information stalking" as well as the cost of censoring are both negligible in this dynamic learning problem, at least with respect to the regret criterion. Furthermore, we modify the proposed policy in order to perform well in terms of the tracking regret, that is, using as benchmark the best sequence of inventory decisions that switches a limited number of times. Numerical experiments suggest that the proposed approach outperforms existing ones (that are tailored to, or facilitated by, time stationarity) on non-stationary demand models. Finally, we consider the "combinatorial" version of the repeated newsvendor problem, that is, single-warehouse multi-retailer inventory management of a perishable product. We extend the proposed approach so that, again, it achieves near-optimal performance in terms of the regret.

## 13:30-14:30 - Invited Keynote (Suite 2)

# On Radical Extensions to Multi-armed Bandits and to Notions of Indexation

**Invited Speaker:** Kevin Glazebrook

Lancaster University, UK

It is nearly 50 years since Gittins (and Jones) elucidated solutions to important classes of multi-armed bandit problems (MABs) in the form of index policies. Such policies assign a calibrating index function to each option available at each decision stage and choose the option with maximal current index. There is now a huge literature related to this work and interest in MABs grows apace. The talk will discuss recent work seeking to develop appropriate notions of indexation for radical extensions to MABs. These include

1. General models for the dynamic allocation of a single resource to a set of stochastic projects which are in competition for it. Here indices emerge as measures of the cost effectiveness of increasing the resource available to a project from a given level when in a given state;
2. Models for optimal search in which an object is hidden in one of several locations according to a known probability distribution and the goal is to discover the object in minimum expected time by successive searches of individual locations. The work extends a classical result of Blackwell by allowing two search modes- slow and fast- to look for the object;
3. A model for the effective sourcing of intelligence data when analytical capability is in short supply takes the form of a MAB with finite horizon in which only a small (pre-assigned) number of the bandit rewards observed may be claimed. The goal is to maximise the aggregate expected reward claimed.

In all cases an appropriate indexation emerges from a Lagrangian relaxation of the original problem.

## 14:45-15:50 - Healthcare (Suite 2)

# A Clustered Overflow Configuration of Inpatient Beds in Hospitals

Navid Izady

Cass Business School, UK

The shortage of inpatient beds is a major cause of treatment delays and procedure cancellations in hospitals. It may also lead to patients being admitted to inappropriate wards, resulting in lower quality of care, longer length of stay and higher rate of mortality. Adding new beds is not often feasible due to financial, staffing or space constraints. Instead, we propose a new configuration of beds which we refer to as the clustered overflow configuration. In this configuration patients who are denied admission to their primary wards as a result of beds being fully occupied are admitted to overflow wards, each designated to serve overflows from a certain subset of specialties. We propose an analytical methodology for optimal partitioning and bed allocation in the proposed configuration. Applying our methodology on real data, we show that the proposed configuration could substantially improve the number of patients admitted at the expense of marginal increase in nursing costs

# Admission Control in an Intensive Care Unit with Readmissions

Faruk Akin and E. Lerzan Örmeci

Koç University, Turkey

We consider an Intensive Care Unit (ICU) where we focus on the effects of early discharge decisions and possible readmissions on the hospital bed management. The system may admit, reject or admit an arriving patient by early discharging a current patient in the ICU. Arrivals to the system occur from two sources: 1) first-time patients from the outside population and 2) recurring patients who have previously visited the ICU but seek another admission, i.e. readmission. To represent such a setting, we developed a discrete-time Markov Decision Process (MDP) with the aim of minimising the total expected $\beta$-discounted cost over an infinite horizon. Each discharged patient may join the orbit and cause readmission, where we assume that early discharged patients are more likely to join the orbit than regularly discharged patients. We use event-based dynamic programming to model a framework, which seeks policy implications in the existing problem as well as in similar systems that can be modelled by these operators. Using these operators we investigate the structure of the optimal admission control policy. We propose some heuristic policies and evaluate their performances with respect to the optimal policy, which results from solving the MDP formulation.

# Minimising Bed Occupancy Variance by Scheduling Patients under Uncertainty

Ad Ridder[1], Anne van den Broek d'Obrenan[1], Dennis Roubos[2] and Leen Stougie[3]

[1] Vrije Universiteit Amsterdam, Netherlands
[2] HOTflo, Netherlands
[3] CWI, Netherlands

In this paper we consider the problem of scheduling patients in allocated surgery blocks in a Master Surgical Schedule. Whereas extensive research efforts have been devoted on how to use the available surgery blocks as effectively as possible, little attention has been paid to the effect on the necessary bed capacity in hospital wards. However, for an efficient use of a hospital both types of resources should be taken into account. More specifically, large probabilities of overtime in each surgery block are undesirable and costly, while large fluctuations in the number of used beds requires extra buffer capacity and makes the staff planning more challenging. The stochastic nature of surgery durations and length of stay on a ward hinders the use of classical techniques. Transforming the stochastic problem into a deterministic problem does not result into practically feasible solutions. In this paper we develop a technique to solve the stochastic scheduling problem in order to minimise variation in the necessary bed capacity while guaranteeing a small probability of overtime in surgery blocks, keeping track of desirable surgery waiting list sizes and the number of available beds at wards. We decouple the problem into three stages. First, we solve an ILP. Second and third, simulation and local search techniques are applied to guarantee small probabilities of overtime and to improve upon the ILP solution. Numerical experiments applied to a Dutch hospital show promising results.

## 14:45-15:50 - Networks (Suite 3)

# The Optimisation of Traffic Count Locations in Multi-Modal Networks

Thomas Koch[1], Rob van der Mei[1] and Elenna Dugundji[2]

[1] Centrum Wiskunde en Informatica (CWI), Netherlands
[2] Vrije Universiteit Amsterdam, Netherlands

In this paper we will look at ways to optimise the placement and number of traffic counters used in transportation studies for cars, bicycles and pedestrians. The goal is to strike a balance between using as few as possible traffic counters for economical efficiency and deploying more counters which could collect more data.

By using shortest path algorithms to determine the paths between the centroids of statistical divisions, we derive from origin-destination matrices which traffic is flowing to where. Using centrality measures such as betweenness, we determine the links in the transportation networks that capture the most useful traffic in terms of as much unique traffic as possible.

Secondly we look at ways to implement additional criteria in the selection of locations: those that are permanently covered, locations that were used for previous studies in prior years for which historical analyses can be made, and locations that capture more than one modality for cars, bicycles and pedestrians.

Thirdly we study groups of traffic counters, organised in screen-lines.

# A Load Dependent Queueing Model for Epidemic Disease Control

Maria Rieders, Michael Levy and Patrick Emedom-Nnamdi

University of Pennsylvania, USA

A critical component of preventing the spread of vector borne diseases are door-to-door campaigns by public health officials that implement insecticide application in order to eradicate the vector infestation of households. The success of such campaigns depends on adequate household participation during an active phase as well as on sufficient follow-up during the surveillance phase when newly infested houses or infested houses that had not participated in the active phase will receive treatment. Our research is motivated by an ongoing Chagas disease control campaign in Arequipa, Peru and aims to investigate the operational needs for containing the spread of disease. For this purpose, we have developed a queueing model where the queue consists of all infested houses in a given locality. The model captures the dynamics of the insect population due to current prevalence and to the additional growth of infestation by redispersion, i.e. by the spread of infestation to previously uninfested houses during the wait time for treatment. In addition, houses waiting for treatment are not known but must be identified through a search process by public health workers. Thus, both the arrival rate of houses to the queue as well as the removal rate from the queue may depend on the current level of infestation. We incorporate these dependencies through a load dependent queueing model which allows us to evaluate the likelihood of success of containing the prevalence and the expected benefit of adding resources to the public health teams working in the field. Both modelling and data collection have been done in collaboration with the Chagas Disease Working Group in Arequipa, Peru.

# Direct Transmission Models for Indirectly Transmitted Environmental Pathogens

Lee Benson[123], Ross Davidson[13], Mike Hutchings[1], Andy Hoyle[2], Darren Green[2], Glenn Marion[3]

[1] SRUC, UK
[2] University of Stirling, UK
[3] BioSS, UK

Compartmental epidemiological models are used extensively in human and land-based animal disease systems, with the disease transmission process often characterised as resulting from a series of discrete contacts between individuals – so called 'direct transmission' models. Typically, such models assume the mass-action principle acts across the whole population or within subcomponents. In such models the force of infection on susceptible individuals is proportional to the absolute or relative size of the infectious sub-population. However, in some disease systems, especially those found in aquaculture, the 'environmental pathogen load' can play a significant role in infection spread, e.g. white spot syndrome virus in penaeus monodon (Asian tiger shrimp). In such scenarios proportionality between the force of infection and the number, or proportion, of infectious individuals cannot be assumed to hold, a priori.

However, in practice modelling environmental pathogen load alongside host population disease dynamics is problematic. This is because although disease data on aquaculture systems often records time of death and/or the onset of symptoms of the focal host species, it typically does not include extensive measurement of environmental pathogen load over time. Nevertheless, from these data Bayesian Markov chain Monte Carlo methods (MCMC) can be used to infer direct transmission model parameters plus host latent infection and recovery times and associated 'residuals'. We therefore investigate when direct transmission models are sufficient to capture disease dynamics governed by the environmental pathogen load.

Embedded within an MCMC algorithm, the method of latent residuals is investigated as a means of detecting departures from the direct transmission assumption, including the quantity of data required. Considering a range of scenarios, we identify a subclass of host-pathogen systems in which pathogen population dynamics are sufficiently 'fast' relative to host population dynamics that we are able to model the system without needing to account for the pathogen load.

## 16:20-17:25 - Simulation (Suite 2)

# Using Observed Route Complexity to Validate Choice Sets for Simulations

Luk Knapen[1], Niels Wardenier[2], Thomas Koch[3] and Elenna Dugundji[3]

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[2] Utrecht University, Netherlands
[3] Centrum Wiskunde en Informatica (CWI), Netherlands

Activity-based travel behaviour simulation models are used to predict travel demand for several modes (walk, bike, public transport (PT), car) for a given period of time (usually a single day). Such simulations include stochastic models for activity selection and timing, mode choice, location choice and route choice. The latter are notoriously difficult discrete choice models because the choice set is (1) specific for each individual, (2) specific for each origin-destination (OD) pair, (3) very large and (4) contains many overlapping routes.

Several choice set (CS) generators and choice models are currently in use.

In the choice set generation stage, particular properties of the candidate routes are evaluated and determine whether or not the candidate is kept such as number of speed bumps, the number of left turns at junctions (in right hand driving countries), number of traffic lights, route length, etc. Values for the selection parameters are extracted from prior surveys (recorded routes).

We add the route complexity as a new criterion to select route candidates. For a given path in graph, the route complexity is the minimum number of shortest paths that is required to construct the path. About 290k paths for bikers in the Netherlands have been decomposed and a distribution for the complexity was computed. Roughly 95% of the observed routes have a complexity of less than 10.

A particular Doubly Stochastic CS generator was used to create choice sets for the observed OD pairs. These too were decomposed and it turned out that the distribution was shifted (mean value was nearly twice the one for the observed routes) although the other attributes including length are realistic.

In order to improve the CS the following procedure was used. $N0$ candidates are generated (if possible). Then every combination of $N1 < N0$ of them is considered. The combination that has the highest probability to comply with the observed route complexity distribution is kept as the final choice set.

# Airline Disruption Management using Symbiotic Simulation and Multi-Fidelity Modelling

Luke Rhodes-Leader[1], Bhakti Stephan Onggo[2], David J. Worthington[1] and Barry L. Nelson[3]

[1] Lancaster University, UK
[2] Trinity College Dublin, Ireland
[3] Northwestern University, USA

The airline industry is prone to disruption due to various causes, from weather conditions to unplanned maintenance on its aircraft. Whilst an airline may not be able to control the causes of disruption, it can reduce the impact of a disruptive event with its response by revising the schedule. Potential actions include swapping aircraft, delaying flights and flight cancellations. However, the situation is complex and stochastic, making decisions difficult to evaluate by the Operations Control Centre of the airline.

A variety of deterministic methods have been proposed to aid the decision process. However, these fail to capture the stochastic nature of the industry, which can lead to a variety of problems. Symbiotic simulation offers a natural decision support system that can cope with a complex and dynamic behaviour. Symbiotic simulation is a methodology in which a physical system and the simulation modelling it have a close interaction. New data from the physical system is fed into the simulation model to update the input parameters. In turn, the model outputs are used for what-if analysis that an external decision maker can use to improve the performance of the physical system.

We study out how symbiotic simulation could potentially be used to improve the response to a disruptive event by evaluating potential revised schedules. Due to the large solution space and non-negligible time to perform a high fidelity simulation, exhaustive searches are infeasible. The simulation must be used selectively on solutions that are worth testing. We are investigating the use of multi-fidelity models to help guide the search of an optimisation algorithm, combining both deterministic models and simulation optimisation methods. The aim of this approach is to produce a set of good solutions within the time constraints of disruption management.

# Simulation-Based Benders Cuts: A New Cutting Approach to Solve Simulation-Optimisation Problems

Mengyi Zhang[1], Andrea Matta[1], Arianna Alfieri[1] and Giulia Pedrielli[2]

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[2] Arizona State University, USA

Large solution space is one of the main features of simulation-optimisation problems. Reducing the cardinality of the set of alternatives is a key point for increasing the efficiency of simulation-optimisation methods. In this work, a new cutting approach is proposed to this purpose. The approach exploits the Benders Decomposition framework that can be effectively applied when the simulation-optimisation problems are represented using Discrete Event Optimisation (DEO) models.

The basic idea behind DEO is to fully integrate the simulation and the optimisation in a unique model, using mathematical programming. The DEO approach shows how discrete event simulation can be used not only for performance evaluation of the modeled stochastic system but also to define the feasible region of the optimisation problem. Benders Decomposition subproblems represent the simulation components, hence cuts can be easily generated and effectively approximated exploiting the information included in the simulation sample path of a system alternative, without solving any subproblem. The simulation-based Benders cut generation approach significantly improves the computational efficiency, and extends the application of DEO on complex systems.

The cut generation procedure is proposed to approximately solve the Server Allocation Problem in a tandem queueing system, which has never been addressed in the literature under the framework of DEO because of the complexity of the mathematical programming model. Results on randomly generated instances show its effectiveness in decreasing the computational effort by reducing the solution space.

Future research will be dedicated to: 1) generalising the approach, 2) efficiently allocating the computational effort across iterations, and 3) embedding generated cuts into general partitioning algorithms.

## 16:20-17:25 - Machine Learning and Data Science (Suite 3)

# Asymptotically Optimal Multi-Armed Bandit Policies under Side Constraints

Odysseas Kanavetas[1], Apostolos Burnetas[2] and Michael Katehakis[3]

[1] Koç University, Turkey
[2] University of Athens, Greece
[3] Rutgers University, USA

We develop asymptotically optimal policies for the multi-armed bandit (MAB), problem, under side constraints. Such models are applicable in situations where each sample (or activation) from a population (bandit) incurs known bandit dependent costs. We consider the class of feasible uniformly fast (f-UF) convergent policies, that satisfy sample path wise the constraints. We first establish a necessary asymptotic lower bound for the rate of increase of the regret function of f-UF policies. Then we provide conditions under which a simple class of f-UF policies attain this lower bound and are asymptotically optimal within the class of f-UF policies.

# Combinatorial Bandits for Multi-Searcher Surveillance Problems

James Grant[1], David Leslie[1], Kevin Glazebrook[1] and Roberto Szechtman[2]

[1] Lancaster University, UK
[2] Naval Postgraduate School, USA

We consider a scenario where a collection of searchers is available to patrol a border with a view to monitoring (and taking action upon) intrusions. The underlying rate at which intrusions appear is unknown and the deployment of searchers to cells of a grid along the border may be updated sequentially. The aim of the searchers is to detect as many intrusions as possible, and to realise this they must learn effective deployment of searchers to grid cells.

We model the resulting exploration-exploitation trade-off using a Combinatorial multi-armed bandit with non-linear rewards and a novel "filtered" feedback model. This filtering aspect arises since agents may not detect all intrusions and the number that are missed will remain unknown – introducing additional variance to the estimates of the underlying rates. Non-linearity arises since the larger a region an agent is assigned to, the less likely they are to detect events therein. In other words, pulling more arms does not necessarily lead to larger rewards.

We propose an upper confidence bound approach to this problem which incorporates an efficient integer programming approach to determine actions in the face of the non-linearity. We derive an $O(\log(n))$ upper bound on regret for our algorithm and demonstrate that this matches the lower bound for the problem up to a constant. We conclude with a numerical study which demonstrates that the upper confidence bound approach is a more reliable choice than Thompson Sampling which can suffer badly from poorly selected priors in this setting.

# An LP-based Forecasting Method for Times Series with Seasonality and Trend

Ger Koole

Vrije Universiteit Amsterdam, Netherlands

Forecasting is essential for good planning. Call centre volume is characterised by triple seasonality and events. Starting with the statistical technique of smoothing splines we designed a forecasting method that uses linear programming.

# Friday 15th June

## 9:00-10:30 - Markov Decision Processes 1 (Suite 2)

### An Approximate Dynamic Programming Approach to Attended Home Delivery Management

Xinan Yang[1] and Arne Strauss[2]

[1] University of Essex, UK
[2] University of Warwick, UK

We propose a new method of controlling demand via delivery time slot pricing in attended home delivery management. The focus is on development of an approach that is suitable for industry-scale implementation. To that end, we exploit a relatively simple yet effective way of approximating the delivery cost by decomposing the overall delivery problem into a collection of smaller, area-specific problems. This cost estimation serves as an input to an approximate dynamic programming method which provides estimates of the opportunity cost associated with having a customer from a specific area book delivery in a specific time slot. These estimates depend on the area and on the delivery time slot under consideration.

Using real, large-scale industry data, we estimate a demand model including a multinominal logit model of the customers' delivery time slot choice, and show in simulation studies that we can improve profits by over 2% in all tested instances relative to using a fixed price policy that is commonly encountered in e-commerce. These improvements are achieved despite having made strong assumptions in the delivery cost estimation. These assumptions allow us to reduce computational runtime to a degree suitable for real-time decision making on delivery time slot feasibility and pricing. Our approach provides quantitative insight to the importance of incorporating expected future order displacement cost into the opportunity cost estimation alongside marginal delivery costs.

# MDP Model for the Preference-Based Appointment Scheduling Problem with Multi-Priority Patients

Feray Tunçalp and Lerzan Örmeci

Koç University, Turkey

We consider appointment scheduling mechanism of a physician or a diagnostic resource in a healthcare facility. There are multiple types of patients with different priorities. At the beginning of each day, the facility observes the number of appointment requests from each patient type and decides on how to allocate available appointment slots to those requests. Furthermore, we take patient preferences into account, where each type of patient prefers a day with a specific probability. Patients may be rejected for two reasons: Capacity may be limited or the system may want to protect appointment slots for higher-priority patients. We model this system with a discrete-time constrained Markov Decision Process in order to maximise the infinite-horizon expected discounted profit subject to the constraint that expected discounted rejection cost is below a fixed threshold. We develop three different models. In the first model, patients have only one preference for the appointment day. Each patient is either given an appointment on the day he/she prefers or the appointment request of that patient is denied. We prove that the optimal policy is a randomised booking limit policy. To solve the model, we use Approximate Dynamic Programming (ADP) techniques. We conduct some numerical experiments and compare the results obtained with ADP techniques with some benchmark policies. In the second model, patients inform the hospital about their first choice for the appointment day. Each patient is either given an appointment on the day he/she prefers or offered another day different from his/her preferred day which he/she may accept or reject. In the third model, whenever a patient arrives with an appointment request, the clinic offers her a set consisting of appointment days. It is also possible to offer an empty set. Patients either select one of the appointment days in this set or reject the offer. We prove that it is optimal to follow a randomised threshold policy in both of the second and third models and these thresholds are decreasing in the number of occupied slots on the other days in the booking horizon.

# Dynamic Bid Price Control for Car Rental Network Revenue Management

Dong Li[1], Zhan Pang[2] and Dali Zhang[3]

[1] Loughborough University, UK
[2] City University of Hong Kong, Hong Kong
[3] Shanghai Jiao Tong University, China

This work considers the dynamic bid price control for car rental revenue management concerning a network of rental stations. Both round trip and one way rentals are considered. Moreover, cars can be transshipped between stations to adjust local capacities on a daily basis. Our aim is to develop efficient bid price control policies that maximise the total discounted revenue. We model this problem as a cyclic dynamic program. Due to the high dimension of the state space, we propose two approximation approaches based on booking limit policies. The first one only concerns the mean future demand and approximates the problem as a deterministic mixed-integer program. The second one considers the uncertainty of demand in a probabilistic non-linear program.

# Purchasing, Production, and Sales Strategies for a Production System with Limited Capacity and Fluctuating Sales and Purchasing Prices

Oktay Karabağ and Barış Tan

Koç University, Turkey

In many industries, the revenue and cost structures of manufacturers are directly affected by the volatility of purchasing and sales prices in the markets. We analyse the purchasing, production, and sales policies for a continuous-review discrete material flow production/inventory system with fluctuating and correlated purchasing and sales prices, exponentially distributed raw material and demand inter-arrival times, and processing time. The sales and purchasing prices are driven by the random environmental changes that evolve according to a discrete state space continuous-time Markov process. We model the system as an infinite-horizon Markov decision process under the average reward criterion and prove that the optimal purchasing, production, and sales strategies are state-dependent threshold policies. We propose a linear programming formulation to compute the optimal threshold levels. We examine the effects of the sales price variation, purchasing price variation, correlation between sales and purchasing prices, customer arrival rate and limited inventory capacities on the system performance measures, through a range of numerical experiments. We also examine under which circumstances the use of the optimal policy notably improves the system profit compared to the use of the buy low and sell high naive policy. We show that using the optimal purchasing, production, and sales policies allow manufacturers to improve their profits when the purchasing and sales prices fluctuate.

## 9:00-10:30 - Stochastic Processes (Suite 3)

# Approximating Two-Stage Chance Constrained Programs using Bonferroni Inequalities

Bismark Singh

Sandia National Laboratories, USA

We consider a joint-chance constraint (JCC) as a union of events, and approximate this union using bounds from classical probability theory. When these bounds are used in an optimization model constrained by the JCC, we obtain corresponding upper and lower bounds on the optimal objective function value. We investigate the strength of these bounds under two different sampling schemes, and observe that a larger correlation between the uncertainties results in a more computationally challenging optimization model.

# Simultaneous and Correlated Events Modelled by the Batch Markov-Modulated Poisson Process

Yoel Yera[1], Rosa E. Lillo[1] and Pepa Ramirez-Cobo[2]

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[2] Universidad de Cádiz, Spain

In this work, we consider the estimation for a wide subclass of the Batch Markovian Arrival Process (BMAP), namely, the Batch Markov-Modulated Poisson processes (BMMPP) which generalise the well-known Markov-Modulated Poisson process. The BMMPP is a general class of point processes suitable for the modelling of dependent and correlated batch events (as arrivals, failures or risk events). A matching moments technique, supported by a theoretical result that characterises the process in terms of its moments, is considered. Numerical results with both simulated and real datasets will be presented to illustrate the performance of the novel approach.

# Bayesian Estimation of Initial Conditions in an Infinite Dimensional Gaussian Process with Unknown Covariance Operator

Alexandros Pasiouras[1], Apostolos Burnetas[1] and Athanasios Yannacopoulos[2]

[1] National and Kapodistrian University of Athens
[2] Athens University of Economics and Business

We consider the model of a Gaussian Process taking values in a Hilbert space, with unknown covariance operator and unknown initial condition. The inverse problem of identifying the initial condition from a realisation is ill-posed. We employ the Bayesian inversion regularisation strategy proposed by Stuart (2013) and extend it to the case of known covariance operator. The proposed method develops an estimator of the covariance operator, and uses the estimator in the Bayesian update scheme for the initial condition. We develop a set of sufficient conditions under which the posterior distribution of the proposed strategy converges to the corresponding posterior under known covariance, with respect to the Hellinger distance metric. We also present numerical results of a computational implementation of this problem in the framework of a Heath-Jarrow-Morton model of interest rate curve prediction.

# Hybrid Spectral Technique for solving SDEs with Combined Uncertainties

Mohamed El-Beltagy[1] and Amnah Al-Johani[2]

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In this presentation, a new technique is suggested to solve the Stochastic differential equations (SDEs) with combined sources of randomness. The SDE will be assumed to have random coefficients in addition to a forcing additive or multiplicative Wiener noise term. The uncertain parameters and the Wiener noise are assumed to be independent. This will allow to use the L2 theory where each event can be realised independently. Previous researches handled the problem by using a spectral (decomposition) technique for the random coefficients and using sampling for the Wiener noise. Sampling is expensive and will not enable to obtain analytical, exact or approximate, solutions.

The suggested technique uses spectral expansions for both types of randomness. Particularly, the polynomial chaos expansion (PCE) is used for the random coefficients where the Wiener-Ito expansion (WIE) is used to handle the Wiener noise. A system of deterministic differential equations in the solution statistics will be produced and can be solved using the well-known techniques for the differential equations.

Using spectral techniques for both randomness will allow to obtain analytical formula for the solution statistics for many SDEs. The classical numerical techniques for solving the deterministic differential equations can be used when the analytical solutions are not easily obtained.

The new technique will be helpful in solving, analytically and/or numerically, many models appear in economics, reliability analysis and other applications.

## 11:00-12:30 - Markov Decision Processes (Suite 2)

# Effective Heuristic Policies for Time-Critical Intelligence Gathering Operations

Christopher Kirkbride[1], Kevin Glazebrook[1], Roberto Szechtman[2] and Jak Marshall[1]

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We consider a multi-source intelligence-gathering problem where, over a finite horizon, an analyst is required to retain a subset of the sampled intelligence items of highest value (or reward) to allocate (or claim) for further processing. In each period, the analyst decides which one of the available information sources to sample from, guided by the posterior distribution of each source. Given the constraint that a small subset of intelligence items are to be collected, the analyst must further decide whether to claim a sampled reward or pass it over for potentially higher value rewards later in the horizon. Formulating the optimisation problem as a Multi-Armed Bandit Allocation model, the objective is to determine a joint source selection and reward allocation policy to maximise the expected total reward claimed.

Classical solution methods are impractical for problems of realistic size, hence, the requirement is to develop effective heuristic polices for the problem. We approach this through the application of a Lagrangian relaxation to the problem, the solution of which allows for the development a class of index heuristics with source specific indices. Index generation itself is a significant challenge and we utilise an approximative method for their creation employing ideas from the Knowledge Gradient approach. The resulting index heuristic, in comparison to other approaches from the literature including Thompson Sampling and KL-UCB, is shown to have consistently strong performance.

# Modelling the use of Patient Activation Measure (PAM) in Complex Patient Care

Lerzan Ormeci[1], Evrim Didem Gunes[1], Odysseas Kanavetas[1] and Christos Vasilakis[2]

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We develop a Markov decision process framework to manage care for patients with multiple chronic conditions via a complex care hub. Complex care provision influences both the patient health state and the evolution of PAM, an indicator for healthy behavior, which affects the evolution of health state of patients. We explore optimal policies to minimise healthcare costs.

# A Graph Patrol Problem with Locally-Observable Random Attackers

Thomas Lowbridge and David Hodge

University of Nottingham, UK

A problem for those faced with managing the security of a vulnerable facility is the scheduling of a patroller, whose job it is to guard the facility. We model the facility as a graph, and attackers as random entities, who will attack at random times according to some Poisson process at each node on the graph. Their attacks will last a random length of time, drawn from some distribution (which is possibly unknown to the patroller). An attack is successful if it is not caught by the patroller at a node, causing the patroller to incur a penalty. Extending some work done in this area we permit semi-intelligent attackers; meaning attackers who arrive at the node while the patroller is present will not start their attack until the next time period, that is when the patroller makes her next decision. The patroller is able to observe these 'suspicious' attackers at her current node and incorporate this information into her decision of where to visit next. We consider the patroller as a resource to be allocated and in doing so we take an index policy approach, by studying the relaxation of the problem to a one node service charge problem. Through a dynamic programming approach we extend some existing heuristics to exploit graph structure; for example on a generalised star graph. Heuristics can be compared to patrol strategies for less stochastic problems on the same graph.

# Bounds for Threshold and Switching Curve Optimal Policies via Dynamic Programming

Dwi Ertiningsih[1,2], Floske Spieksma[2] and Sandjai Bhulai[3]

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Consider a single server queueing system with service control. Customers arrive according to a Poisson process and require an exponentially distributed amount of service. Control is exercised by selecting the speed at which the server operates: a low or a high one. Switching the server to the high speed gives high operating cost. On the other hand, serving at low cost tends to increase the holding cost for customers in queue.

It is known that the optimal control policy minimising the expected average cost per unit time is a threshold policy, and the value function is convex as a function of state, if e.g. the holding cost is convex as a function of state. This can be shown by applying value iteration to the uniformised time-discretised control problem.

It does not seem to be known, that choosing appropriate initial functions in the value iteration step, yields upper and lower bounds for both the threshold optimal policy and the value function in each iteration step. Moreover, the bounds converge monotonically to optimal threshold and value function. We will illustrate this procedure by numerical examples, and discuss preliminary extensions to the 2-competing queues model.

## Analysis of Maximum Age of Data in Data Backup Services

Apoorv Saxena, Dieter Claeys and Joris Walraevens

Ghent University, Belgium

Data backups to the cloud are known to be power intensive processes both in terms of energy consumption as well as infrastructural resources. The Quality of Service (QoS) of data backup processes is determined by measures such as the amount of time data packets have to wait for backup, the number of connections established to the cloud and power consumption. These measures are found to be sensitive to small changes in process parameters. Therefore, computing QoS measures numerically and accurately is of crucial importance to provide high QoS.

In our previous work, we modelled data backup processes using a general batch service queueing model with vacations. We also showed that this model is a natural way of modelling a wide range of exhaustive data backup processes. The backup process parameters immediately translate to modelling parameters and the performance measures of the queueing model are used to compute the QoS measures of the backup process. The most critical performance measure of this model is the maximum age of data. It is defined as the time spent by the first packet in a data backup cycle waiting for the backup service to restart. A higher maximum age of data results in higher probability of data loss. Therefore, keeping this measure as low as possible is critical to provide high QoS. Previously, we were able to compute only the first moment of this measure. However, now we have formulated a way to compute its complete distribution. Therefore, we are able to calculate, for instance, the variance of the maximum age of data and the probability that the maximum age of data exceeds a given threshold. Moreover, it assists us in the selection of optimal model parameters to obtain a guaranteed QoS level.

# Stationary Analysis of an Adaptive Two-Class Retrial System Under the Join the Shortest Orbit Queue Policy

Ioannis Dimitriou and Konstantina Katsanou

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We consider a single server retrial system with adaptive retransmission control and two "smart" orbit queues of finite capacity. Arriving customers that find the server unavailable join the least loaded orbit queue, i.e. the blocked customer is routing in the shortest orbit queue. Customers from the orbits try to access the server according to an adaptive constant retrial policy. More precisely, each orbit queue adjusts its retransmission parameters based on the knowledge of the state of the other. Under this smart operation, each orbit queue reduces the delay experienced by the blocked customers and improves its performance by exploiting the idle periods of the other orbit queue. Moreover, the join-the-shortest-orbit-queue (JSOQ) policy ensures a fair balance among the queues of the network and contributes on the reduction of the delay experienced by the blocked customers. Our work is motivated by challenging questions arising in the emerging research area of cooperative wireless networks. Cooperative communication is a new communication paradigm in which different terminals in the wireless network share their antennas and resources for distributed transmission and processing. Recent studies have shown that cooperative communications yield significant performance improvements for 5G networks, which need massive uncoordinated access, low latency and ultra-reliability. Despite their emergence, the theory of cooperative communications is however still immature to fully understand its broader impacts on the design of future networks. In this work, we go one-step further and consider for the first time the smart JSOQ policy with adaptive retransmission control that contributes towards self-aware networks. We consider a three-dimensional Markovian queueing model and show that its steady-state distribution can be computed in terms of a level-dependent quasi-birth-death process. Basic performance metrics of the system are determined. Extensive numerical examples are obtained and show insights into the system performance.

# Fluid Analysis of Closed Queueing Networks with Discriminatory Processor Sharing

Lulai Zhu[1], Giuliano Casale[1] and Iker Perez[2]

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As a multi-class generalization of the classical egalitarian processor-sharing (EPS) discipline, discriminatory processor sharing (DPS) provides a suitable approach to model time-sharing operating systems and packet-switched communication networks where the service shares exhibit substantial variation between jobs with heterogeneous characteristics. Under the DPS discipline, each class-$k$ job in the system is assigned a positive weight $w_k$ and the service capacity is divided among all the jobs in proportion to their weights. If there are $n_r(t)$ class-$r$ jobs in the system at time $t$, then each class-$k$ job is allotted a fraction $w_k/\sum_r w_r n_r(t)$ of the service capacity. By adjusting the class-dependent weights, one can therefore effectively control the instantaneous service shares of jobs belonging to different classes.

Although DPS delivers more diverse modeling capabilities than EPS, little attention is paid to the behavior of the DPS discipline in closed queueing networks (QNs). In this presentation, we propose a fluid method for the transient and steady-state analysis of closed QNs consisting of delay and DPS queueing stations. Our reference model may be parametrized with an arbitrary topology. It also assumes the service time distribution of a class in a station to be of phase type and allows a job to switch to another class on service completion in the station. Particularly, we manage to remove the discontinuity of the resulting ordinary differential equations (ODEs) at the origin, which is recognized as a common problem in fluid approximation of QNs with DPS. The proposed method is verified against discrete-event simulation with a large set of model instances.

**Keywords:** fluid approximation; closed queueing networks; discriminatory processor sharing; Markov processes; transient and steady-state analysis

# Performance Evaluation of Depth Based Routing in Underwater Sensor Networks

Kishor Patil[1], Mohsin Jafri[2], Dieter Fiems[1] and Andrea Marin[2]

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Underwater wireless sensor networks (UWSNs) rely on acoustic communication between the sensor nodes and sinks, drawing power from on-board batteries. Since battery replacement may be costly or completely infeasible for UWSNs, it is crucial that the communication protocols not only take into account various performance metrics, but also the energy efficiency of the protocol. While a thorough understanding of routing protocols is crucial for the operational efficiency of UWSNs, only a few studies propose and analyse stochastic models for assessing and optimising the performance and energy efficiency of such networks. In this work, we propose a stochastic model for Depth Based Routing (DBR), which is a popular routing protocol for UWSNs. Characteristics of DBR taken into account include transmission delays on the acoustic channel, node mobility and holding times based on the depth differences as defined by DBR.

We propose an algorithm to efficiently calculate various performance indices, including the distribution of the number of hops it takes to send from bottom to surface, the level dependent energy consumption and the mean end-to-end delay. As the model incorporates the impact of node deployment and the high transmission loss of the acoustic channel, it can be used to understand the behaviour of DBR at the network level, for example to assist the network designer to select the DBR configuration parameters which optimise the trade-off between delivery probability, energy consumption and end-to-end delay. Some numerical experiments illustrate our approach.

## 13:30-14:30 - Invited Keynote (Suite 2)

# Traffic Issues for Rational Drivers

**Invited Speaker:** Kalyan Talluri

Imperial College Business School, UK

Traffic problems and their resolution were an early preoccupation for many Operations Researchers. However, the topic has fallen on the wayside of top OR journals over the last couple of decades. The research in the area now is driven primarily by physicists and civil and traffic engineers where the modelling either has a physics flavour (to take an extreme example, the kinetic gas traffic model) or relies on discrete-event simulations to test out policies.

The advent of driverless cars and vehicle-to-vehicle communications however ought to revive interest in this problem as it has great relevance to practice and requires considerable modelling skill. In this talk we present our recent research on a simple traffic situation—a two-lane highway has one of its lanes blocked, say due to an accident. The traffic on the blocked lane has to merge to the free lane. For each car, this is akin to the classic parking problem but with a velocity decision variable, in addition to the merge decision. This can be formulated as a dynamic program and the optimal policy shown to be of a bi-threshold type. Now, however incentive compatibility comes into play. Drivers are rational and minimise their travel time. Even simple situations with just two cars on the blocked lane can result in a traffic jam (a subgame-perfect equilibrium) because of the dynamics and instantaneous best-response functions. We devise simple policies for central planner based on our insights and compare them with the optimal solutions.

*(Joint work with Mihalis Markakis and Dmitrii Tikhonenko (UPF).)*

## 14:30-15:45 - Open Discussion about Teaching (Suite 2)

# Teaching of Stochastic Modelling in the Era of Business Analytics and Data Science

**Chair:** Ger Koole

Vrije Universiteit Amsterdam, Netherlands

An open discussion themed ”Teaching of stochastic modelling in the era of business analytics and data science” chaired by Prof. Ger Koole. The discussion panel members will be Prof. Ger Koole (VU Amsterdam), Prof. Raik Stolletz (University of Mannheim), Prof. Margaret Brandeau (Stanford University), and Prof. Warren Powell (Princeton University).

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