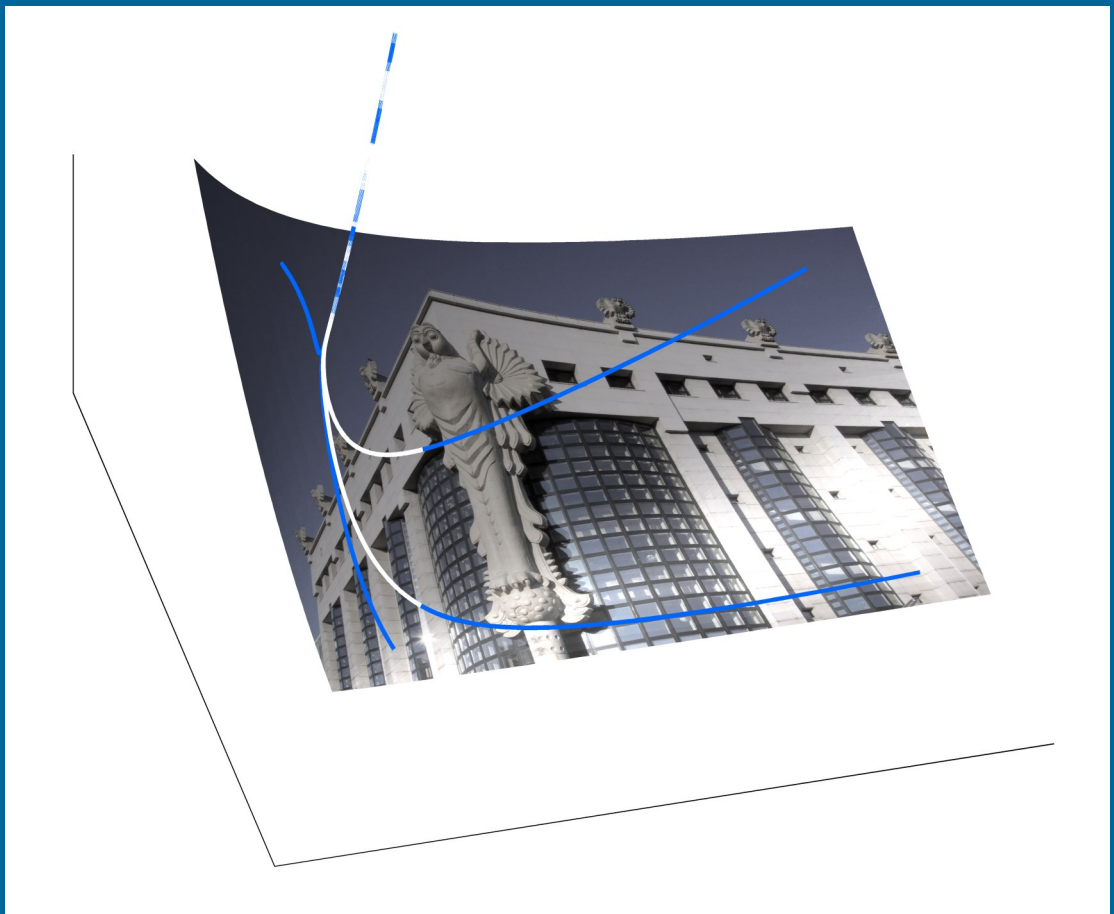




TECHNISCHE  
UNIVERSITÄT  
WIEN  
Vienna University of Technology

# 14<sup>th</sup> Viennese Conference Optimal Control and Dynamic Games



**July 3<sup>rd</sup> - July 6<sup>th</sup>, 2018**

## **Imprint**

### **Publisher:**

Research Unit ORCOS,  
Institute of Statistics and Mathematical Methods in Economics  
Vienna University of Technology  
1040 Wien, Austria  
<https://orcos.tuwien.ac.at>

### **Images:**

Front Page: ORCOS  
Maps: <http://wien.gv.at>, <http://www.wegweiser.ac.at>, [www.openstreetmap.org](http://www.openstreetmap.org)

### **Print:**

Digidruck GmbH, Brunn/Gebirge

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## Scientific Committee

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H. Dawid (DE)  
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F. Gozzi (IT)  
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J. L. Haunschmied  
M. Kainerstorfer  
R. Kovacevic  
G. Tragler  
V.M. Veliov (chair)

## Plenary Speakers

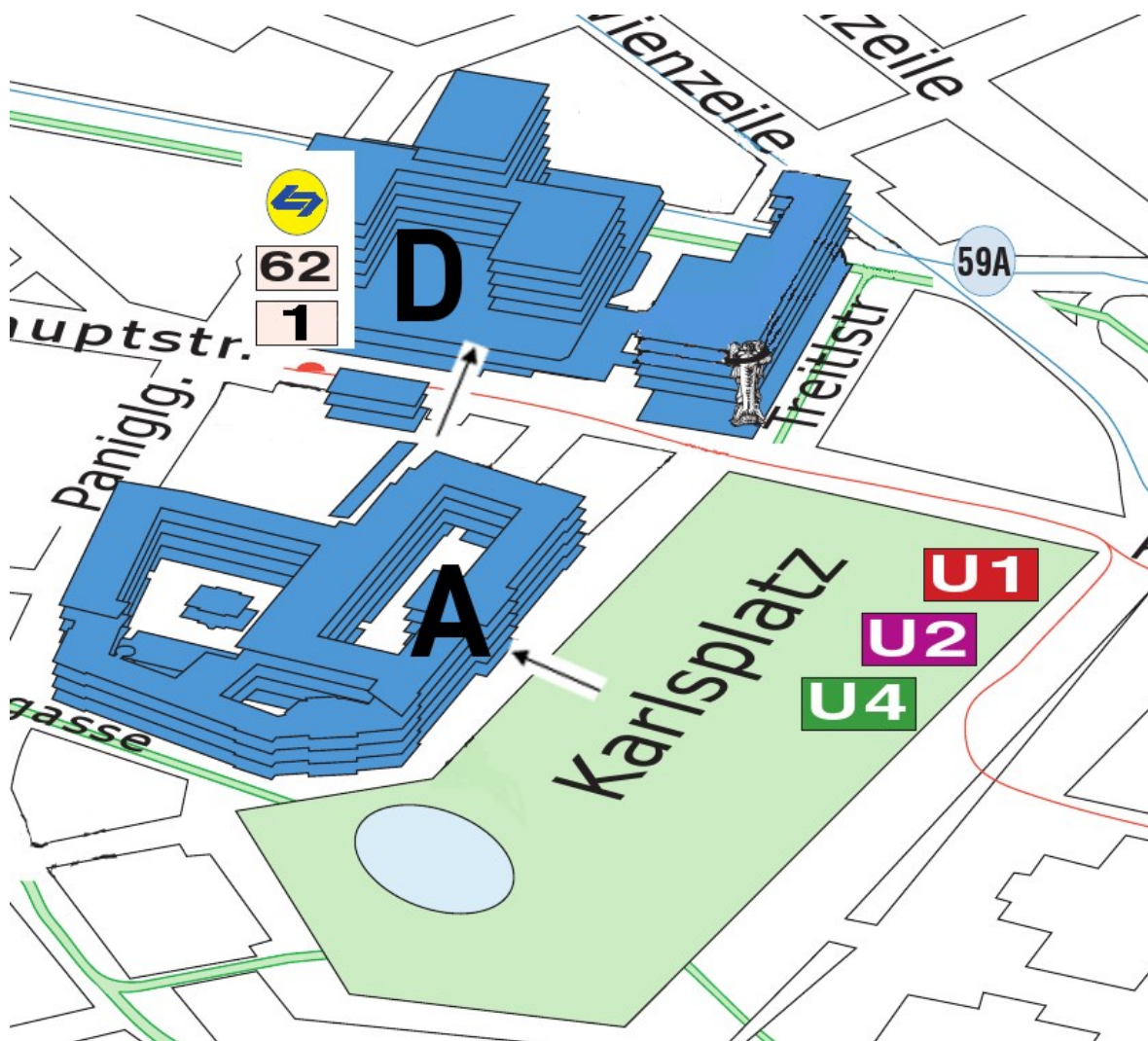
H.-G. Bock (DE)  
G. Deffuant (FR)  
M. Fornasier (DE)  
H. Schaettler (US)  
W. Semmler (US)

# I. Practical Information

## 1. Conference Venue

### Vienna University of Technology (TU Wien)

Vienna University of Technology is located in the heart of Vienna. The conference takes place in the „Freihaus“ (building D), Wiedner Hauptstrasse 8-10, 1040 Vienna. As indicated on the map, the TU Wien can be reached by the underground lines U1, U2 and U4, station „Karlsplatz“, or tram lines 1 and 62 or „Badner Bahn“, station „Resselgasse“.



## Lecture Rooms

All lecture rooms are in the **Freihaus** (D), red and yellow area at first and second floor. For an overview see the map on the next page.

**FH HS 1:** The main entrance of **FH Hörsaal 1** is on the first floor of the red area. It can also be accessed from the second floor of the red area.

**FH HS 2:** is located on the second floor of the yellow area.

**FH HS 3:** is located on the second floor of the yellow area..

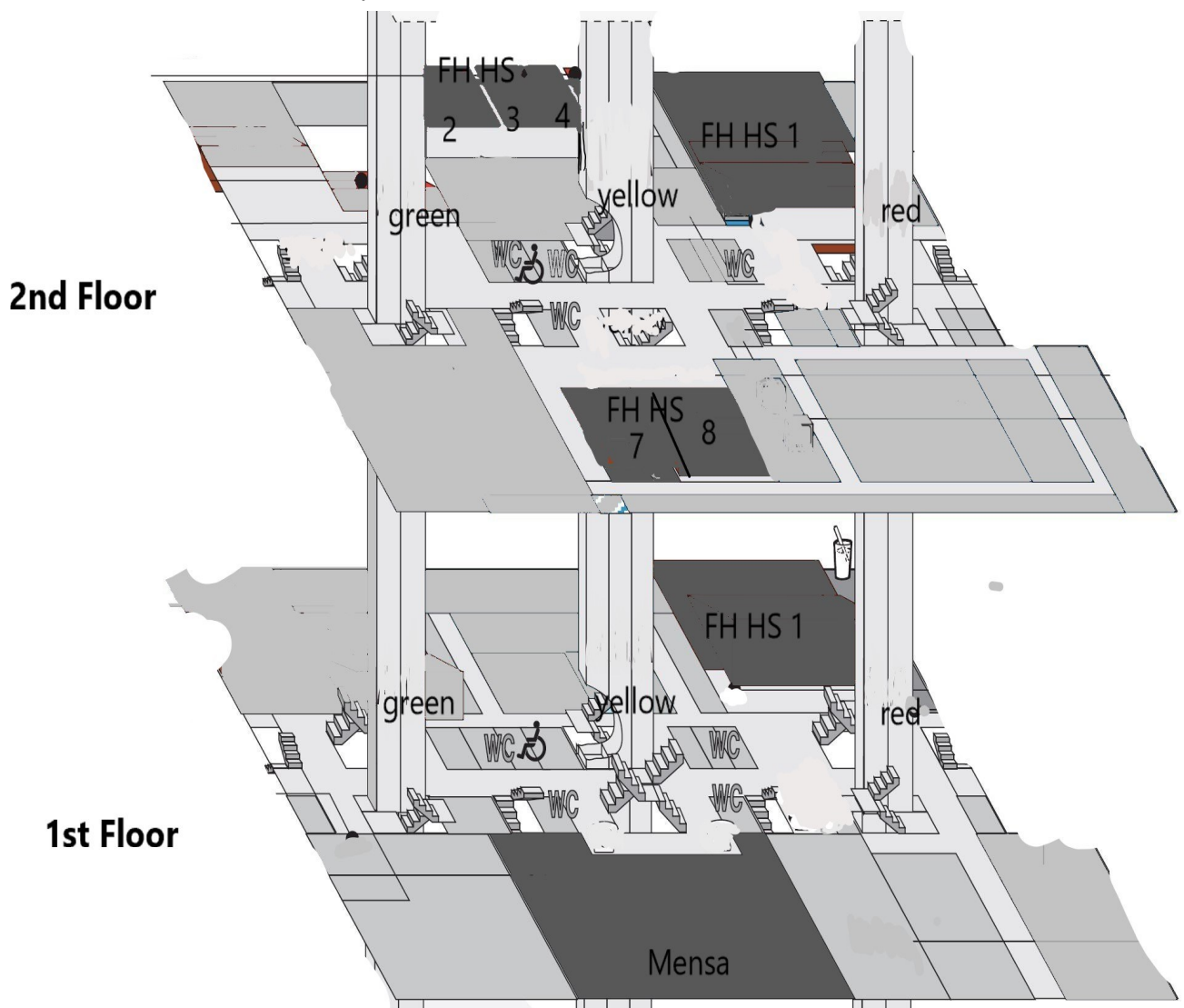
**FH HS 4:** is located on the second floor of the yellow area.

**FH HS 7:** is located on the second floor of the yellow area..

**FH HS 8:** is located on the second floor of the yellow area.

**Coffee Breaks** will take place on the hallway of the yellow and red areas on the second floor.

**The mensa** is located in the yellow area of the first floor.



## 2. Registration, Conference Desk and Welcome Reception

The **Registration Desk** will be open on Monday, July 2<sup>nd</sup>, from 17:00 to 19:00 on the first floor in the Freihaus (building D) in front of the Mensa (yellow area). The **Welcome Reception** will take place in the mensa and begins at 18:00. **Late registration** will be possible at the **Conference Desk** on the second floor, yellow area, on Tuesday July 3<sup>rd</sup>, from 07:45 to 8:25 and during the coffee and lunch breaks.

Upon registration you receive your confirmation of payment, an information package including this booklet, vouchers for lunches in the university mensa and invitation cards for the social events.

## 3. Guidelines for Speakers and Session Organizers

All rooms are equipped with notebooks and projectors. Please prepare your presentation as pdf-file (recommended) or ppt-file on a USB memory-stick and copy it on the notebook **before** the session has started. Your presentation may last **25 minutes, including preparation and discussions**, thus 20 min. should be the actual duration of the talk.

The session organizers are supposed to chair their sessions or to take care of alternative chair persons. The chair persons are responsible for strictly keeping the schedule.

## 4. Poster Session

The posters will be accessible during the entire conference. A time-slot for poster presentations is included in the program, during which the presenters should be available near their posters: Thursday July 5<sup>th</sup> 13:15-14:00 on the second floor of Freihaus, yellow area.

## 5. WLAN and Internet, Charging of devices

We encourage all participants to use their eduroam accounts, if provided by their university. A limited number of TU-based internet accounts is available at the conference desk.

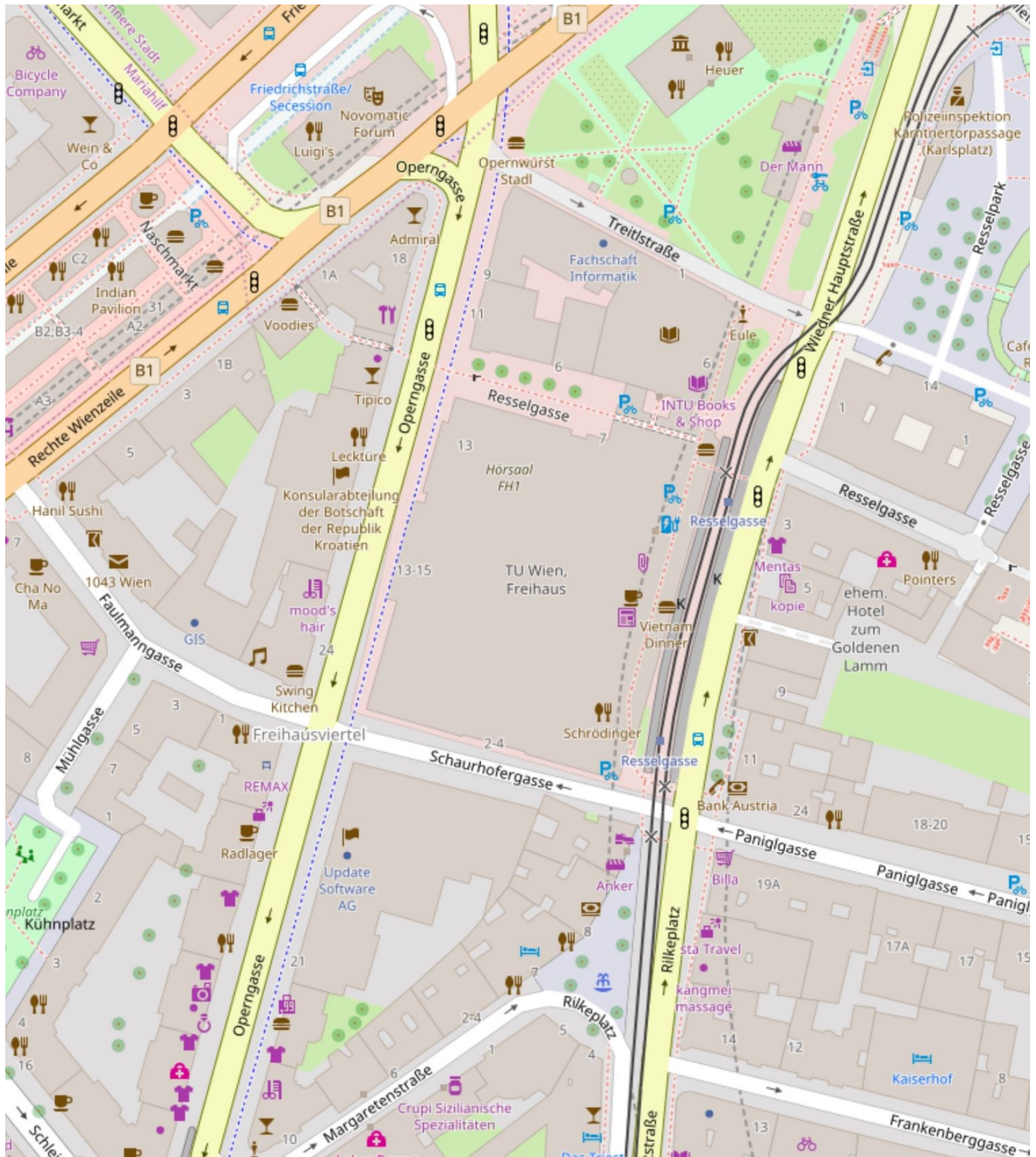
It is possible to charge devices in Seminar room DB gelb 04 (4th floor of Freihaus, yellow area).

## 6. Lunch

Upon registration you receive vouchers which can be used for menu (including one drink from the machine) at the university mensa. The mensa is located at Freihaus, yellow area, first floor (see the map of Freihaus for details). It is self-service and will be open Tuesday to Friday 11:00-14:30.

Restaurants and grocery stores near the university are shown on the next page.






## 7. Transportation

### Transportation from/to the Airport

#### Public Transportation

There are buses and trains going from and to the airport. The cheapest is the “Schnellbahn” (see rates below).

	Place of Departure	Interval (min)	Duration (min)	Price (€)
Railjet	Vienna Central Station (Wien Hauptbahnhof— Südtiroler Platz)	~30	15	4.10
City Airport Train	Wien Mitte	~30	16	11,-
Airport Bus 1187	Westbahnhof (Europaplatz)	~30	45	8,-
Airport Bus 1185	Schwedenplatz (Morzinplatz)	~30	20	8,-
S-Bahn 	Wien Mitte	~30	25	4,10

Websites: [www.cityairporttrain.com](http://www.cityairporttrain.com), [www.postbus.at](http://www.postbus.at), [www.oebb.at](http://www.oebb.at).

All timetables can also be found on [www.wienerlinien.at](http://www.wienerlinien.at).

#### Airport Taxi:

A taxi from/to the center costs about € 40.00, see [www.airporttaxi-wien.at](http://www.airporttaxi-wien.at) (Telephone +43 (0) 1/707 13 77).

### Transportation from/to Vienna’s Railway Stations

- **Westbahnhof:** Metro U3 and U6, station “Westbahnhof”
- **Wien Meidling:** Metro U6, station “Philadelphiabrücke”
- **Wien Hauptbahnhof:** Metro U1, station “Hauptbahnhof(Südtiroler Platz)”, Bus 13A station “Hauptbahnhof”, Tram D station “Hauptbahnhof Ost”
- **Franz-Josefs-Bahnhof:** Metro U4, station “Friedensbrücke”, Tram D station “Franz-Josefs-Bahnhof”

Homepage of the Austrian Federal Railways (ÖBB): [www.oebb.at](http://www.oebb.at)

## Wiener Linien (Public Transport)

### Map

See the city map of Vienna in your Welcome Package or [www.wienerlinien.at](http://www.wienerlinien.at).

### Metro operation hours:

Mo-Thu, Su: 05:00 – approx. 00:20, then Nightlines (buses).

Fr-Sa: 05:00 - 00:20 in the usual intervals, then every 15 min for the whole night.

### Tickets

Single Trip	24/48/72 Hours Ticket	The 8 Days Climate Ticket	One Week Ticket *	The Vienna Card **
2,40 €	8,00/14.10/ 17.10 €	40.80 €	17.10 €	72.00€

\* valid from Monday 00:00 till Monday 09:00

\*\* 72 hour ticket plus discounts for many sights, museums, concerts and more.

### Timetables, route planner and real time information

All information about tickets, time tables, nightlines, route planner, etc. can be found at [www.wienerlinien.at](http://www.wienerlinien.at). The app „qando“ provides all information directly on your smartphone.

## Taxi

The closest taxi stand in walking distance from the university is at Linke Wienzeile 4.

### Some numbers and websites to order a taxi:

Phone 01/60160  
[www.taxi60160.at](http://www.taxi60160.at)

Phone 01/40100  
[www.taxi40100.at](http://www.taxi40100.at)

Phone 01/31300  
[www.taxi31300.at](http://www.taxi31300.at)

## City Bike

You can rent a bike from one of over 100 stations in Vienna and discover the city on a bike. The bike can be returned at any other station. Registration €1 by credit card, the first hour of every ride is free. Other rates and more information online: [www.citybikewien.at](http://www.citybikewien.at).

## 8. Social Program

### Welcome Reception

The Welcome Reception will take place in the Mensa on July 02, 2018, from 18:00-21:00 on the first floor, yellow area.

This event is covered by your registration fee.

### Conference Dinner/Cocktail Reception

The Mayor and Governor of Vienna demands the pleasure of your company at a Cocktail Reception on July 04, 2018, 20:00 at the “Wiener Rathaus (town hall) - Wappensaal”.

**Entrance:** 1010 Vienna, Lichtenfelsgasse 2.

#### Public Transportation:

Metro U2 to station Rathaus

or Tram 1 or D to station Rathausplatz/Burgtheater.

#### Walking distance:

about 2 km (25 min) from TU Wien.

This event is covered by your registration fee. Please bring the invitation you received upon registration.





## Discussion Dinner

A joint discussion dinner will take place on Thursday, July 5<sup>th</sup>, 19:00 at a “Heurigen” in Grinzing, “Feuerwehr Wagner”, 1190 Vienna, Grinzinger Straße 53. Participants who paid for the dinner will receive invitations in their package.

### Public Transportation:

Take Metro U4 to station Spittelau, from there use tram D to Grinzinger Straße and finally bus 38A to station Neugebauerweg.



## 9. Tourist Information

### Tourist map

In the conference package a tourist map of the center of Vienna is included. The most important sights with opening hours are described therein.

### Tourist Information

At the corner Albertinaplatz/Maysedergasse, 1010 Vienna  
[www.wien.info](http://www.wien.info) or [www.wien.gv.at/tourismus](http://www.wien.gv.at/tourismus)

### Tickets for Concerts and Theater

WIEN-TICKET Pavillon in the State Opera House, 1010 Vienna (5 minutes from Vienna University of Technology)



## II. Scientific Program

### List of Sessions

<i>Session name (session numbers)</i>	<i>Organizers</i>
Plenaries (2,23,24,45,66)	Scientific committee
Sub-optimal solutions in games and control (40,82)	Y. Averboukh, D. Gromov
Approximation of differential inclusions and control problems (15,20)	R. Baier, E. Farkhi
Infinite dimensional stochastic modeling in economics and finance (18,72)	E. Bandini, F. Gozzi, G. Fabbri
Spatially distributed harvesting (52)	S. Behringer, T. Upmann
Spatial resource and environmental economics and dynamic games (4,9,37)	S. Behringer, T. Upmann
Variational analysis in optimization (In honor of A.L.Dontchev) (5,10,79,84)	R. Cibulka, F. Aragon
Model order reduction in control and optimization (36,62)	M. Falcone, V. Simoncini
Optimal stopping, singular and impulse control and their applications (3,8)	S. Federico, G. Ferrari, T. De Angelis
Stochastic control and optimization in finance (35)	S. Federico, M. Maggis
New trends in theory of stochastic control (13,46,51)	H. Frankowska, M. Quincampoix
PDE-constrained optimization in economics (14)	F. Gozzi, S. Faggian, G. Fabbri
Turnpike properties for ODEs and PDEs (6,11,43)	L. Grüne
Infinite horizon optimal control and applications (49,54,59)	N. Hayek , S. Pickenhain
Dynamic economic policy (22)	B. Heijdra, P. Heijnen
Dynamic games in industrial organization (7)	M. Kopel
Real options (29,34,71,76)	P. Kort
Shape optimization (68,73)	R. Kovacevic
Dynamics of health and health care (65)	M. Kuhn
Information provision and signalling games (77)	C. Langbort, J. Marecek, R. Shorten
Application of optimal control to problems in biomedicine (39,44,50,55,60)	U. Ledzewicz, M.R. de Pinho
Modeling and computational methods for financial applications (25,30,56,61)	A. Picarelli, C. Reisinger
Ageing and inequality (75)	A. Prskawetz, M. Sanchez
Numerical analysis for PDE constrained optimization (26,31,41,57,78)	A. Rösch, J. Pfefferer
Regime change modeling in economics and finance (86)	W. Semmler, M. Gross
Non-standard preferences, discounting, and time inconsistency (17)	T. Trimborn
Variational analysis and optimal control problems (42,58,63,69,74)	P. Wolenski, H. Zidani
Model based control: analysis and modelling (21,28,33,38,64)	K. Worthmann, K. Chudej
Dynamic games in economics (48,81)	S. Wrzaczek
Applications of optimal control (12,16,70)	Scientific committee
Dynamic games (32,83)	Scientific committee
Economic dynamics (27,53,80,85)	Scientific committee
Optimal control (19,47,67)	Scientific committee
Poster session	Scientific committee

# Program Overview

Tue July, 3		FH Hörsaal 1				
08:30-9:10		Session 1: Opening				
09:10-10:00		Session 2: Plenary, Bock				
		Coffee Break at 2nd floor, red/yellow area				
Freihaus Session	FH Hörsaal 7	FH 8 Nöbauer HS	FH Hörsaal 3	FH Hörsaal 2	FH Hörsaal 4	
	3 Frederico, Ferrari, De Ang.	4 Behringer, Upmann	5 Cibulka, Aragon	6 Gruene	7 Kopel	
10:30-11:45	Aid Bandini Campi	Faggian Fabbri Gozzi	López-Cerdá Ribarska Scarinci	Berberich Pirkelmann Faulwasser	Gezer Lambertini Radi	
Session	8 Frederico, Ferrari, De Ang.	9 Behringer, Upmann	10 Cibulka, Aragon	11 Gruene	12 Scientific Committee	
11:55-12:45	Palczewski Steg	Singh Davydov	Cánovas Aragon Artacho	Di Bartolomeo Guglielmi	Apreutesei El Ouardighi	
Lunch at Canteen, 1st floor, Freihaus						
Session	13 Frankowska, Quincampoix	14 Gozzi, Faggian, Fabbri	15 Baier, Farkhi	16 Scientific Committee	17 Trimborn	
14:00-15:40	Bensoussan Zhang X. Tessitore Bouchard	Augeraud-Véron Brito Sanchez-Romero Yannacopoulos	Filippova Baier Gabor Mokhov	Wrzaczek Seidl De Giovanni Feichtinger	Dugan Werner Wendner Trimborn	
Coffee Break at 1st/2nd floor, Freihaus						
Session	18 Bandini, Fabbri, Gozzi	19 Scientific Committee	20 Baier, Farkhi	21 Worthmann, Chudej	22 Heijdra, Heijnen	
16:00-17:15	Confortola Sun Bonaccorsi	Shvartsman Gaitsgory Pereira F.	Reissig Preininger Martens	Chudej Berger	Heijnen van der Kwaak Zwart	
17:30-18:20	Session 23: Plenary, Deffuant					

Wed July, 4		FH Hörsaal 1				
08:40-09:30		Session 24: Plenary, Schättler				
		Coffee Break at 2nd floor, red/yellow area				
Freihaus Session	FH Hörsaal 7	FH 8 Nöbauer HS	FH Hörsaal 3	FH Hörsaal 2	FH Hörsaal 4	
	25 Picarelli, Reisinger	26 Roesch, Pfefferer	27 Scientific Committee	28 Worthmann, Chudej	29 Kort	
10:00-11:15	Pham Tan Garcia Trillos	Mateos Winkler Beuchler	Fruchter Kogan Li Zhi	Gerdts Grüne Flaßkamp	Hagspiel Chevalier-Roignant Lavrutich	
Break						
Session	30 Picarelli, Reisinger	31 Roesch, Pfefferer	32 Scientific Committee	33 Worthmann, Chudej	34 Kort	
11:30-12:45	Glas Bokanowski Jakobsen	Wollner Hinze Harbrecht	Dawid Wu Zou	Hans Kepplinger Kimmerle	Boyarchenko Dangl Gapeev	
Lunch at Canteen, 1st floor, Freihaus yellow area						
Session	35 Federico, Maggis	36 Falcone, Simoncini	37 Behringer, Upmann	38 Worthmann, Chudej	39 Ledzewicz, de Pinho	
14:00-15:40	Bartl Colaneri Fontana Källblad	Meerbergen Volkwein Breiten Gräble	Papayiannis Quaas Uecker Upmann	Seydenschwanz Kolo Leidereiter Reis	Bayen Lykina Foroozandeh Kaya	
Coffee Break at 2nd floor, red/yellow area						
Session	40 Averboukh, Gromov	41 Roesch, Pfefferer	42 Wolenski, Zidani	43 Gruene	44 Ledzewicz, de Pinho	
16:00-17:40	Averboukh Khlopin Lopez-Barrientos Troeva	Kruse Walter Neitzel Meyer	Bettiol Bivas Bonnet Carrere	Trélat Schaller Porretta Zhang Can	Goellmann Swierniak Silva	



Thu July, 5		FH Hörsaal 1							
08:40-09:30		Session 45: Plenary, Fornasier							
		Coffee Break at 2nd floor, red/yellow area							
Freihaus Session	FH Hörsaal 7	FH 8 Nöbauer HS	FH Hörsaal 3	FH Hörsaal 2	FH Hörsaal 4				
46	Frankowska, Quincamp.	47	Scientific Committee	48	Wrzaczek	49	Hayek, Pickenhain	50	Ledzewicz, de Pinho
10:00-11:15	Yin Cannarsa Quincampoix	Banz Bastos Sanchez Licea	Martin-Herran Cabo de Frutos	Crettez Belyakov Brunovský	Bunimovich Ouifki Pouchol				
		Break							
Session	51	52	53	54	55				
	Frankowska, Quincamp.	Behringer, Upmann	Scientific Committee	Hayek, Pickenhain	Ledzewicz, de Pinho				
11:30-12:45	Guatteri Zhang H. Frankowska	Stahn Yegorov Lokutsievskiy	Greiner Sorgor Takahashi	Burtchen Bachir Hayek	Fernandez Ledzewicz Bajger				
		Lunch at Canteen, 1st floor, Freihaus yellow area							
Session	56	57	58	59	60				
	Picarelli, Reisinger	Roesch, Pfefferer	Wolenski, Zidani	Hayek, Pickenhain	Ledzewicz, de Pinho				
14:00-15:40	Insley Forsyth Carlini dos Reis	Casas Chrysafinos Leykehman Vexler	Cellina de Pinho Desilles Ferretti	Maurer Worthmann Ziemann Aseev	Grigorieva Nunes Nogueira Nowakowski Volpert				
		Coffee Break at 2nd floor, red/yellow area							
Session	61	62	63	64	65				
	Picarelli, Reisinger	Falcone, Simoncini	Wolenski, Zidani	Worthmann, Chudej	Kuhn				
16:00-17:40	Bonnans Chassagneux Sulem	Benner Urban Stoll Alla	Gajardo Ghilli Hermosilla Ledyaev	Schneider Trenn Villanueva Zuyev	Bisceglia Galama Kuhn Schünemann				

Fri July, 6		FH Hörsaal 1							
08:40-09:30		Session 66: Plenary, Semmler							
		Coffee Break at 2nd floor, red/yellow area							
Freihaus Session	FH Hörsaal 7	FH 8 Nöbauer HS	FH Hörsaal 3	FH Hörsaal 2	FH Hörsaal 4				
67	Scientific Committee	68	Kovacevic	69	Wolenski, Zidani	70	Scientific Committee	71	Kort
10:00-11:15	Cavagnari Gusev Ghoddsi	Blank Dapogny Geiersbach	Khalil Marigonda Palladino	Lemos Palokangas Mirescu	Kort Compernelle Nagy				
		Break							
Session	72	73	74	75	76				
	Bandini, Fabbri, Gozzi	Kovacevic	Wolenski, Zidani	Prskawetz, Sanchez	Kort				
11:30-12:45	Calvia Federico Thieullen	Jouve Rieger Sturm	Pfeiffer Rampazzo Wachsmuth	Strulik Leite Prskawetz	Olsen Thijssen Vergalli				
		Lunch at Canteen, 1st floor, Freihaus yellow area							
Session	77	78	79	80	81				
	Langb., Marecek, Shorten	Roesch, Pfefferer	Cibulka, Aragon	Scientific Committee	Wrzaczek				
14:00-15:40	Langbort Le Treust Marecek Shorten	Blechschildt Geiger Betz Schiela	Cibulka Dontchev Fabian Farkhi	Growiec Sordi Privileggi Martinez-García	Gromova Bondarev Palestini Wisniewska-Matyskiel				
		Coffee Break at 2nd floor, red/yellow area							
Session	82	83	84	85	86				
	Averboukh, Gromov	Scientific Committee	Cibulka, Aragon	Scientific Committee	Semmler, Gross				
16:00-17:40	Pogodaev Staritsyn Yufereva Malakhova	De Lara Kelis Pachter	Ioffe Krastranov Thera Maruyama	Eigruber Wen Zimka	Asada Gross Macchiarelli Tahri				



Tuesday, July 3<sup>rd</sup>

<b>1 Opening</b>	<b>08:30 – 09:10</b>
	<b>FH HS 1</b>
<b>2 Plenary</b>	<b>09:10 – 10:00</b>
<i>Chair: L. Grüne</i>	<b>FH HS 1</b>
<i>H. G. Bock: Nonlinear mixed-integer optimal control – from the Maximum Principle Approach to online computation of closed loop controls in real time . . . . .</i>	37
<b>Coffee Break</b>	
<hr/>	
<b>3 Optimal stopping, singular and impulse control and their applications 1</b>	<b>10:30 – 11:45</b>
<i>Chair: S. Federico, G. Ferrari, T. De Angelis</i>	<b>FH HS 7</b>
<i>R. Aïd, L. Li, M. Ludkovski: Capacity expansion games with application to competition in power generation investments . . . . .</i>	38
<i>E. Bandini, T. De Angelis, G. Ferrari, F. Gozzi: The dividend problem with stochastic discount</i>	38
<i>R. Aïd, M. Basei, G. Callegaro, L. Campi, T. Vargiolu: Nonzero-sum stochastic differential games with impulse controls: a verification theorem with applications . . . . .</i>	39
<b>4 Spatial resource and environmental economics and dynamic games 1</b>	<b>10:30 – 11:45</b>
<i>Chair: S. Behringer, T. Upmann</i>	<b>FH 8 Nöbauer HS</b>
<i>G. Fabbri, S. Faggian, G. Freni: Spatial resource wars: a two regions example . . . . .</i>	39
<i>G. Fabbri, S. Faggian, G. Freni: A spatial model of resource wars . . . . .</i>	40
<i>R. Boucekkine, G. Fabbri, S. Federico, F. Gozzi: Optimal economic growth through capital accumulation in a spatially heterogeneous environment . . . . .</i>	40
<b>5 Variational analysis in optimization (In honor of A.L.Dontchev) 1</b>	<b>10:30 – 11:45</b>
<i>Chair: R. Cibulka, F. Aragon</i>	<b>FH HS 3</b>
<i>M.A. López-Cerdá, G. Beer, M.J. Cánovas, J. Parra: A uniform approach to Hölder calmness of subdifferentials . . . . .</i>	41
<i>N.K. Ribarska, M.I. Bivas, M.I. Krastanov: Tangential transversality . . . . .</i>	41
<i>T. Scarinci, J. Preininger, V.M. Veliov: Stability analysis for optimal control problems with bang-bang solutions . . . . .</i>	42
<b>6 Turnpike properties for ODEs and PDEs: theory and application 1</b>	<b>10:30 – 11:45</b>
<i>Chair: L. Grüne</i>	<b>FH HS 2</b>
<i>J. Berberich, J. Köhler, F. Allgöwer, M.A. Müller: Indefinite linear quadratic optimal control: Periodic dissipativity and turnpike properties . . . . .</i>	42
<i>L. Grüne, S. Pirkelmann, M. Stieler: Turnpike properties for time-varying systems . . . . .</i>	43
<i>T. Faulwasser, M. Zanon: Economic MPC with gradient-correcting end penalties . . . . .</i>	43
<b>7 Dynamic games in industrial organization</b>	<b>10:30 – 11:45</b>
<i>Chair: M. Kopel</i>	<b>FH HS 4</b>
<i>H. Dawid, S. Gezer: Delaying product introduction in a duopoly: a strategic dynamic analysis . . . . .</i>	44
<i>L. Lambertini: Regulating the tragedy of commons: nonlinear feedback solutions of a differential game with a dual interpretation . . . . .</i>	44
<i>G.P. Crespi, D. Radi, M. Rocca: Robust games: theory and application to a Cournot duopoly model . . . . .</i>	44
<b>Break</b>	
<hr/>	

<b>8</b>	<b>Optimal stopping, singular and impulse control and their applications 2</b>	<b>11:55 – 12:45</b>
	<i>Chair: S. Federico, G. Ferrari, T. De Angelis</i>	<b>FH HS 7</b>
	<i>J. Palczewski, E. Stettner: Impulse control of non-uniformly ergodic processes with average cost criterion . . . . .</i>	45
	<i>J.-H. Steg: Preemptive investment under uncertainty . . . . .</i>	45
<b>9</b>	<b>Spatial resource and environmental economics and dynamic games 2</b>	<b>11:55 – 12:45</b>
	<i>Chair: S. Behringer, T. Upmann</i>	<b>FH 8 Nöbauer HS</b>
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**Wednesday, July 4<sup>th</sup>**

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Thursday, July 5<sup>th</sup>

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Tuesday, July 3<sup>rd</sup>

## Abstracts

Tuesday, July 3<sup>rd</sup>

- |                        |               |
|------------------------|---------------|
| 1. Opening             | 08:30 – 09:10 |
|                        | FH HS 1       |
| 2. Plenary             | 09:10 – 10:00 |
| <i>Chair:</i> L. Grüne | FH HS 1       |

Nonlinear mixed-integer optimal control – from the Maximum Principle Approach to online computation of closed loop controls in real time

Hans Georg Bock (1),

(1) Interdisciplinary Center for Scientific Computing (IWR), Heidelberg University, Heidelberg, Germany

The presentation discusses theoretical and numerical aspects of optimal control problems with integer-valued controls. Despite the practical relevance and ubiquity of integer or logical valued controls such as valves, gears or the start-up, resp., the reconfiguration of sub-units in production plants or networks, optimization methods capable of solving such nonlinear mixed-integer optimal control problems (MIOCP) that can be practically applied to large-scale systems and in real-time, have only recently come within reach.

Nonlinear MIOCP - such as the minimum energy operation of subway trains equipped with discrete acceleration modes – were solved as early as the late seventies for the city of New York applying an “indirect” approach by Pontryagin’s Maximum Principle. Based on a “Competing Hamiltonians” algorithm open loop and closed loop optimal control solutions for problems with discontinuous dynamics were computed that allowed a tested reduction of 18 per cent in traction energy. However, such “indirect” methods are relatively difficult to apply to large-scale and real-time optimization problems.

As an alternative, a new “direct” approach is presented based on functional analysis arguments approach, which leads to a relaxed problem without integer gap – the so-called “outer convexification”. The resulting problem can then be solved by the well-known “direct” multiple shooting method as an “all-at-once” approach. Moreover, the optimal solution can be arbitrarily closely approximated by an integer solution with finitely many switches. The gain in performance is enormous, orders of magnitude of speed-up over a state-of-the-art MINLP approach to a control problem, where the NP hardness of the discretized problem is demonstrated to be computationally prohibitive. Real-time applications of a “multi-level real-time iteration” NMPC method to compute energy optimal feedback cruise control on-board of Daimler heavy-duty trucks, as well as minimum time control of a fictitious racecar around the Hockenheim race-track are presented. The presentation is based on joint work with F. Kehrle, C. Kirches, E. A. Kostina, F. Lenders, R. W. Longman, D. B. Muralidhara, S. Sager and J. P. Schlöder.

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### 3. Optimal stopping, singular and impulse control and their applications 1

10:30 – 11:45

*Chair:* S. Federico, G. Ferrari, T. De Angelis

FH HS 7

#### Capacity expansion games with application to competition in power generation investments

René Aïd (1), Liangchen Li (2), Michael Ludkovski (2),

(1) Université Paris-Dauphine, PSL Research University. (2) University of California at Santa Barbara, Department of Statistics and Applied Probability.

We consider competitive capacity investment for a duopoly of two distinct producers. The producers are exposed to stochastically fluctuating costs and interact through aggregate supply. Capacity expansion is irreversible and modeled in terms of timing strategies characterized through threshold rules. Because the impact of changing costs on the producers is asymmetric, we are led to a nonzero-sum timing game describing the transitions among the discrete investment stages. Working in a continuous-time diffusion framework, we characterize and analyze the resulting Nash equilibrium and game values. Our analysis quantifies the dynamic competition effects and yields insight into dynamic preemption and over-investment in a general asymmetric setting. A case-study considering the impact of fluctuating emission costs on power producers investing in nuclear and coal-fired plants is also presented.

#### The dividend problem with stochastic discount

Elena Bandini (1), Tiziano De Angelis (2), Giorgio Ferrari (3), Fausto Gozzi (4),

(1) Università degli Studi di Milano-Bicocca, Milano, Italy (2) School of Mathematics, University of Leeds, Leeds, United Kingdom (3) Center for Mathematical Economics, Bielefeld University, Bielefeld, Germany (4) LUISS Roma, Roma, Italy

We study the optimal dividend problem for a fund manager who aims at maximizing the flow of dividends discounted according to an interest rate which is stochastic, and in particular follows a CIR dynamics. The fund income is modeled as a Brownian motion with drift, and is required to be greater than a nonnegative minimum capital  $\alpha$ . We characterize the value function of the dividend problem as the unique classical solution of a suitable Hamilton-Jacobi-Bellman equation. Moreover, we prove that the optimal dividend strategy is realized by a Skorokhod reflection of the fund value at the optimal boundary evaluated at the stochastic interest rate. Our results are obtained by establishing a connection between the dividend problem and a suitable optimal stopping problem on a diffusion reflected at  $\alpha$  and created at a rate proportional to its local time.

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### Nonzero-sum stochastic differential games with impulse controls: a verification theorem with applications

Luciano Campi (1), René Aïd (2), Matteo Basei (3), Giorgia Callegaro (4), Tiziano Vargiolu (4),

(1) London School of Economics, London, United Kingdom (2) University Paris Dauphine, Paris, France  
(3) University of California, Berkeley, USA (4) University of Padua, Padua, Italy

We consider a general nonzero-sum impulse game with two players. The main mathematical contribution of the paper is a verification theorem which provides, under some regularity conditions, a suitable system of quasi-variational inequalities for the value functions and the optimal strategies of the two players. As an application, we study an impulse game with a one-dimensional state variable, following a real-valued scaled Brownian motion, and two players with linear and symmetric running payoffs. We fully characterize a Nash equilibrium and provide explicit expressions for the optimal strategies and the value functions. We also prove some asymptotic results with respect to the intervention costs. Finally, we consider two further non-symmetric examples where a Nash equilibrium is found numerically.

### 4. Spatial resource and environmental economics and dynamic games 1

10:30 – 11:45

*Chair:* S. Behringer, T. Upmann

FH 8 Nöbauer HS

#### Spatial resource wars: a two regions example

Silvia Faggian (1), Giorgio Fabbri (2), Giuseppe Freni (3),

(1) Department of Economics, Ca' Foscari University of Venice, Italy (2) Univ. Grenoble Alpes, CNRS, INRA, Grenoble INP, GAEL, Grenoble, France (3) Department of Business and Economics, Parthenope University of Naples, Italy

We develop a spatial resource competition model in continuous time in which two agents strategically exploit a mobile resource in a two-locations setup.

In order to contrast the overexploitation of the resource (the *tragedy of commons*) that occurs when players are free to choose where to fish/hunt/extract/harvest, the regulator can establish a series of spatial-structured policies. We compare the three following situations: (i) the regulator leaves the player free to choose where to harvest; (ii) the regulator establishes a natural reserve where nobody is allowed to harvest; (iii) the regulator assigns to each player a specific (and exclusive) location to harvest.

We show that in the situations where the agents are in a position to choose a low harvesting intensity, the policies cannot mitigate the overexploitation and, in addition, they typically worsen the utilities of the players. Conversely, in a context of high harvesting intensity, the regulator's intervention can help to safeguard the resource, both preventing the extinction and improving the welfare of both players.

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### A spatial model of resource wars

Giorgio Fabbri (1), Silvia Faggian (2), Giuseppe Freni (3),

(1) Univ. Grenoble Alpes, CNRS, INRA, Grenoble INP, GAEL, Grenoble, France (2) Department of Economics, Ca' Foscari University of Venice, Venice, Italy (3) Department of Business and Economics, Parthenope University of Naples, Naples, Italy

Continuous time in models where a common property resource stock is exploited simultaneously by  $N$  agents, and in particular their Stationary Markov perfect Nash equilibria, have been widely studied in literature under different sets of hypotheses.

Here we treat the case of a resource which is distributed in space and mobile through the entire territory (such as a fish population or a transboundary oil deposit). As a spatial support we consider a generic finite simple graph, where we specify productivity at each node. We also assume that the diffusion process follows Fick's first law among connected nodes, and we specify for each arc the "intensity" of the connection.

We characterize internal linear Markov Nash equilibria for the dynamic game of  $N$  symmetric players having the same isoelastic utility. We show how they depend on the structure of the graph and we describe the efficiency of the related spatial public policies.

### Optimal economic growth through capital accumulation in a spatially heterogeneous environment

Raouf Boucekkine (1), Giorgio Fabbri (2), Salvatore Federico (3), Fausto Gozzi (4),

(1) Aix-Marseille Université, AMSE, Marseille, France (2) Univ. Grenoble Alpes, CNRS, INRA, Grenoble INP, GAEL, Grenoble, France (3) Dipartimento di Economia Politica e Statistica, Università di Siena, Siena, Italy (4) Dipartimento di Economia e Finanza, LUISS University, Rome, Italy

We design a general set-up for the study of a generic economy whose development process is entirely driven by the spatio-temporal dynamics of capital accumulation. It allows us to take into account spatial heterogeneity in technological level and population distribution. We solve analytically, via dynamic programming in infinite dimensions, the optimal control problem associated to the model, finding explicitly the optimal feedback and the value function. The expression of the optimal dynamics of the system in terms of eigenfunctions of an appropriate Sturm-Liouville problem allows to simulate the behavior of the variables and, in particular, their optimal discounted long-run spatial distribution.



5. Variational analysis in optimization (In honor of A.L.Dontchev) 1

10:30 – 11:45

*Chair:* R. Cibulka, F. Aragon

FH HS 3

A uniform approach to Hölder calmness of subdifferentials

Marco A. López-Cerdá (1), Gerald Beer (2), María J. Cánovas (3), Juan Parra (3),

(1) University of Alicante, Alicante, Spain (2) California State University, Los Ángeles, California, USA  
 (3) Universidad Miguel Hernández, Elche, Spain

For finite-valued convex functions  $f$  defined on the  $n$ -dimensional Euclidean space, we are interested in the set-valued mapping assigning to each pair  $(f, x)$  the subdifferential of  $f$  at  $x$ . Our approach is uniform with respect to  $f$  in the sense that it involves pairs of functions close enough to each other, but not necessarily around a nominal function. More precisely, we provide lower and upper estimates, in terms of Hausdorff excesses, of the subdifferential of one of such functions at a nominal point in terms of the subdifferential of nearby functions in a ball centered in such a point. In particular, we obtain the (1/2)-Hölder calmness of our mapping at a nominal pair  $(f, x)$  under the assumption that the subdifferential mapping viewed as a multifunction from  $\mathbb{R}^n$  to  $\mathbb{R}^n$  with  $f$  fixed is calm at each point of  $\{x\} \times \partial f(x)$ .

Tangential transversality

Nadezhda K. Ribarska (1, 2), Mira I. Bivas (1, 2), Mikhail I. Krastanov (1, 2),

(1) Faculty of Mathematics and Informatics, Sofia University, Sofia, Bulgaria (2) Institute of Mathematics and Informatics, Bulgarian Academy of Sciences, Sofia, Bulgaria

The concept of tangential transversality in Banach spaces is introduced (c.f. [1]). We show that it is weaker than transversality (see [4]) and strong tangential transversality (see [2]), and (may be) stronger than subtransversality (see [4]). Sufficient conditions for tangential transversality are discussed, including the case when one of the sets is more general than compactly epi-Lipschitz (introduced in [3]). New abstract Lagrange multiplier rule is proven and applied to an infinite-dimensional optimal control problem.

[1] M. Bivas, M. Krastanov, N. Ribarska, On tangential transversality, preprint, 2018.

[2] M. Bivas, M. Krastanov, N. Ribarska, On strong tangential transversality, preprint, 2018.

[3] J.M. Borwein, H.M. Strojwas, Tangential approximations, *Nonlinear Analysis: Theory, Methods & Applications*, Volume 9, Issue 12 (1985), 1347-1366.

[4] A. Ioffe, Transversality in Variational Analysis, *J Optim Theory Appl* (2017), 174(2), 343-366.

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## Stability analysis for optimal control problems with bang-bang solutions

Teresa Scarinci (1), Jakob Preininger (2), Vladimir M. Veliov (2),

(1) ISOR, University of Vienna, Vienna, Austria (2) ORCOS, Vienna University of Technology, Vienna, Austria

In this talk we investigate a class of linear-quadratic optimal control problems where the control variable appears linearly and is constrained in a box  $[-1, 1]^m$ . Thus, the cost functional does not involve the usual quadratic term for the control variable. In this setting the optimal controls may be discontinuous with a finite number of switching points. Firstly, we discuss the stability of the optimal solutions under a certain class of perturbations of the problem. Then, we deduce some metric regularity properties for the mapping associated to the generalized equation of the Pontryagin Maximum Principle. The main results presented in this talk are shown in [1].

[1] J. Preininger, T. Scarinci, V. Veliov. *Metric regularity properties in bang-bang type linear-quadratic optimal control problems*. Preprint, 2017.

## 6. Turnpike properties for ODEs and PDEs: theory and application 1

10:30 – 11:45

*Chair:* L. Grüne

FH HS 2

### Indefinite linear quadratic optimal control: Periodic dissipativity and turnpike properties

Julian Berberich (1), Johannes Köhler (1), Frank Allgöwer (1), Matthias A. Müller (1),

(1) Institute for Systems Theory and Automatic Control, University of Stuttgart, Stuttgart, Germany

This talk is about discrete-time indefinite linear quadratic (LQ) optimal control problems in the presence of constraints on states and inputs. In the recent literature, a characterization of the optimal trajectories of LQ-problems was given in terms of strict dissipativity and turnpike properties at steady-states, provided that the stage cost is positive semidefinite. By taking the particular shape of the constraints into account, we show that these results can be generalized to *indefinite* cost functions and *periodic orbits*.

In particular, sufficient conditions for strict dissipativity with respect to periodic orbits and steady-states in constrained indefinite LQ-problems are discussed. It is shown that the corresponding optimal periodic orbit can be computed explicitly using a non-strict dissipation inequality and is, in many cases, located on the boundary of the constraints. A similar technique is applied to analyze strict dissipativity at steady-states, where some of the arguments simplify. In particular, negative eigenvalues of the cost, the exact shape of the constraints, and the location of the optimal steady-state are highly intertwined and allow for an intuitive geometric interpretation.

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### Turnpike properties for time-varying systems

Lars Grüne (1), [Simon Pirkelmann](#) (1), Marleen Stieler (1),

(1) University of Bayreuth, Bayreuth, Germany

The classical turnpike property states that open-loop optimal trajectories will stay close to an optimal equilibrium most of the time. In the case of time-varying systems we have to deal with a more general time-varying optimal trajectory instead of an optimal equilibrium. Accordingly, we have to consider a time-varying version of the turnpike property.

While the turnpike property is easily observed in simulations it is in general difficult to be verified directly for a given system. In the talk we will present sufficient conditions for establishing the time-varying turnpike property by means of strict dissipativity.

Furthermore, we also show that under additional controllability conditions a continuity property of the optimal value function can be established, which turns out to be useful for proving performance estimates for model predictive control schemes in the time-varying setting.

As an illustration of the theoretic results we present examples of time-varying systems for which we can establish the turnpike property both numerically and by verifying the sufficient conditions of our results.

### Economic MPC with gradient-correcting end penalties

[Timm Faulwasser](#) (1), Mario Zanon (2),

(1) Institute for Automation and Applied Informatics, Karlsruhe Institute of Technology, Karlsruhe, Germany (2) IMT Lucca, Lucca, Italy

In recent years, Economic MPC (EMPC) has gained popularity due to the promise of increasing performance by directly optimizing the performance index rather than tracking a given steady state [1,2]. Moreover, EMPC formulations without terminal cost nor constraints are appealing for the simplicity of implementation. However, the stability and convergence analysis for such formulations is rather involved and so far only practical stability (in discrete time), respectively, practical convergence (in sampled-data continuous time) has been proven; i.e., convergence to a horizon-dependent neighborhood of the optimal steady state. Here, we show that, whenever the cost has a non-zero gradient at the optimal steady-state and the MPC formulation satisfies a regularity assumption, nominal stability to the economic optimum cannot be achieved. Moreover, we show that in a sampled-data setting this problem is caused by limit-cycle behavior close to the optimal steady-state. We propose to solve this problem by introducing a linear terminal penalty correcting the gradient at steady state [3]. We prove that this simple correction enforces uniform exponential stability of the economically optimal steady state. We illustrate our findings in simulations using three examples.

- [1] M. Ellis, H. Durand & P.A. Christofides. A tutorial review of economic model predictive control methods. *Journal of Process Control*, 2014, 24, 1156-1178.
- [2] T. Faulwasser, L. Grüne & M. Müller. Economic Nonlinear Model Predictive Control: Stability, Optimality and Performance. *Foundations and Trends in Systems and Control*, 2018, 5, 1-98.
- [3] M. Zanon, M. & T. Faulwasser. Economic MPC without terminal constraints: Gradient-correcting end penalties enforce stability. *Journal of Process Control*, 2018.

## 7. Dynamic games in industrial organization

10:30 – 11:45

Chair: M. Kopel

FH HS 4

### Delaying product introduction in a duopoly: a strategic dynamic analysis

Herbert Dawid (1), [Serhat Gezer](#) (1),

(1) Department of Business Administration and Economics and Center for Mathematical Economics, Bielefeld University, Bielefeld, Germany

We consider an economy where initially two firms are active on a homogeneous product market. One of the firms has an option to introduce a substitute product in addition to the existing product by incurring adoption costs. We numerically derive the optimal introduction time and the associated Markov-perfect equilibria for investment in capacities and find that depending on the initial capacities on the established market and the value of adoption costs, three scenarios are possible for the innovator, namely innovating immediately, delaying introduction and abstaining from product introduction. In case of delay, the innovator strategically reduces investment in capacities on the established market prior to product introduction in order to increase the marginal value of the new product when switching.

### Regulating the tragedy of commons: nonlinear feedback solutions of a differential game with a dual interpretation

[Luca Lambertini](#) (1),

(1) Dipartimento di Scienze Economiche, Università di Bologna, Bologna, Italy

A well established dynamic model describing the impact of oligopolistic interaction on a renewable resource is revisited here to illustrate its dual interpretation as a waste removal differential game. The regulatory implications are illustrated by assuming that the public agency may control market price and possibly also access to the commons. Two different formulations of the managerial or CSR objective are envisaged, based on a combination of profits and either output or the individual share of the waste stock. It is shown that if the representative firm's objective includes the residual waste stock, there exists a unique regulated price driving to zero the steady state stock itself. Hence, the present analysis delivers some useful indications concerning an appropriate definition of the CSR objective firms should adopt.

### Robust games: theory and application to a Cournot duopoly model

[Davide Radi](#) (1), [Giovanni P. Crespi](#) (2), [Matteo Rocca](#) (2),

(1) Department of Economics and Management, University of Pisa, Pisa, Italy (2) Department of Economics, Insubria University, Varese, Italy

In this paper the *robust game* model proposed by Aghassi and Bertsimas, see [1], for matrix games is extended to games with a broader class of payoff functions. This is a distribution-free model of incomplete information for finite games where players adopt a robust optimization approach to contend with payoff uncertainty. They are called *robust players* and seek the maximum guaranteed payoff given the strategy of the others. Consistently with this decision criterion, a set of strategies is an equilibrium, *robust-optimization*

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*equilibrium*, if each player's strategy is a best response to the other player's strategies, under the worst-case scenarios.

The aim of the paper is twofold. In the first part, we provide robust-optimization equilibrium's existence result for a quite general class of games and we prove that it exists a suitable value  $\epsilon$  such that robust-optimization equilibria are a subset of  $\epsilon$ -Nash equilibria of the nominal version, i.e. without uncertainty, of the robust game. This provides a theoretical motivation for the robust approach, as it provides new insight and a rational agent motivation for  $\epsilon$ -Nash equilibrium. In the last part, we propose an application of the theory to a classical Cournot duopoly model which shows significant differences between the robust game and its nominal version.

- [1] M. Aghassi and D. Bertsimas. Robust game theory. *Mathematical Programming Series B* 107: 231–273, 2006.

## 8. Optimal stopping, singular and impulse control and their applications 2

11:55 – 12:45

*Chair:* S. Federico, G. Ferrari, T. De Angelis

FH HS 7

### Impulse control of non-uniformly ergodic processes with average cost criterion

Jan Palczewski (1), Ł. Stettner (2),

(1) School of Mathematics, University of Leeds, Leeds, United Kingdom (2) Mathematical Institute, Polish Academy of Sciences, Poland

We study a problem of impulse control of a Feller-Markov process that maximises the average cost per unit time criterion:

$$\liminf_{T \rightarrow \infty} \frac{1}{T} E^x \left\{ \int_0^T f(X_s) ds - \sum_{i=1}^{\infty} 1_{\tau_i \leq T} c(X_{\tau_i-}, \xi_i) \right\},$$

where  $f$  is a running reward and  $c \geq 0$  is an impulse cost. We characterise optimal strategies via a solution to an auxiliary Bellman equation. The novelty of the paper is a general treatment of models in which  $(X_t)$  is supported on unbounded space and not uniformly ergodic. We also allow for the cost of an impulse to be unbounded, e.g., proportional to the distance the process is shifted. Our results have applications in balancing of energy systems and in managing inventories.

### Preemptive investment under uncertainty

Jan-Henrik Steg (1),

(1) Center for Mathematical Economics, Bielefeld University, Germany

This paper provides a general characterization of subgame-perfect equilibria for strategic timing problems, where two firms have the (real) option to make an irreversible investment. Profit streams are uncertain and depend on the market structure. The analysis is based directly on the inherent economic structure of the model. In particular, determining equilibria with preemptive investment is reduced to solving a single class of constrained optimal stopping problems. Further tools are derived for analyzing Markovian state-space models. Applications to typical models from the literature complete commonly insufficient equilibrium arguments, show when uncertainty leads to qualitatively different behavior, and establish additional equilibria that are Pareto improvements.

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## 9. Spatial resource and environmental economics and dynamic games 2

11:55 – 12:45

*Chair:* S. Behringer, T. Upmann

FH 8 Nöbauer HS

Self enforcing environmental agreements, delayed information and external enforcement in a continuous time Fish Wars model with state dependent constraints

Rajani Singh (1), Agnieszka Wiszniewska-Matyszkiewicz (1),

(1) University of Warsaw, Faculty of Mathematics, Informatics and Mechanics, Poland

In this paper, we analyse a continuous time version of Fish Wars with the infinite time horizon and state dependent constraints on controls. We calculate the social optimum and a Nash equilibrium which always leads to the depletion of the resource even if the social optimum results in the sustainability. We propose two ways of solving the problems of enforcing optimality: either by a tax-subsidy system or by an environmental agreement even if we assume that it takes time to detect any defection of a player. We also propose a general algorithm of finding financial incentives enforcing the optimal profile in a large class of differential games.

### Stationary solutions in populations dynamic: stability and optimization

Alexey A. Davydov (1, 2, 3),

(1) National University of Science and Technology “MISIS”, Moscow, Russia (2) Lomonosov Moscow State University, Moscow, Russia (3) International Institute for Applied System Analysis, Laxenburg, Austria

Dynamic of exploited population under a selected management mode can converge to some stationary state. To see this effect it is sufficient to consider the simplest case of logistic model [1]. But for more general cases, for example, with dynamic accounting population structure or some nonlinear law of reproduction of new generation, or else some other natural processes or parameters, such effects could be non-obvious and need to be justified (see, for example, [2]-[3]).

We consider a generalization of known McKendrick model [4] and analyze the existence of nontrivial stationary solution for a given (and also stationary) admissible exploitation mode. It is proved that there exists nontrivial stationary solution, and in addition, there is an optimal exploitation mode that for a given objective function provides the maximum profit over all stationary solutions (see, for example, [5], [6]). Illustrated numerical examples are also presented.

The work is done by partial financial support by Ministry of Education and Science of the Russian Federation under the project 1.638.2016/FPM.

[1] V.I. Arnold, *"Hard" and "soft" mathematical models*. MCCME, Moscow, 2004.

[2] A.Calsina, J.Saldana. Asymptotic behaviour of a model of hierarchically structured population dynamic. *J.Math. Biol.*, 35 : 967-987, 1997.

[3] A.O.Belyakov, A.A.Davydov, V.M.Veliiov. Asymptotic behaviour of a model of hierarchically structured population dynamic. *Journal of Dynamical and Control Systems*, 21 (3): 475-494, 2015.

[4] J.D.Murray, *Mathematical Biology: an introduction. third edition. Interdisciplinary Applied Mathematics. Mathematical Biology*. Springer: 2002.

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- [5] A.A.Panesh, A.S.Platov. Optimization of size-structured population with interacting species. *Journal of Mathematical Sciences*, 188(3): 293-298, 2013.
- [6] A.A.Davydov, A.F.Nassar. On the Uniqueness of a Positive Stationary State in the Dynamics of a Population with Asymmetric Competition. *Proc. Steklov Inst. Math.*, 291: 78-86, 2015.

## 10. Variational analysis in optimization (In honor of A.L.Dontchev) 2

11:55 – 12:45

Chair: R. Cibulka, F. Aragon

FH HS 3

### Metric regularity and subregularity in linear optimization

María J. Cánovas (1), Marco A. López (2), Juan Parra (1), F. Javier Toledo (1),

- (1) Center of Operations Research, Miguel Hernández University of Elche, Elche (Alicante), Spain  
(2) Department of Mathematics, University of Alicante, Spain

This talk presents a brief overview of our research, together with some international collaborators, on the metric regularity and subregularity in the context of linear optimization problems under canonical perturbations. Our first results on this subject grew out of the cooperation with Asen Dontchev giving rise to the publication of [1] in 2005. These first results provide formulae for computing the modulus of metric regularity in the context of linear constraint systems. It is well-known that the modulus of metric regularity (resp. subregularity) of a multifunction does coincide with the Lipschitz (resp. calmness) modulus of its inverse. After the announced starting point, in this talk we present new formulae/estimations for the Lipschitz modulus in the context of linear problems, for both, the optimal set mapping and the optimal value function (some of them very recent). Moreover, the counterpart results on the calmness modulus are also presented.

- [1] M. J. Cánovas, A. L. Dontchev, M. A. López, J. Parra, *Metric regularity of semi-infinite constraint systems*, Math. Programming 104B (2005), pp. 329–346.

This research has been partially supported by Grant MTM2014-59179-C2-(1-2)-P from MINECO, Spain, and FEDER “Una manera de hacer Europa”, European Union. The third author was partially supported by the Australian Research Council, Project DP160100854.

### Local convergence of the Levenberg–Marquardt method under Hölder metric subregularity

Masoud Ahokhosh (1), Francisco J. Aragón-Artacho (2), Ronan M.T. Fleming (1), Phan Tu Vuong (3),

- (1) Systems Biochemistry Group, LCSB, University of Luxembourg, Luxembourg (2) Dept. of Mathematics, University of Alicante, Spain (3) Institute of Statistics and Mathematical Methods in Economics, Vienna University of Technology, Austria

We describe and analyze Levenberg–Marquardt methods for solving systems of nonlinear equations. More specifically, we propose an adaptive formula for the Levenberg–Marquardt parameter and analyze the local convergence of the method under Hölder metric subregularity of the function defining the equation and Hölder continuity of its gradient. Further, we analyze the local convergence of the method under

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the additional assumption that the Lojasiewicz gradient inequality holds. We finally report encouraging numerical results confirming the theoretical findings for the problem of computing moiety conserved steady states in biochemical reaction networks. This problem can be cast as finding a solution of a system of nonlinear equations, where the associated mapping satisfies the Lojasiewicz gradient inequality assumption.

## 11. Turnpike properties for ODEs and PDEs: theory and application 2

11:55 – 12:45

*Chair:* L. Grüne

FH HS 2

**Predictive control with multiple interacting agents: The NMPC Feedback Nash Equilibrium**

Giovanni Di Bartolomeo (1), Enrico Saltari (1), Willi Semmler (2),

(1) Department of Economics and Law, Sapienza University of Rome, Rome, Italy (2) Schwartz Center for Economic Policy Analysis, New School, New York, United States

Our paper extends the non-linear model predictive control techniques to differential strategic games. We consider a game where players interact in each instant of time by forecasting the dynamics of some target variables and opponents' moves along a given future time horizon. Each adopt a receding horizon strategy, so that at each instant the horizon is moved towards the future. This involves the application of the first control signal of the sequence calculated at each step. Our solution results in a control defined on an infinite horizon with feedback structure, we thus refer to it as Non-linear model predictive control Feedback Nash Equilibrium.

### Turnpike properties and strict dissipativity for LQ optimal control problems

Lars Grüne (1), Roberto Guglielmi (2),

(1) Mathematical Institute, University of Bayreuth, Germany (2) Mathematics Department, Gran Sasso Science Institute, L'Aquila, Italy

In the talk we present some recent results on the connection between turnpike behaviors and strict dissipativity properties for finite dimensional linear quadratic (LQ) optimal control problems. The focus is on providing characterizations of strict dissipativity and the newly introduced property of strict pre-dissipativity in terms of the system matrices related to the LQ problem. These characterizations then lead to new necessary conditions for the turnpike properties under consideration, and thus eventually to necessary and sufficient conditions in terms of spectral criteria and matrix inequalities. In particular, the techniques allow to encompass the presence of state and input constraints. Finally, several examples illustrate the different turnpike behaviors of the system in the presence or absence of constraints. The talk is based on a joint work with Lars Grüne [1].

[1] L. Grüne and R. Guglielmi. Turnpike properties and strict dissipativity for discrete time linear quadratic optimal control problems. *accepted for publication in SIAM Journal on Control and Optimization (SICON)*, 1–21, 2018.



**12. Contributed session: applications of optimal control 1**

**11:55 – 12:45**

*Chair:* G. Tragler

**FH HS 4**

**Optimal control for a harmful population model**

Narcisa C. Apreutesei (1),

(1) Department of Mathematics and Informatics, “Gheorghe Asachi” Technical University of Iasi, Romania

We study an optimal control problem associated to a reaction-diffusion system that models the dynamics of a harmful invasive population. Assume that the population is composed by normal females and males and some genetically modified organisms. The last ones are considered as supermales and feminized supermales. Mating with them produces only males and supermales. In time the number of normal females decreases, thus finally leading to the extinction of the population. This is also a way to eradicate a harmful invasive species. Regarding the problem as an optimal control one, our goal is to minimize the female population, maximize the male population, and to minimize the rate of introduction of the feminized supermales. The existence of an optimal solution is established and some optimality conditions are found.

**Control of addictive behaviours with relapsing**

Fouad El Ouardighi (1), Dieter Grass (2),

(1) ESSEC Business School, Avenue Bernard Hirsch, Cergy Pontoise, France

(2) ORCOS, Vienna University of Technology, Vienna, Austria

One important consequence of addictions is the high occurrence of relapsing after treatment, which often lies between 40 and 60% depending on the kind of addiction and population [1]. While the importance of prevention-treatment policies against addictions is widely acknowledged in the economic literature, the consequences of relapsing on the effectiveness of such policies remain yet under-investigated. This paper seeks to bridge the gap by introducing a dynamic model where individuals can move back and forth between active addiction and temporary abstinence. Though both states are socially costly, active addiction promotes initiation by others while temporary abstinence discourages it. Our main purpose here is to evaluate how the tradeoff between eradication and accommodation of addiction is affected by the occurrence of relapsing.

- [1] A. Thomas McLellan and David C. Lewis and Charles O’Brien and Herbert D. Kleber. Constant versus periodic fishing: Drug dependence, a chronic medical illness: Implications for treatment, insurance, and outcomes evaluation. *JAMA*, 284(13):1689–1695, 2000.

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13. New trends in theory of stochastic control 1

14:00 – 15:40

*Chair:* H. Frankowska, M. Quincampoix

FH HS 7

Systems of quasilinear parabolic equations in  $\mathbb{R}^n$  and systems of quadratic BSDE

Alain Bensoussan (1), Jens Frehse (2), Phillip Yam (3),

(1) University of Texas, Dallas, United States of America (2) University of Bonn, Bonn, Germany (3) The Chinese University of Hong Kong, Hong Kong

The objective of this paper is twofold. On the one hand, we complete the work of A. Bensoussan and J. Frehse. One big limitation of this work was the fact that systems of P.D.E. were set on a bounded domain. One can then expect solutions to be bounded, since one looks for smooth solutions. This is a very important property for the development of the method. It is true also that solutions which exist in a bounded domain may fail to exist on  $\mathbb{R}^n$ , because of the lack of bounds. We give conditions so that the results of Bensoussan-Frehse can be extended to  $\mathbb{R}^n$ . The second objective is to consider the BSDE (Backward stochastic differential equations) version of the system of P.D.E. This is the objective of a more recent work of H. Xing and G. Žitković. They consider systems of BSDE with quadratic growth, which is a well-known open problem in the BSDE literature. Since the BSDE are markovian, the problem is equivalent to the analytic one. However, because of this motivation the analytic problem is in  $\mathbb{R}^n$  and not on a bounded domain. Xing and Žitković develop a probabilistic approach. The connection between the analytic problem and the BSDE is not apparent. Our objective is to show that the analytic approach can be completely translated into a probabilistic one. Nevertheless, probabilistic concepts are also useful, after translation into the analytic framework. This is in particular true for the uniqueness result that is obtained.

Characterization of optimal feedback for stochastic linear quadratic control problems

Qi Lü (1), Tianxiao Wang (1), Xu Zhang (1),

(1) School of Mathematics, Sichuan University, Chengdu, China

One of the fundamental issues in Control Theory is to design feedback controls. It is well-known that, the purpose of introducing Riccati equations in the study of deterministic linear quadratic control problems is to construct the desired feedbacks. To date, the same problem in the stochastic setting is only partially well-understood. In this work, we establish the equivalence between the existence of optimal feedback controls for the stochastic linear quadratic control problems with random coefficients and the solvability of the corresponding backward stochastic Riccati equations in a suitable sense. We also give a counterexample showing the nonexistence of feedback controls to a solvable stochastic linear quadratic control problem.

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### Ergodic maximum principle for stochastic systems

Gianmario Tessitore (1), Carlo Orrieri (2), Petr Veverka (3),

(1) Università di Milano Bicocca, Milan, Italy (2) Sapienza University of Roma, Rome, Italy (3) Czech Technical University, Prague, Czech Republic

We present a version of the stochastic maximum principle (SMP) for ergodic control problems. In particular we give necessary (and sufficient) conditions for optimality for controlled dissipative systems in finite dimensions. The strategy we employ is mainly built on duality techniques. We are able to construct a dual process for all positive times via the analysis of a suitable class of perturbed linearized forward equations. We show that such a process is the unique bounded solution to a Backward SDE on infinite horizon from which we can write a version of the SMP.

### A smoothing-verification approach for a stochastic target problem

Bruno Bouchard (1), Grégoire Loeper (2), Yiyi Zou (1),

(1) Université Paris-Dauphine, PSL Research University, CEREMADE, CNRS, Paris, France (2) Monash University, School of Mathematical Sciences, Victoria, Australia

We consider a stochastic target problem motivated by applications in mathematical finance. We prove that the value function is the viscosity solution of a fully non-linear parabolic equation. The main novelty comes from the derivation of the sub-solution property. We can not use standard techniques by lack of the appropriate dynamic programming principle. Instead, we use a smoothing/verification approach. This method can be used whenever the Hamiltonian is convex, which is the case for our application, namely the problem of hedging a covered European option under a gamma constraint and with market impact. This presentation is based on [1]. A similar approach was first used in [2].

[1] B. Bouchard, G. Loeper and Y. Zou. Hedging of covered options with linear price impact and gamma constraint. *SIAM Journal on Control and Optimization*, forthcoming.

[2] B. Bouchard and M. Nutz. Stochastic target games and dynamic programming via regularized viscosity solutions. *Mathematics of Operation Research.*, 41(1):109–124, 2016.

## 14. PDE-constrained optimization in economics

14:00 – 15:40

*Chair:* F. Gozzi, S. Faggian, G. Fabbri

FH 8 Nöbauer HS

### Habits and neighborhood effects

Emmanuelle Augeraud-Véron (1), Mauro Bambi (2),

(1) GREThA, University of Bordeaux, Bordeaux, France (2) Department of Economics, University of York, York, England

In this paper we modify a standard habit formation model to include a spatial dimension. As a consequence the external habits of an agent now depend more strongly on the consumption of those agents living closer to her. This feature is relevant because there are evidences that addictive behavior

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may also depend on the location where an agent is consuming and, therefore, our framework seems a natural way to investigate these issues. On a methodological side, the key equations describing the agents' rational decisions are a system of PDEs, with non-local interactions. We study how the interaction kernel modifies the equilibrium dynamics.

### Capital accumulation and the growth-inequality nexus

Paulo B. Brito (1),

(1) ISEG and UECE, Universidade de Lisboa, Lisbon, Portugal

In this paper we address the joint income and wealth distributions and economic growth processes by combining the inherent conservative property of distributions, highlighted by the mean-field game literature, and simple capital accumulation dynamics of benchmark economic growth theory. Given an initial unequal distribution of capital, and assuming a deterministic setting, we show that there are three main types of evolutions: asymptotic equality but no long run growth, asymptotic growth and a stationary distribution featuring inequality, or growth together with increasing inequality. The last type of evolution is Pareto optimal if capital accumulation depends linearly on the capital stock. Introducing a multiplicative random capital redistribution process, we show that we always get an increase in inequality although it can occur together with growth (if noise is relatively low) or within a non-growth context (when noise is very high).

### Does demography change wealth inequality?

Miguel Sánchez-Romero (1), Stefan Wrzaczek (1,2), Alexia Prskawetz (1,2), Gustav Feichtinger (1,2),

(1) Wittgenstein Centre for Demography and Global Human Capital (IIASA, VID/ÖAW, WU) (2) ORCOS, Vienna University of Technology, Vienna, Austria

In this article, we investigate the effect of demography on wealth inequality. We propose an economic growth model with overlapping generations in which individuals are altruistic towards their children and differ with respect to the age of their parent. We denote the age gap between the parent and their child as generational gap. The introduction of the generational gap allows us to analyze wealth inequality not only across cohorts but also within cohorts. Our model predicts that a decline in fertility raises wealth inequality within cohorts and, simultaneously, it reduces inequality at the population level (across cohorts). In contrast, increases in life expectancy result in a non-monotonic effect on wealth inequality by age and across cohorts.

### Robust control of spatially extended economic systems under uncertainty

Athanasios N. Yannacopoulos (1), Ioannis Baltas (2), Anastasios Xepapadeas (3),

(1) Department of Statistics, Athens University of Economics and Business, Athens, Greece (2) Department of Financial and Management Engineering, University of the Aegean, Chios, Greece (3) Department of International and European Economics Studies, Athens University of Economics and Business, Athens, Greece

The present paper is devoted to the study of robust control problems of parabolic stochastic partial differential equations under model uncertainty. To be more precise, the robust control problem under

investigation is expressed as a stochastic differential game in a real separable infinite dimensional Hilbert space. By resorting to the theory of mild solutions, we prove that the elliptic partial differential equation associated with the problem at hand, also known as the Hamilton-Jacobi-Bellman-Isaacs equation, admits a unique solution, which is the value function of the game. Furthermore, we prove the existence of an optimal control pair that satisfies a saddle point property. Finally, as a demonstration of the proposed approach, we apply our results to the study of a certain robust control problem arising in the spatiotemporal management of natural resources.

## 15. Approximation of differential inclusions and control problems 1

14:00 – 15:40

*Chair:* R. Baier, E. Farkhi

FH HS 3

### Approximation approaches for trajectory tubes of differential inclusions with impulsive terms

Tatiana F. Filippova (1, 2),

(1) N.N.Krasovskii Institute of Mathematics and Mechanics, Ural Branch of Russian Academy of Sciences, Ekaterinburg, Russia (2) Ural Federal University, Ekaterinburg, Russia

We consider the problem of estimating reachable sets of nonlinear dynamical systems with impulsive controls and with uncertainty in initial states when we assume that we know only the bounding set for initial system positions and any additional statistical information is not available. The problem may be reformulated as the problem of describing the motion of set-valued states for related differential inclusions containing impulsive control components and uncertain initial states. Using recent results of the theory of control systems under uncertainty [1, 2] and techniques of differential inclusions theory we find set-valued estimates of related reachable sets of such nonlinear uncertain control system.

The research was supported by Russian Science Foundation (RSF Project No.16-11-10146).

- [1] T.F. Filippova. Ellipsoidal estimates of reachable sets for control systems with nonlinear terms. *IFAC-PapersOnLine: 20th World Congress of the International Federation of Automatic Control (IFAC-2017), Toulouse, France, July 9-14, 2017: proceedings*, 50(1):15925–15930, 2017.
- [2] T.F. Filippova. Estimation of Star-Shaped Reachable Sets of Nonlinear Control Systems. *Lirkov I., Margenov S. (eds) Large-Scale Scientific Computing (LSSC 2017). Lecture Notes in Computer Science*. Springer, Cham, 2018. Vol.10665:210–218.

### Discrete Filippov-type stability for one-sided Lipschitzian difference inclusions

Robert Baier (1), Elza M. Farkhi (2),

(1) Chair of Applied Mathematics, University of Bayreuth, Bayreuth, Germany (2) School of Mathematical Sciences, Tel Aviv University, Tel Aviv, Israel

The *one-sided Lipschitz (OSL)* regularity of set-valued maps is a notion for weakening the usual Lipschitz continuity and even allowing certain types of discontinuities. It is applied e.g., in the analysis of approximations of reachable sets of nonlinear control problems. In this area, Filippov theorems in continuous and discrete time are useful tools for stability analysis and convergence proofs for reachable sets of set-valued Runge-Kutta methods.

The focus lies on (discrete) difference inclusions for which perturbations in the initial set, in the right-hand side as a set (outer perturbation) and in the state variable entering the right-hand side (inner perturbation) are studied. The estimates typically involve the square root of the step size for the discrete method and imply the existence of a (neighboring) discrete solution which is close to a given trajectory (slightly) violating the difference inclusion. The estimates are improved for *strengthened one-sided Lipschitz (SOSL)* set-valued maps.

As applications infinite time horizon problems, estimates for reachable sets of the (set-valued) explicit Euler method and its variants and discrete relaxation results are shown. For the latter reachable sets of nonconvex difference inclusions are compared with the one for convexified right-hand side extending a theorem of Grammel to the OSL case.

**Continuous selection of the solution map for a one-sided Lipschitz differential inclusion and an application in the study of viable solutions**

Grzegorz Gabor (1),

(1) Faculty of Mathematics and Computer Science, Nicolaus Copernicus University in Toruń, Poland

Several important properties of Lipschitz multivalued maps have been applied in control problems described in the form of a differential inclusion  $\dot{x}(t) \in F(x(t))$ , with some initial or boundary conditions. For instance, one can prove that the *solution map*  $x_0 \mapsto S_F(x_0)$ , where  $S_F(x_0)$  denotes the set of solutions of the above inclusion with the initial condition  $x(0) = x_0$ , has a continuous single-valued selection, and that  $S_F(x_0)$  is an absolute retract. It occurs that a larger class of maps, the class of one-sided Lipschitz continuous (OSL) multivalued maps, also has several important analogs. Here by an OSL-map we mean the map  $F : X \multimap E$  such that there is a constant  $L \in \mathbb{R}$  such that, for every  $x, y \in X$  and every  $f_x \in F(x)$ , there exists  $f_y \in F(y)$  with

$$\langle x - y, f_x - f_y \rangle_+ \leq L|x - y|^2.$$

In particular, a closed set  $K$  is invariant for the above differential inclusion if  $F$  is an OSL-map and the tangency condition  $F(x) \subset T_K(x)$  is satisfied. If it is not satisfied, the problem of the existence of viable (in  $K$ ) solutions is essentially nontrivial. The Ważewski retract method is an excellent and one of the most known tools to solve this problem. In the talk the way how to use this method for OSL-maps will be presented. The key point is that the solution map  $S_F(\cdot)$  for OSL-maps has a continuous selection (comp. [1]).

[1] G. Gabor. Continuous selection of the solution map for a one-sided Lipschitz differential inclusions. *Nonlinear Anal.* 66:1185-1197, 2007.

**Metric approximation of set-valued functions of bounded variation.**

Alona Mokhov (1, 2), Elza M. Farkhi (1), Nira Dyn (1), Elena E. Berdysheva (3),

(1) Afeka, Tel-Aviv Academic College of Engineering, Dept. of Mathematics, Israel (2) Tel-Aviv University, Israel (3) Justus Liebig University Giessen, Germany

The talk presents results on the approximation of SVFs of bounded variation which are not necessarily continuous.

The known approximating procedures involving Minkowski sum of sets, which are appropriate for SVFs with convex images, turn out to be convexifying for the case of general images (possibly non-convex) in

the sense that the limit SVFs of these procedures have convex images. Therefore, these methods fail to approximate SVFs with general images. To avoid convexification we adapt approximation methods by replacing linear combinations of reals by metric linear combinations of sets.

First we investigate the adaptations of two types of sample-based approximation operators, namely, local operators like the Schoenberg spline operator and the Bernstein operator. The third type of approximation we consider is a set-valued analogue of the Steklov function, adapted by replacing the Riemann integral by the metric integral of SVFs introduced in [1]. The metric integral is free of the convexification drawback, which is typical to the commonly used Aumann integral of SVFs. Error bounds, obtained in the averaged Hausdorff metric, provide rates of approximation similar to those for real-valued functions of bounded variation.

- [1] N. Dyn, E. Farkhi, A. Mokhov, The metric integral of set-valued functions, *Set-Valued Var. Anal.*, published online (2017).

## 16. Contributed session: applications of optimal control 2

14:00 – 15:40

Chair: D. Grass

FH HS 2

Using vintage structure for a multi-stage optimal control model with random switching time

Stefan Wrzaczek (1), Ivan Frankovic (1), Michael Kuhn (1),

(1) Wittgenstein Centre (IIASA, VID/ÖAW, WU), VID/ÖAW, Vienna, Austria

The paper presents a transformation of a multi-stage optimal control model with random switching time to a vintage optimal control model. Following the mathematical transformation the advantages compared to a standard backward approach are discussed. The paper closes with a simple example on a climate shock. The model is used to highlight the advantages of the approach, which are numerical solution, analytical insights and illustration of variables.

### History-dependence in a bi-objective capital accumulation problem

Richard F. Hartl (1), Peter M. Kort (2,3), Andrea Seidl (1),

(1) Faculty of Business, Economics and Statistics, University of Vienna, Vienna, Austria (2) Department of Econometrics and Operations Research & CentER, Tilburg University, Tilburg, The Netherlands (3) Department of Economics, University of Antwerp, Antwerp, Belgium

We consider the problem of a firm which decides about investing into a capital stock needed for production. On the one hand the firm wants to maximize revenues, on the other hand it wants to minimize emissions which are caused by production. To handle the conflicting objectives, we apply the  $\varepsilon$ -constraint method. We sequentially solve the optimal control problem for the first objective with the constraint that the second objective must be lower than its value from the previous step minus a constant. In this manner we calculate the Pareto front for different initial state values.

We analyze the impact of multiple objectives on the optimal solution path and determine a threshold curve which separates areas on the Pareto front differing with respect to the long-run steady state which is approached.

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### Evolutionary tax evasion and optimal regulation under prospect theory

Fabio Lamantia (1, 2), Domenico De Giovanni (1), Mario Pezzino (2),

(1) Department of Economics, Statistics and Finance, University of Calabria, Italy (2) School of Social Sciences, University of Manchester, UK

The paper studies the dynamics of compliance in a population of agents that decide whether to engage in tax evasion depending on an evolutionary adaptation process. Payoffs are assumed to have the realistic features of Prospect Theory utilities. The paper also considers an optimal control problem to study the long-run level of tax evasion when a tax authority attempts to maximize the expected stream of tax revenues choosing auditing effort. The analysis provides conditions for the evolution of tax evasion to converge to an asymptotically stable interior equilibrium where only a portion of the population engages in tax evasion. Moreover, the study of the intertemporal optimal auditing produces novel and rich results, including the existence of multiple equilibria and discontinuities in the optimal control.

### Optimal scientific production over the life cycle

Gustav Feichtinger (1), Peter M. Kort (2), Dieter Grass (1),

(1) ORCOS, Vienna University of Technology, Vienna, Austria (2) Econometrics and Operations Research, Tilburg School of Economics and Management, Tilburg, Netherlands

The publications of a scientist over his/her career are usually not evenly spaced in time. Productivity patterns quite often show an intuitively plausible time course: scientific creativity tends to rise rapidly to a peak and then gradually declines. There are many studies of career paths of creative people since the famous statistician [1] started pertinent research almost 200 years ago. Typical life cycle patterns are not only observed in academia, but also in artistic production, in criminal behavior and other fields.

One important purpose of the present paper is to explain how such a diversity might come about. While virtually all models dealing with the dynamics of scientific production are *descriptive*, e.g. [2], in what follows we propose a *normative* approach.

Solving the resulting optimal control model by using Pontryagin's maximum principle shows that the shape of the optimal paths depends crucially on the initial situation. If the stock of knowledge is initially too small, it turns out that the researcher's career will not be very productive. If, however, a certain human capital endowment (the so-called Skiba-threshold) is exceeded initially, the career will flourish. A large  $K$  fosters the investment in networking making the leverage effect of  $R$  work. Besides the case of an infinite planning horizon, the case of a given finite end time is considered. Various terminal conditions (ranging from 'there are no pockets in a shroud' until 'the reputation in the posterity is quite important') will lead to different scientific career patterns.

[1] A. Quetelet, Sur l'homme et le développement de ses facultés: ou, Essai de physique sociale (Bachelier), Vol. 1. 1835.

[2] S. Rinaldi, R. Cordone, R. Casagrandi, Instabilities in creative professions: A minimal model. Non-linear Dynamics, Psychology, and Life Sciences, Vol. 4, No. 3 (2000), S. 255–273.



## 17. Non-standard preferences, discounting, and time inconsistency

14:00 – 15:40

*Chair:* T. Trimborn

FH HS 4

### The optimal extraction of non-renewable resources under hyperbolic discounting

Anna Maral Dugan (1),

(1) Vienna University of Technology, Vienna, Austria

This paper focuses on economic growth models with non-renewable resources in the Dasgupta-Heal-Solow-Stiglitz (DHSS) model. I compare hyperbolic and exponential discounting considering a time-consistent method of hyperbolic discounting. For comparing both discounting methods I use the normalization that the present value of a constant utility stream is the same in both frameworks. Sustainable economic development is not feasible with either discounting method. However, there are differences in the optimal paths of consumption and resource extraction between exponential and hyperbolic discounting. With latter discounting, households's discount rate is larger in the short run. Still, their low long-run discount rate makes them more patient in the long-run. Therefore, both the capital stock and the resource stock tend to be larger in the scenario with hyperbolic discounting than with exponential discounting in the long-run. This in turn leads to higher long-run consumption. Overall, although hyperbolic discounting implies higher discount rates for the near future, it implies a smaller extraction rate for non-renewable resources for realistic parameter values.

### Time-Inconsistent health behavior and its impact on aging and longevity

Katharina Werner (1), Holger Strulik (1),

(1) Georg-August-Universität Göttingen, Göttingen, Germany

In the this paper we integrate time-inconsistent decision making due to hyperbolic discounting into a gerontologically founded life cycle model with endogenous aging and longevity. Individuals can slow down aging and postpone death by investing time (e.g. physical exercise) and money in their health and by saving for health investments in old age. We show that hyperbolic discounting leads to a continuous revision of health plans such that aging individuals save less and invest in their health than they would if commitment to the original plans were possible. Consequently, individuals accumulate health deficits faster and die earlier than under commitment. We calibrate the model with U.S. data for an average American in the year 2010 and estimate that time-inconsistent health investment and savings decisions cause a loss of about 2 years of life.

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**Efficiency and distortions with positional preferences under welfarist and paternalistic governments: does one size fit all?**

Ronald Wendner (1), Sugata Ghosh (2),

(1) Department of Economics, University of Graz, Austria (2) Department of Economics and Finance, Brunel University London, UK

This paper analyses the distortionary effects of positional preferences in a simple endogenous growth model, where labor supply is exogenous, under both a welfarist and a paternalistic government. Extending the literature, reference levels may be partially exogenous to the government (e.g., determined by consumption choices in a foreign country), and individuals may be positional with respect to wealth in addition to consumption. Neither consumption nor consumption-cum-wealth positionality necessarily causes intertemporal distortions under either welfare criterion. We derive necessary and sufficient conditions for positional preferences to be non-distortionary. If those conditions are not satisfied, the same reference levels of consumption and wealth can give rise to under-saving or over-saving, depending on the extent to which the reference levels are exogenous to a government. Moreover, we derive the conditions under which positional preferences for wealth and consumption imply over-consumption with respect to the welfarist (paternalistic) criterion but, at the same time, over-saving with respect to the paternalistic (welfarist) criterion.

**Boosting taxes for boasting about houses? Status concerns in the housing market**

Johannes Schünemann (1), Timo Trimborn (2),

(1) University of Göttingen, Göttingen, Germany (2) Vienna University of Technology, Vienna, Austria

There is empirical evidence that households use residential houses as status goods. In particular, people are shown to compare their houses with those at the top of the distribution. In this paper, we introduce a residential housing sector and status concerns for housing into a neoclassical model with heterogeneous agents. We find that status concerns exert a negative externality and calculate a progressive Pigovian tax schedule that corrects for the externality, implying a housing tax for rich households of 4.6%. Implementing the tax schedule is associated with a sizable welfare gain. We also find that when the utilitarian social planner is constrained to housing taxes, Pigovian taxation is not constrained efficient. Further increasing the tax for rich households to 7.9% would maximize welfare in the constrained optimum.

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## 18. Infinite dimensional stochastic modeling in economics and finance 1

16:00 – 17:15

*Chair:* E. Bandini, F. Gozzi, G. Fabbri

FH HS 7

### Optimal control for stochastic Volterra equations driven by Lévy noise

Fulvia Confortola (1), S. Bonaccorsi (2),

(1) Dipartimento di Matematica, Politecnico di Milano, Milano, Italia (2) Dipartimento di Matematica, Università degli studi di Trento, Trento, Italia

We study a class of optimal control problems for stochastic equations driven by Lévy noise and with memory effect in the diffusion term in infinite dimensions. We are concerned with a class of stochastic Volterra integro-differential problem with completely monotone kernels, where we assume that the noise enters the system when we introduce a control. We provide a semigroup setting for the problem, by the state space setting; the applications to optimal control require a precise description of the properties of the generated semigroup. We show that a suitable Backward Stochastic Differential Equation can be used to prove existence of an optimal control and to represent the value function. Our main results are the existence for the optimal feedback control, the existence of a weak solution to the so-called closed loop equation and, finally, the construction of an optimal feedback.

### Systemic risk and stochastic games with delay

Li-Hsien Sun (1), René Carmona (2), Jean-Pierre Fouque (3), Seyyed Mostafa Mousavi (3),

(1) Institute of Statistics, National Central University, Chung-Li, Taiwan (2) ORFE, Bendheim Center for Finance, Princeton University, Princeton, USA (3) Department of Statistics & Applied Probability, University of California, USA

We propose a model of inter-bank lending and borrowing which takes into account clearing debt obligations. The evolution of log-monetary reserves of  $N$  banks is described by coupled diffusions driven by controls with delay in their drifts. Banks are minimizing their finite-horizon objective functions which take into account a quadratic cost for lending or borrowing and a linear incentive to borrow if the reserve is low or lend if the reserve is high relative to the average capitalization of the system. As such, our problem is a linear-quadratic stochastic game with delay between  $N$  players. The Nash equilibria are obtained using coupled forward and advanced backward stochastic differential equations and Hamilton-Jacobi-Bellman (HJB) equations.

### Some notes on stochastic functional equations

Stefano Bonaccorsi (1),

(1) Department of Mathematics, University of Trento, Italy

In this talk we consider a class of functional equations with additive or multiplicative noise. We focus on the large deviation problem and the asymptotic expansion of the solution. Some applications are discussed.

19. Contributed session: optimal control 1

16:00 – 17:15

Chair: M. Quincampoix

FH 8 Nöbauer HS

Linear programming approach to optimality conditions for an infinite horizon optimal control problem with discounting in discrete time

Ilya Shvartsman (1), Vladimir Gaitsgory (2), Alex Parkinson (2),

(1) Penn State Harrisburg, Middletown, PA, USA (2) Macquarie University, Sydney, Australia

Consider the following infinite horizon optimal control problem with discounting in discrete time:

$$\begin{aligned} \text{Minimize } J(u, y_0) &= \sum_{t=0}^{\infty} \alpha^t g(y(t), u(t)), \\ y(t+1) &= f(y(t), u(t)), \quad t = 0, 1, \dots, \\ y(0) &= y_0, \quad y(t) \in Y, \quad u(t) \in U(y(t)). \end{aligned}$$

Here  $Y$  is a nonempty compact subset of  $R^m$ ,  $U(\cdot) : Y \rightarrow U_0$  is an upper semicontinuous mapping to a compact metric space  $U_0$ ,  $f : R^m \times U_0 \rightarrow R^m$  is a continuous function, and  $\alpha \in (0, 1)$  is a discount factor.

In this talk we establish that this problem is related to a certain infinite-dimensional linear programming problem and its dual. We use this relation to establish necessary and sufficient optimality conditions for the problem above and apply them to construct numerical algorithms for finding a near optimal control. We also establish asymptotic relationships between the optimal values in the problems with time discounting and long-run average criteria.

On continuity/discontinuity of the optimal value of long-run average optimal control problems

Vladimir Gaitsgory (1),

(1) Department of Mathematics, Macquarie University, Australia

We will discuss conditions under which the optimal value of a long run average optimal control problem is continuous/discontinuous with respect to a perturbation parameter. A distinctive feature of our approach is that the perturbation analysis of the optimal control problem is carried out on the basis of the perturbation analysis of a certain infinite-dimensional linear programming (LP) problem and that of the corresponding approximating semi-infinite LP problems. The presentation will be based on results obtained in collaboration with M. Mammadov and L. Manic that were partially published in [1].

[1] V. Gaitsgory, M. Mammadov and L. Manic. On stability under perturbations of long-run average optimal control problems. *Pure and Applied Functional Analysis*, 3(2): 461–476, 2017.

Tuesday, July 3<sup>rd</sup>

## A remark on the continuity of the measure Lagrange multiplier in optimal control problems with state constraints

Fernando Lobo Pereira (1), Dmitry Karamzin (1),

(1) University of Porto

This presentation is focused on the necessary optimality condition in the form of Pontryagin's maximum principle for state constrained problems. A certain refinement to these conditions is made. More specifically, it has been noted that the measure-multiplier from the maximum principle is continuous under the regularity conditions imposed in [1], in Chapter 6. The continuity of the measure-multiplier appears to be highly relevant for numerical implementations in the framework of indirect computational approach. The proof substantially relies on the arguments suggested in [2].

- [1] Pontryagin, L.S., Boltyanskii, V.G., Gamkrelidze, R.V., and Mishchenko, E.F.: The Mathematical Theory of Optimal Processes, Interscience, New York (1962)
- [2] Arutyunov, A.V., Karamzin, D.Yu. On Some Continuity Properties of the Measure Lagrange Multiplier from the Maximum Principle for State Constrained Problems. SIAM Journal on Control and Optimization, 53, 4 (2015)

## 20. Approximation of differential inclusions and control problems 2

16:00 – 17:15

*Chair:* R. Baier, E. Farkhi

FH HS 3

### Hypo-convergent controller synthesis for a class of discrete-time minimax optimal control problems

Gunther Reissig (1), Matthias Rungger (2),

(1) Bundeswehr University Munich, Dept. Aerospace Eng., Chair of Control Eng., Germany (2) Technical University of Munich, Dept. Electrical and Computer Engineering, Hybrid Control Systems Group, Germany

We discuss recent results from [1-4] on a class of leavable, undiscounted optimal control problems in the minimax sense for nonlinear, continuous-state, discrete-time plants, where leaving (or “stopping”) is mandatory. Using state and control alphabet discretizations, we compute upper bounds of the value function as well as feedback controllers that are guaranteed to realize those bounds. We prove that the computed bounds and the performance of the controllers hypo-converge to the value function as the discretization parameters approach zero. In particular, if the optimal control problem is solvable on some compact subset of the state space, and if the discretization parameters are sufficiently small, then we obtain a feedback controller solving the problem on that subset. These results do not assume the continuity of the value function or any problem data, and they fully apply in the presence of hard state and control constraints.

- [1] G. Reissig and M. Rungger, “Symbolic optimal control,” Sep. 2017, arxiv: 1709.07333, <http://arxiv.org/abs/1709.07333>

- [2] G. Reissig, “Approximate value iteration for a class of deterministic optimal control problems with infinite state and input alphabets,” CDC 2016, <http://dx.doi.org/10.1109/CDC.2016.7798408>
- [3] M. Rungger and G. Reissig, “Arbitrarily precise abstractions for optimal controller synthesis,” CDC 2017, <http://dx.doi.org/10.1109/CDC.2017.8263904>
- [4] G. Reissig, A. Weber, M. Rungger, “Feedback refinement relations for the synthesis of symbolic controllers,” *IEEE Trans. Automat. Control*, vol. 62, pp. 1781–1796, 2017, <http://dx.doi.org/10.1109/TAC.2016.2593947>

**On regularity properties and the gradient projection method for optimal control problems with bang-bang solutions**

Jakob Preininger (1), Teresa Scarinci (1,2), Vladimir M. Veliov (1), Phan Tu Vuong (1),

(1) Institute of Statistics and Mathematical Methods in Economics, Vienna University of Technology, Austria (2) Dept. of Statistics and Operations Research, University of Vienna, Austria

We investigate the stability of the solutions of optimal control problems with bang-bang controls in terms of metric sub-regularity and bi-metric regularity. New sufficient conditions for these properties are obtained, which strengthen the known conditions for sub-regularity and extend the known conditions for bi-metric regularity to Bolza-type problems. Further we revisit the gradient projection method for these problems where we obtain the strong convergence of the iterative sequence of controls and the corresponding trajectories. Moreover, we establish a convergence rate, depending on a constant appearing in the corresponding switching function and prove that this convergence rate estimate is sharp.

- [1] J. Preininger, T. Scarinci, V.M. Veliov. Metric regularity properties in bang-bang type linear-quadratic optimal control problems. Research Report 2017-07, ORCOS, TU Wien, 2017.
- [2] J. Preininger, P.T. Vuong. On the Convergence of the Gradient Projection Method for Convex Optimal Control Problems with Bang-Bang Solutions. To appear in Computational Optimization and Applications, 2018.

**Convergence analysis for implicit Euler discretizations of optimal control problems subject to index two differential-algebraic equations and mixed control-state constraints**

Björn Martens (1), Matthias Gerds (1),

(1) University of the Federal Armed Forces at Munich, Neubiberg/Munich, Germany

Using the convergence theorem for generalized equations in [1] we prove convergence for the implicit Euler discretization of optimal control problems subject to semi-explicit differential-algebraic equations of index two and mixed control-state constraints. The main difficulty of the analysis is caused by a structural discrepancy between the necessary conditions of the continuous optimal control problem and the necessary conditions of the discretized problems, which does not allow to compare the respective necessary conditions directly. To overcome the discrepancy, we present suitable conditions, which eventually allow us to prove a convergence result for stationary points under moderate assumptions.

- [1] Malanowski, K., Büskens, C., Maurer, H.: Convergence of Approximations to Nonlinear Optimal Control Problems. In: Anthony Fiacco, editor, Mathematical programming with data perturbations, volume 195, pages 253–284. Dekker. Lecture Notes in Pure and Applied Mathematics, 1997

**21. Model based control: analysis and modelling 1****16:00 – 17:15***Chair:* K. Worthmann, K. Chudej**FH HS 2****Optimal control in a mathematical Dengue fever model**Kurt Chudej (1), Anne Fischer (2,3), Gaby Albrecht (1),

- (1) Lehrstuhl für Wissenschaftliches Rechnen, Universität Bayreuth, Germany
- (2) Lehrstuhl für Ingenieurmathematik, Universität Bayreuth, Germany
- (3) Current address: Josef Witt Gruppe, Weiden, Germany

Dengue fever is a virus infection transmitted by mosquitos which affects more than half of the world's population. Only since the 1980s serious epidemics occurred and in the last 25 years the epidemic potential of the virus has increased. The virus is transmitted to human beings by the bite of an infectious Asian Tiger mosquito, especially those of the species *Aedes Aegypti* and *Aedes Albopictus*. The vectors, which become infected by biting an infectious human, require the blood to hatch their eggs. Since the mosquitos prefer to breed in stale water, left used tires, flower pots and even swimming pools offer ideal circumstances for the reproduction of the population. Due to their ability to adapt to new conditions rapidly, international tourism and trade continue to enlarge their habitat. Upto now all dengue cases in Germany could be traced back to an infection outside of Germany. The historical spread of the vector populations and climatic analyses indicate a rising probability of a dengue fever outbreak in Europe. In Europe since the 1990s mosquito populations can be found in France, Italy and Switzerland. Additionally, against prior assumptions, newer studies demonstrate the ability of the species' eggs to survive temperatures as low as  $-10^{\circ}\text{C}$ . In 2014, researchers in Freiburg im Breisgau were able to collect specimens in various breeding places whose total number indicated the existence of a sufficient amount of mosquitos to form a survivable population. Based on the mentioned observations, the upper Rhine Valley, having relatively mild climatic conditions and a major transport axis from the south, offers ideal requirements for the vectors in Germany. Thus, climatic warming and the adaptability of the mosquitos imply a possible spread of a vector population in Freiburg im Breisgau and as a result the threat of infectious diseases.

Due to the fact that at the end of 2015 a vaccine against dengue fever was licensed, the control of the virus infection is no longer merely based on mosquito control and the avoidance of vector to human contact. Thus, this talk examines the effects of various control strategies including vector control and vaccination campaigns, using a system of nonlinear ordinary differential equations.

**Funnel cruise control**Thomas Berger (1), Anna-Lena Rauert (1),

- (1) Fachbereich Mathematik, Universität Hamburg, Hamburg, Germany

We consider the problem of vehicle following, where a safety distance to the leader vehicle is guaranteed at all times and a favourite velocity is reached as far as possible. We introduce the funnel cruise controller as a novel universal adaptive cruise control mechanism which is model-free and achieves the aforementioned control objectives. The controller consists of a velocity funnel controller, which directly regulates the velocity when the leader vehicle is far away, and a distance funnel controller, which regulates the distance to the leader vehicle when it is close so that the safety distance is never violated. The funnel cruise controller is illustrated by a simulation of three different scenarios which may occur in daily traffic.

**22. Dynamic economic policy**

**16:00 – 17:15**

*Chair:* B. Heijdra, P. Heijnen

**FH HS 4**

**Reversible environmental catastrophes in a stochastic overlapping generations economy**

Pim Heijnen (1), Ben J. Heijdra (1,2,3),

(1) University of Groningen, The Netherlands (2) CESifo, Germany (3) Netspar, The Netherlands

We study environmental policy in an economy-ecology model featuring multiple deterministic stable steady-state ecological equilibria. The economy-ecology does not settle in either of the deterministic steady states as the environmental system is hit by random shocks. Individual live for two periods and derive utility from the (stochastic) quality of the environment. They feature warm-glow preferences and therefore will engage in private abatement in order to manipulate the stochastic process governing environmental quality. The government may also conduct abatement activities or introduce environmental taxes. We solve for the market equilibrium abstracting from public abatement and taxes and show that the ecological process may get stuck for extended periods of time fluctuating around the bad (low quality) deterministic steady state. These events are called environmental catastrophes. They are not irreversible, however, as the system typically switches back to the basin of attraction associated with the good (high quality) deterministic steady state. The paper also studies the effects of public abatement and environmental taxation on the duration and frequency of reversible environmental catastrophes.

**Skeletons in the New Keynesian closet: some unfamiliar properties of a work-horse model**

Christiaan G.F. van der Kwaak (1), Ben J. Heijdra (1,2,3),

(1) University of Groningen, The Netherlands (2) CESifo, Germany (3) Netspar, The Netherlands

We revisit the standard New Keynesian model and investigate its properties when monetary policy is implemented through an (exogenous) money supply rule rather than through a standard Taylor-rule. We employ both a discrete and continuous time version of the model. Our most important result is that in discrete time, output goes down in response to a positive productivity shock, which runs counter to any economic intuition. The sign of the impact on output changes when we switch from discrete to continuous time. However, in continuous time consumption and capital go down upon impact. Introducing capital adjustment costs ‘corrects’ the counter intuitive result in discrete time: output increases in response to a positive productivity shock, albeit by a mere 0.25% of steady state output in response to a 1% productivity shock. However, in continuous time the sign of the output response switches from positive to negative. We conclude that while the New Keynesian model produces results that are economically intuitive when monetary policy is implemented through a standard Taylor-rule, the results become counter intuitive when the money supply is exogenous. This is true for both discrete and continuous time versions of the model, which suggests that there might be structural flaws within the standard New Keynesian model.



Tuesday, July 3<sup>rd</sup>

### Optimal procurement and investment in new technologies under uncertainty

Gijsbert T.J. Zwart (1), Malin Arve (2),

(1) University of Groningen, Groningen, The Netherlands (2) NHH Norwegian School of Economics, Norway

We study a buyer's optimal investment strategy for new technologies when costs evolve stochastically and are private information to the suppliers. In a continuous time setting, we show how the asymmetric information on the stochastic variables leads to delays in investment compared to the real option benchmark. We also suggest a payment structure that implements the buyer's optimal investment timing as a Vickrey-type auction.

### 23. Plenary

17:30 – 18:20

*Chair:* H. Frankowska

FH HS 1

### Viability theory and management of sustainability

Guillaume Deffuant (1),

(1) LISC, Irstea, Aubière, France

This talk introduces viability theory and its potential in the management of sustainability. Viability theory addresses the problem of maintaining a dynamical system within a given subset of states, generally called the constraint set. Instead of optimising a criterion, the control strategy thus aims at avoiding crossing the limits of this constraint set. In the case of deterministic dynamics, the main theoretical concept of this theory is the viability kernel. This set includes all states from which there exists a control strategy maintaining the system indefinitely in the constraint set. Different viable control policies can be derived from the viability kernel, which makes this set of high practical interest. The viability kernel has also been used in a mathematical definition of resilience: the resilient states are the ones from which the viability kernel is reachable. Recently, this theory has been completed by other types of sets in a general theory of sustainable management, when making the hypothesis that standard or emergency controls can be applied depending on the situation. The practical application of these theories depends on the algorithms approximating viability kernels and reachable sets, which, unfortunately, face the famous dimensionality curse. The talk finally reports recent progress in improving these algorithms and some remaining challenges.

Wednesday, July 4<sup>th</sup>

Wednesday, July 4<sup>th</sup>

## 24. Plenary

08:40 – 09:30

*Chair:* M. Falcone

FH HS 1

Regular synthesis and sufficient conditions for optimality in optimal control problems

Heinz M. Schättler (1),

(1) Dept. of Electrical and Systems Engr., Washington University, St. Louis, USA

Selected aspects of regular synthesis type sufficient conditions for optimality in optimal control problems will be discussed using application oriented practical examples. The emphasis will be on illustrating how arguments based on explicit constructions of extremals (e.g., the method of characteristics) can be utilized to prove the (global and/or local) optimality of extremals also in non-classical, but realistic practical settings. Examples include problems with unusual switching structures (minimum-time frictionless atomic cooling in harmonic traps), syntheses involving singular and/or chattering controls (antiangiogenic therapies in the presence of pharmacometric equations), problems with loss of small-time local controllability which have discontinuous value functions (selective spiking of integrate-and-fire neurons), problems with state-space constraints (minimization of the base transit time in HBT semiconductors) or perturbation feedback control laws with free terminal time (return to level flight for an airplane in nose dive).

## 25. Modeling and computational methods for financial applications 1

10:00 – 11:15

*Chair:* A. Picarelli, C. Reisinger

FH HS 7

Deep learning algorithms for stochastic control problems

Huyên Pham (1, 2), Achref Bachrouf (3), Côme Huré (1), Nicolas Langrené (4),

(1) LPSM, University Paris Diderot, Paris, France (2) CREST-ENSAE, Saclay, France (3) University of Oslo, Norway (4) CSIRO, University of Melbourne, Australia

We develop several deep learning-based algorithms for solving high-dimensional discrete-time stochastic control problems, which arise in the context of reinforcement learning or in the time-discretization of fully nonlinear Hamilton-Jacobi-Bellman (HJB) partial differential equations. Optimal state/action function (the so-called  $Q$ -function) from the Backward Bellman equation and policy functions are approximated by neural networks (NN) in the spirit of deep reinforcement learning. By relying on control randomization, NN approximation for  $Q$ -function are performed according to a regress now or a regress later Monte-Carlo approach joint with quantization, using value or performance iterations, and combined with the NN approximation of the policy function, either in a two-stage or in a simultaneous stochastic gradient descent. Our algorithms are illustrated and compared on various examples ranging from a HJB equation in high-dimension to option hedging and energy storage problems.

Wednesday, July 4<sup>th</sup>

### Numerical approximation of BSDEs using local polynomial drivers and branching processes

Bruno Bouchard (1), [Xiaolu Tan](#) (1), Xavier Warin (2), Yiyi Zou (1),

(1) University Paris-Dauphine, PSL Research University, France (2) EDF, France

We propose a new numerical scheme for Backward Stochastic Differential Equations based on branching processes. We approximate an arbitrary (Lipschitz) driver by local polynomials and then use a Picard iteration scheme. Each step of the Picard iteration can be solved by using a representation in terms of branching diffusion systems, thus avoiding the need for a fine time discretization. In contrast to the previous literature on the numerical resolution of BSDEs based on branching processes, we prove the convergence of our numerical scheme without limitation on the time horizon. Numerical simulations are provided to illustrate the performance of the algorithm.

### Solution of mean reflected BSDEs and applications in finance

[Camilo A. Garcia Trillos](#) (1), Paul E. Chaudru de Raynal (2),

(1) University College London, London, UK (2) Université Savoie-Mont Blanc, Le Bourget-du-Lac, France

We discuss the numerical solution of a class of equations: mean-reflected Backward Stochastic Differential Equations (MR-BSDEs). This family, introduced in [1], contains backward SDEs constrained to satisfy a condition on their marginal laws at almost all intermediate times. As in the case of classical reflected BSDEs, an increasing process is introduced to guarantee that the constraint is satisfied. However, given that the obstacle is in this case uniquely determined by the law of the solution, the added process is taken to be deterministic.

By their nature, MR-BSDEs are a great tool to encode several problems in finance: for example, they allow us to calculate the effect of risk constraints of the hedging portfolio into pricing, especially when considering partial hedging.

In this talk, we consider an application of MR-BSDEs to the problem of margin calculation for life insurances with investment. Then, we examine a numerical scheme that generalises the so-called BTZ scheme to the mean reflected case.

[1] P. Briand, R. Elie, Y. Hu, *BSDEs with mean reflection*. arXiv:1605.06301, 2016.

## 26. Numerical analysis for PDE constrained optimization 1 10:00 – 11:15

*Chair:* A. Rösch, J. Pfefferer

FH 8 Nöbauer HS

### Hybridizable discontinuous Galerkin methods for the approximation of Dirichlet control problems

[Mariano Mateos](#) (1), John R. Singler (2), Yangwen Zhang (2),

(1) Dpto. de Matemáticas, Universidad de Oviedo, Spain (2) Department of Mathematics and Statistics, Missouri University of Science and Technology, Rolla, MO, USA

We propose the use of Hybridizable Discontinuous Galerkin (HDG) methods to discretize and solve Dirichlet control problems. HDG were introduced by Cockburn; see e.g. [2]. As Discontinuous Galerkin

(DG) methods, they have proved very useful in solving computational fluid problems or convection-diffusion PDEs. The advantage of HDG is that the number of globally coupled unknowns is typically smaller than for DG.

One of the features that makes HDG interesting to discretize Dirichlet control problems is that, by construction, gradients are directly approximated by the method. Let us recall, [1], that the optimal control can be characterized as the normal derivative of the adjoint state, this is: the gradient of the adjoint state times the unit vector normal to the boundary. Taking again advantage of the good performance of HDG to approximate gradients a problem governed by the Poisson equation is studied in [3].

We show how to discretize and obtain error estimates for unconstrained Dirichlet control problems governed by the convection-diffusion equation or the Stokes system. One of the main difficulties in the obtention of error estimates is that the original method requires high regularity of the solution, which is something we cannot expect for Dirichlet control problems. We show how to obtain the results in the high regularity case and how to modify the method to obtain results for the low regularity case.

- [1] Eduardo Casas and Jean-Pierre Raymond, *Error estimates for the numerical approximation of Dirichlet boundary control for semilinear elliptic equations*, SIAM J. Control Optim. 45(5):1586–1611 (2006).
- [2] Bernardo Cockburn, Jayadeep Gopalakrishnan, Ngoc Cuong Nguyen, Jaume Peraire, *Unified hybridization of discontinuous Galerkin, mixed, and continuous Galerkin methods for second order elliptic problems*, SIAM J. Numer. Anal. 47(2):1319–1365, (2009).
- [3] Weiwei Hu, Jiguang Shen, John R. Singler, Yangwen Zhang, and Xiabo Zheng, *A Superconvergent Hybridizable Discontinuous Galerkin Method for Dirichlet Boundary Control of Elliptic PDEs*, arXiv:1712.02931 (2017)

#### Numerical analysis for Dirichlet control problems on boundary concentrated meshes

Max Winkler (1), Johannes Pfefferer (2),

(1) Technische Universität Chemnitz, AG Numerische Mathematik, Chemnitz, Germany (2) Technische Universität München, Lehrstuhl für Optimalsteuerung, Munich, Germany

In this talk we discuss improved discretization strategies for Dirichlet boundary control problems constrained by elliptic partial differential equations. The computational domains are assumed to be polygonal but not necessarily convex. A standard approximation with piecewise linear finite elements for control, state and adjoint state variable on a sequence of quasi-uniform meshes leads to a convergence rate of  $\min\{1, \pi/\omega - 1/2\} - \varepsilon$ ,  $\varepsilon > 0$ , for the control in the  $L^2(\Gamma)$ -norm. Here,  $\omega \in (0, 2\pi)$  denotes the largest opening angle at the corners of the polygonal domain, and obviously, the convergence rate is close to 1 unless all angles are smaller than  $2\pi/3$  but it tends to zero as  $\omega$  tends to  $2\pi$ . We show that this rate can be improved when local mesh refinement towards the domain's boundary is used such that the boundary mesh size is the square of the mesh size in the interior. Although the computational effort is not increased significantly, the convergence rate is doubled by this a priori refinement. We moreover present some numerical experiments which confirm that these error estimates are sharp.

Wednesday, July 4<sup>th</sup>

## Fast solvers for hp-FEM discretized PDE-constrained optimization problems

S. Beuchler (1), K. Hofer (2),

(1) IfAM, Leibniz University, Hannover, Germany (2) Fraunhofer, St. Augustin, Germany

In this talk, we investigate the minimization of a quadratic functional

$$J(u, y) = \frac{1}{2} \int_{\Omega} (y - y_d)^2 dx + \frac{\alpha}{2} \int_{\Omega} u^2 dx$$

governing the boundary value problem

$$-\Delta y + y = u \quad \text{in } \Omega$$

with some boundary conditions for  $y$ . This problem is discretized by  $hp$ -finite elements. The main focus of this talk is the development of efficient solution methods for the corresponding system of linear algebraic equations. We consider the solvers:

- a conjugate gradient method in a special inner product, following Schöberl/Zulehner
- the minimal residual method (MINRES)

In both methods, efficient preconditioners for mass and stiffness matrix accelerate the convergence speed of the iterative method. This contribution presents overlapping  $hp$ -FEM preconditioners for mass and stiffness matrix.

## 27. Contributed session: economic dynamics 1

10:00 – 11:15

*Chair:* A. Greiner

FH HS 3

### Evolution of customers' quality expectations

Gila E. Fruchter (1, 2), Thomas Reutterer (1),

(1) Graduate School of Business, Bar-Ilan University, Israel (2) Department of Marketing, WU Vienna University of Economics and Business, Vienna, Austria

This study investigates the dynamic properties of customers' quality expectation updating from an analytical perspective. We develop a mathematical expectation updating model that is well grounded in behavioral theories and empirical evidence from customer satisfaction research. Using a nonlinear complex systems approach, our findings reveal some novel insights into how customers learn their quality expectations and to appropriately align them with the product/service quality levels delivered by a company. We show that the capability to correctly calibrate quality expectations is an important prerequisite for being satisfied with a specific product or service. However, our theoretical findings suggest the existence of individuals who fail to do so, and those customers tend to be dissatisfied in the long run. We show that merely delighting customers does not help to prevent this tendency, but firms can assist more customers in becoming more realistic in their post-consumption quality evaluations by being more attuned to customer expectations. However, such a customer-oriented quality strategy entails a higher risk of negative disconfirmation for other customer groups. We discuss the theoretical, empirical and managerial implications of our findings.

Competition under industry-stock-driven prevailing market price: environmental consequences and the effect of uncertainty

Konstantin Kogan (1),

(1) Department of Management, Bar-Ilan University, Ramat-Gan, Israel

We address competition between several firms that cause pollution when producing fully substitutable products. These firms comprise the industry and each individual firm charges for its products the market price determined by the difference between cumulative market supply and demand, i.e., by the industry's stock. We find that although the greater the number of firms competing for the same primary market, the lower the market price and the higher the industry inventory surplus, the reduction in price at market equilibrium, is insufficient to stimulate greater aggregate sales. That is, as competition intensifies the output of the entire industry may decrease along with the overall pollution. Furthermore, we show that commitment production/pollution strategies compared to contingent strategies do not necessarily result in lower pollution, especially when market uncertainty is low and proportional pollution taxation is high. Commitment strategies, however, are more sensitive to increasing uncertainty which may lead to their environmental advantage.

Durable public goods games with a tipping point

Zhi Li (1), Christopher M. Anderson (2),

(1) School of Economics and The Wang Yanan Institute for Studies in Economics (WISE), Xiamen University, Xiamen, China (2) School of Aquatic and Fishery Sciences, University of Washington, Seattle, United States

We study a continuous-time, infinite-horizon, durable public good game with an endogenously determined tipping point, below which collapsing the stock is optimal. With a payoff function linear in stock and monetary income, and a logistic growth function, we show that a tipping point always exists in the game. We characterize how the equilibrium stock level and the tipping point change under various game structures. Under a dynamic voluntary contribution mechanism (DVCM), for the first time we construct a set of Markov perfect equilibria (MPE) for a linear optimal control problem, and show that the unique singular solution in the open-loop equilibrium can be extended to a non-singleton interval of singular stock levels in MPE. Under DVCM, both the open-loop equilibrium and the Markov perfect equilibrium (MPE) result in inefficiently low steady states and higher tipping points. A higher stable steady state and a lower tipping point is shown to be supported in the MPE as compared to the open-loop solution and the highest stable steady state in MPE approaches the efficient stock level asymptotically as the discount rate approaches zero. Lastly, we extend DVCM by introducing a provision point to a dynamic provision point mechanism (DPPM). We characterize a class of MPE of DPPM and show that the *most rapid approach path* to the socially efficient stock level is supported in a symmetric MPE of DPPM. These results are potentially useful in designing markets or mechanisms for private provision of durable environmental public goods.

28. Model based control: analysis and modelling 2

10:00 – 11:15

Chair: K. Worthmann, K. Chudej

FH HS 2

Differential-algebraic equations in tracking control and coupled motion

Matthias Gerdts (1),

(1) Institute of Mathematics and Applied Computing, Department of Aerospace Engineering, Bundeswehr University Munich, Neubiberg, Germany

We present and discuss prototype applications occurring in path planning tasks for mobile robots and vehicle dynamics which involve differential-algebraic equations (DAEs). Herein, the DAE arises from the task to follow a prescribed trajectory and leads to a dynamic system of type

$$\begin{aligned}x'(t) &= f(t, x(t), u(t)), \\ 0 &= g(t, x(t)),\end{aligned}$$

where  $x$  denotes the state and  $u$  the control. Naturally these DAEs have a higher index and it is necessary to identify control components, which serve as algebraic states and allow to follow the path constraints. We discuss control aspects and issues arising from the DAE formulation such as inverse dynamics and piecewise defined dynamics with appropriate coupling conditions. The latter problem occurs, e.g., in docking maneuvers whenever two individual systems at some time instance turn into a physically or virtually coupled system. Selected examples arising in control tasks in robotics and vehicle dynamics are presented.

- [1] M. Gerdts. *Optimal control of ODEs and DAEs*. Walter de Gruyter, Berlin/Boston, 2012.
- [2] M. Burger, M. Gerdts. DAE Aspects in Vehicle Dynamics and Mobile Robotics. submitted to DAE Forum, Applications of Differential-Algebraic Equations: Examples and Benchmarks

Periodic forcing of the master equation

Lars Grüne (1), Michael Margaliot (2), Thomas Kriecherbauer (1),

(1) Department of Mathematics, University of Bayreuth, Germany (2) School of Electrical Engineering and Sagol School of Neuroscience, Tel Aviv University, Israel

The master equation is an ordinary differential equation which describes the development of probabilities in finite state Markov processes. When parameters of these Markov processes can be controlled from the outside, the corresponding master equation can be interpreted as a nonlinear control system. In this talk we investigate the asymptotic stability properties of this control system for periodic input. We show that under suitable conditions there is a unique periodic solution which attracts all other solutions. We will comment on the implication of this result on the optimal control of the stochastic system and illustrate our findings using examples from statistical physics and from epidemiology.

- [1] Michael Margaliot, Lars Grüne, and Thomas Kriecherbauer, Entrainment in the Master Equation, arXiv Preprint, <http://arxiv.org/abs/1710.07321>, 2017.

## Optimal control with structure-preserving discrete-time models for mechanical systems

Kathrin Flaßkamp (1), Christof Büskens (1),

(1) Center for Industrial Mathematics, University of Bremen

In optimal control, the optimization problem is typically phrased on the basis of a time-continuous model for the system dynamics. However, numerical methods have to approximate solutions to this model. Therefore, structure-preserving methods aim to link more closely modeling and optimal control techniques by using discrete variational calculus (cf. [1]) to obtain discrete-time models, which can then be used as constraints in the optimization problem (cf. [2]). In analogy to classical methods, the structure-preserving transcription approach allows to use state-of-the-art NLP solver, e.g. WORHP (cf. [3]).

This contribution presents current results on structure-preserving optimal control for linear-quadratic problems, nonlinear problems, and parameter identification problems of mechanical systems.

- [1] J.E. Marsden and M. West. Discrete mechanics and variational integrators. *Acta Numerica*, 10:357–514, 2001.
- [2] S. Ober-Blöbaum, O. Junge, and J.E. Marsden. Discrete mechanics and optimal control: an analysis. *Control, Optimisation and Calculus of Variations*, 17(2):322–352, 2011.
- [3] C. Büskens and D. Wassel. The ESA NLP solver WORHP. *Modeling and optimization in space engineering*, pp. 85–110, Springer, 2012.

## 29. Real options 1

10:00 – 11:15

*Chair:* P.M. Kort

FH HS 4

### Green investment under policy uncertainty and Bayesian learning

Verena Hagspiel (1), Peder A. O. Dalby (1), Gisle R. Gillerhaugen (1), Tord Leth-Olsen (1),  
Jacco J.J. Thijssen (2),

(1) Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Trondheim, Norway (2) The York Management School, University of York, Heslington, York, UK

Many countries have introduced support schemes to accelerate investments in renewable energy (RE). Experience shows that, over time, retraction or revision of support schemes become more likely. Investors in RE are greatly affected by the risk of such subsidy changes. This paper examines how investment behavior is affected by updating a subjective belief on the timing of a subsidy revision, incorporating Bayesian learning into a real options modeling approach. We analyze a scenario where a retroactive downward adjustment of fixed feed-in tariffs (FIT) is expected through a regime switching model. We find that investors are less likely to invest when the arrival rate of a policy change increases. Further, investors prefer a lower FIT with a long expected lifespan, while policy makers prefer a higher FIT with shorter life span. We also consider an extension where, after retraction, electricity is sold in a free market. We find that if policy uncertainty is high, an increase in the FIT will be less effective at accelerating investment. However, if policy risk is low, FIT schemes can significantly accelerate investment, even in highly volatile markets.



### Sequential capacity expansion options

Benoît Chevalier-Roignant (1), Alain Bensoussan (2,3),

(1) King's College, London, United Kingdom (2) UT Dallas, Dallas, USA (3) City University of Hong Kong, Hong Kong

This paper considers a firm's capacity expansion decisions under uncertainty. The firm has leeway in timing investments and in choosing how much capacity to install at each investment time. We model this problem as the sequential exercising of compound capacity expansion options with embedded optimal capacity choices. We employ the impulse control methodology and obtain a quasi-variational inequality that involves two state variables: an exogenous, stochastic price process and a controlled capacity process (without a diffusion term). We provide a general verification theorem and identify—and prove the optimality of—a two-dimensional  $(s, S)$ -type policy for a specific case. The firm delays investment in capacity to ensure that the perpetuity value of newly installed capacity exceeds the total opportunity cost, including the fixed cost component, by a sufficient margin. Our general model for “the option to expand” transcends a single-option exercise and yields predictions of both the optimal investment timing and the optimal scale of production.

### Technology adoption in a declining market

Verena Hagspiel (1), Kuno J.M. Huisman (2,3), Peter M. Kort (2,4), Maria N. Lavrutich (1), Cláudia Nunes (5), Rita Pimentel (5),

(1) Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Trondheim, Norway (2) CentER, Department of Econometrics and Operations Research, Tilburg University, Tilburg, The Netherlands (3) ASML Netherlands B.V., Veldhoven, The Netherlands (4) Department of Economics, University of Antwerp, Antwerp, Belgium (5) Department of Mathematics and CEMAT, Instituto Superior Técnico, Lisboa, Portugal Rapid technological developments are inducing

the shift in consumer demand from existing products towards new alternatives. When operating in a declining market, the profitability of incumbent firms is largely dependent on the ability to correctly time the introduction of product innovations. In this paper, we contribute to the existing literature on technology adoption, by considering the optimal innovation investment in the context of the declining market. We study the problem of a firm that has an option to undertake the innovation investment and thereby to replace the established product by the new one. We are able to quantify the value of the option to adopt a new technology, as well as the optimal timing to exercise it. We find that it can be optimal for the firm to innovate not only because of the significant technological improvement, but also due to demand saturation. In the latter case profits of the established product may become so low that the firm will adopt a new technology even if the newest available innovation has not improved for some time. This way, our approach allows to explicitly account for the effect of a decline in the established market on technology adoption.

## 30. Modeling and computational methods for financial applications 2

11:30 – 12:45

Chair: A. Picarelli, C. Reisinger

FH HS 7

Model reduction for Hamilton-Jacobi-Bellman equations resulting from intraday trading of electricity

Silke Glas (1), Karsten Urban (1),

(1) Institute of Numerical Mathematics, Ulm University, Ulm, Germany

Due to the growth of renewable energy, the future perspective of energy markets is seen in short-term trading markets. In this talk, we consider the intraday trading of electricity and derive a Hamilton-Jacobi-Bellman (HJB) equation for this setting, extending the work of [1]. A recent change in regularity constraints even allows that the participants of the intraday market can trade every 15 minutes instead of every hour.

Our aim is to find an optimal trading strategy within 15 minutes/an hour using the most recent information of the market. As solving the HJB equation is a nonlinear and nonsmooth problem, fine discretizations, that are needed, can resolve in long computation times. Therefore, we use the reduced basis method (RBM) [2,3] to derive a reduced model.

The RBM is a well-known technique to efficiently reduce the numerical efforts for many parametrized problems. We introduce the parametric formulation of our HJB equation, in which the parameter is the incoming data of the market and analyze the reducibility of this problem. We provide numerical investigations for our method.

This is joint work with N. von Luckner and R. Kiesel, Chair for Energy Trading and Finance, University Duisburg-Essen.

- [1] R. Aïd, P. Gruet and H. Pham. An optimal trading problem in intraday electricity markets. *Mathematics and Financial Economics*, 10(1):49–85, 2016.
- [2] J.S. Hesthaven, G. Rozza and B. Stamm. *Certified reduced basis methods for parametrized partial differential equations*. Springer, Cham, 2016.
- [3] A. Quarteroni, A. Manzoni and F. Negri. *Reduced basis methods for partial differential equations*. Springer, Cham, 2016.

### Backward differentiation schemes for parabolic Hamilton-Jacobi-Bellman equations

O. Bokanowski (1), A. Picarelli (2), C. Reisinger (2),

(1) Laboratoire Jacques-Louis Lions, University Paris Diderot, Paris, France (2) Mathematical Institute, University of Oxford, Oxford, United Kingdom

We study second order BDF (Backward Differentiation Formula) schemes for the numerical approximation of parabolic Hamilton-Jacobi-Bellman (HJB) equations, following [1]. Second order BDF approximations are used in both time and space. The resulting scheme is implicit, non-monotone, and second order accurate in both time and space. Although in implicit form, we will explain how the scheme can be solved efficiently. A similar scheme has already been studied in the particular context of a diffusion problem with

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an obstacle term (such as the American obstacle option problem in mathematical finance [2,3]). The lack of monotonicity of the scheme prevents the use of known convergence results for solutions in the viscosity sense. Here we generalize the use of the scheme to general non-linear HJB equations and establish stability, convergence and error estimates results in  $L^2$ -type norms in different situations. Numerical tests will be given to show the robustness and precision of the method even near the singularities of the solution.

- [1] O. Bokanowski, A. Picarelli, C. Reisinger Stability and convergence of second order backward differentiation schemes for parabolic Hamilton-Jacobi-Bellman equations. Preprint hal-01628040.
- [2] C. W. Oosterlee, On multigrid for linear complementarity problems with application to American-style options, *Electron. Trans. Numer. Anal.*, 15, pp. 165–185 (electronic), 2003.
- [3] O. Bokanowski, K. Debrabant. High order finite difference schemes for some nonlinear diffusion equations with an obstacle term. Preprint hal-01686742.

### Convergence rates for monotone numerical schemes for nonlocal Isaacs equations

Imran H. Biswas (1), Indranil Chowdhury (2), Espen R. Jakobsen (2),

(1) Centre for Applicable Mathematics, TIFR, Bangalore, India (2) Department of Mathematical Sciences, NTNU, Norway

We present new results for monotone numerical schemes for nonlocal Isaacs equations, the dynamic programming equations of stochastic differential games with jump-diffusion state processes. These equations are fully-nonlinear non-convex equations of order less than 2. Here they are also allowed to be degenerate and have non-smooth solutions. The main contribution is a series of new a priori error estimates for a class of monotone numerical methods. These results are (i) the first results for *nonlocal* Isaacs equations, (ii) the first general results for degenerate non-convex equations of order greater than 1, and (iii) the first results in a viscosity solution setting giving *the precise dependence on the fractional order* of the equation. We also observe a new phenomena, that the rates differ when the nonlocal diffusion coefficient depend on  $x$  and  $t$ , only on  $x$ , or on neither.

- [1] I. H. Biswas, I. Chowdhury, and E. R. Jakobsen. On the rate of convergence for monotone numerical schemes for nonlocal Isaacs equations.  
<https://arxiv.org/abs/1709.07743> (submitted for publication)

### 31. Numerical analysis for PDE constrained optimization 2      11:30 – 12:45

*Chair:* A. Rösch, J. Pfefferer

FH 8 Nöbauer HS

#### Approximation error for control problems involving phasefield damage models

Masoumeh Mohammadi (1), Ira Neitzel (2), Thomas Wick (3), Winnifried Wollner (1),

(1) Fachbereich Mathematik, TU Darmstadt, Darmstadt, Germany (2) Institut für Numerische Simulation, Universität Bonn, Bonn, Germany (3) Fakultät für Mathematik und Physik, Leibniz Universität Hannover, Hannover, Germany

Within this talk, we will briefly discuss the function-space setting for a class of optimization problems involving fracture processes modeled by a phase-field approach. Although this problem need not satisfy a constraint qualification a quadratic-approximation, as needed in SQP-type algorithms, admits a unique solution for the considered class. We will discuss the regularity of the linearized equations. Based on the regularity, convergence with rates of a finite element approximation will be shown.

### Optimal control of multiphase flows

Michael Hinze (1, 2), Harald Garcke (3), Christian Kahle (4),

(1) Fachbereich Mathematik, Universität Hamburg, Hamburg, Germany (2) Lothar Collatz Center for Computing in Science, Universität Hamburg, Hamburg, Germany (3) Lehrstuhl für Mathematik VIII, Universität Regensburg, Regensburg, Germany (4) Lehrstuhl für Optimalsteuerung, Technische Universität München, Munich, Germany

We consider the optimal control of a two-phase fluid that is described by the thermodynamically consistent diffuse interface model proposed in 2012 by Abels/Garcke/Grün [1]. As key ingredient we present an energy stable simulation scheme proposed by the authors in 2016 [2]. It allows us to simulate two-phase fluids in an energy stable way and provides enough regularity to apply classic theory from optimal control [3]. We prove existence of solutions to a semi-discrete in time optimal control problem, and present a convergence analysis for its finite element discretization. We illustrate the performance of our approach with some numerical examples.

- [1] H. Abels, H. Garcke, and G. Grün. Thermodynamically consistent, frame indifferent diffuse interface models for incompressible two-phase flows with different densities. *Mathematical Models and Methods in Applied Sciences*, 22(3):40 (2012).
- [2] H. Garcke, M. Hinze, C. Kahle: A stable and linear time discretization for a thermodynamically consistent model for two-phase incompressible flow. *Applied Numerical Mathematics* 99:151-171 (2016).
- [3] H. Garcke, M. Hinze, C. Kahle: Optimal Control of time-discrete two-phase flow driven by a diffuse-interface model. *arXiv:1612.02283* (2016).

### Optimization of current carrying multicables

Helmut Harbrecht (1),

(1) Department of Mathematics and Computer Science, University of Basel, Switzerland

Intense electric currents in cable bundles contribute to hotspot generation and overheating of essential car elements, especially in connecting structures. An important aspect in this context is the influence of the positioning of wires in cable harnesses. In order to find an appropriate multicable layout with minimized maximum temperatures, we formulate an optimization problem. Depending on the packing density of the cable bundle, it is solved via different optimization strategies: in case of loosely packed cable bundles solely by a gradient based strategy (shape optimization), densely packed ones by arrangement heuristics combined with a standard genetic algorithm, others by mixed strategies.

In the simulation model, the temperature dependence of electric resistances and different parameter values for the multitude of subdomains are respected. Convective and radiative effects are summarized

by a heat transfer coefficient in a nonlinear boundary condition. Finite elements in combination with an interior-point method and a genetic algorithm allow the solution of the optimization problem for a large number of cable bundle types. Furthermore, we present an adjoint method for the solution of the shape optimization problem. The jumps at the interfaces of different materials are essential for the Hadamard representation of the shape gradient. Numerical experiments are carried out to demonstrate the feasibility and scope of the present approach.

### 32. Contributed session: dynamic games 1

11:30 – 12:45

*Chair:* R. Hartl

FH HS 3

#### Markov perfect equilibria in multi-mode differential games with endogenous timing of mode transitions

Herbert Dawid (1), Serhat Gezer (1),

(1) Department of Business Administration and Economics and Center for Mathematical Economics, Bielefeld University, Bielefeld, Germany

In this paper Markov-perfect equilibria of multi-mode differential games, in which one player controls the transition between modes, are studied. Conditions characterizing the equilibrium feedback strategies and the value functions of both players in such type of games, which have not been previously studied, are derived. These results are applied to analyze Markov-perfect equilibria of a game capturing the dynamic interaction between two incumbent firms among which one has to decide when to extend its product range by introducing a new product. The market appeal of the new product can be (positively or negatively) influenced over time by the competing firms through costly investments. It is shown under which circumstances feedback equilibria exist for this game and demonstrated that the combination of a continuously evolving state variable, which is controlled by both players, with a discrete timing decision can give rise to strategic effects that qualitatively differ from those present in standard timing games.

#### Capacity and partnership management under conflict of interests with customers

Cheng-Hung Wu (1), Jia-Bo Huang (1),

(1) Institute of Industrial Engineering, National Taiwan University, Taipei, Taiwan

This research studies dynamic capacity and partnership game in a two-echelon supply chain. In this two-echelon supply chain, the upstream firm provides key components to the downstream firm while both firms produce and sell finished products. Therefore, the two firms are in their relationship as supplier-customer of key components but also competitors in their finished products. We stress the “conflict of interest” relationships between firms and study the combination of two cross aspects of cooperation and competition between firms. A dynamic game model is proposed to analyze the strategic interaction between firms in capacity planning, component pricing, and partnership management. Our preliminary result provides the optimal policy and show the factors that the firms have to be concerned with during the decision making processes.

### Dynamic tax competition

Nora Paulus (1), Parice Pieretti (1), Benteng Zou (1),

(1) CREA, University of Luxembourg, Luxembourg

Multinational firms are able to invest in two countries who are engage in tax competition and firms' reallocation of investment takes time. We analyze this "stickiness" of firms' investment in term of a differential game. Both open-loop and Markovian Nash equilibrium strategies are derived, from which the corresponding asymptotically stable steady state equilibrium tax rates are obtained. We find that open-loop strategic Nash equilibrium leads to higher steady state tax rates than the ones from static game while the equilibrium tax rates from Markovian Nash equilibrium strategies, which are subgame perfect, are lower than the outcome from static game. Thus, Markovian Nash equilibrium strategies yield more severe tax competition than static and open-loop competition. As a by product, instead of minimum tax rates or tax harmonization, open-loop strategic Nash equilibrium could be another way of reducing the race to the bottom competition.

### 33. Model based control: analysis and modelling 3

11:30 – 12:45

*Chair:* K. Worthmann, K. Chudej

FH HS 2

#### Hierarchical distributed model predictive control of interconnected microgrids

C. A. Hans (1), P. Braun (2,3), J. Raisch (1,4), L. Grüne (2), C. Reincke-Collon (5),

(1) Control Systems Group, Technische Universität Berlin, Germany (2) Mathematical Institute, Universität Bayreuth, Germany (3) School of Electrical Engineering and Computing, University of Newcastle, Australia (4) Max Planck Institute for Dynamics of Complex Technical Systems, Magdeburg, Germany (5) Younicos GmbH, Berlin, Germany

Microgrids (MGs) gather a combination of generation units, loads and energy storage elements into a system that can be controlled locally. For such MGs, we propose a hierarchical distributed model predictive control (MPC) strategy [1] to operate them in an interconnected way with the goal of increasing the overall infeed of renewable energy sources. In particular, we investigate how renewable infeed of MGs can be increased by using a transmission network allowing the exchange of energy. To obtain an MPC scheme which is scalable with respect to the number of MGs and preserves their independent structure, we make use of the alternating direction method of multipliers leading to local controllers communicating through a central entity. This entity is in charge of the power lines and ensures that the constraints on the transmission capacities are met. The use of the MPC is illustrated in a numerical case study and compared to operation of islanded MGs, operated using the strategy proposed in [2].

[1] C. A. Hans, P. Braun, J. Raisch, L. Grüne, C. Reincke-Collon. Hierarchical Distributed Model Predictive Control of Interconnected Microgrids. *IEEE Trans. Sustain. Energy*, 2018. In press.

[2] C. A. Hans, V. Nenchev, J. Raisch, C. Reincke-Collon. Minimax Model Predictive Operation Control of Microgrids. *19th IFAC World Congress*, 10287–10292, 2014.

## Penalty pricing to control autonomous energy storages for demand side management

Klaus Rheinberger (1), Markus Preißinger (1), Peter Kepplinger (1,2),

(1)illwerke vkw Professorship for Energy Efficiency, Energy Research Center, Vorarlberg University of Applied Sciences, Dornbirn, Austria (2)Josef Ressel Center for Applied Scientific Computing in Energy, Finance, and Logistics, Vorarlberg University of Applied Sciences, Dornbirn, Austria

In electrical grids, generation has to meet demand at all times. However, fulfilling this requirement with the growing share of renewable energies and their strongly transient generation is challenging. Therefore, management of loads on the demand side is considered a mature tool to facilitate the integration of renewables [1].

The storage capacity of devices is considered the key feature to provide demand flexibility, which is why energy storage systems (ESS) are regarded the most promising application. A frequently discussed approach for demand side management is the broadcasting of real-time prices as incentives to drive autonomous optimization of the ESS. The leader's problem of determining optimal prices such that the demand of the ESS matches production as much as possible can be formulated mathematically as a bilevel optimization problem [2].

Linear prices imply a linear programming problem at the level of the ESS. As the optimal decisions are on the boundary of the feasible region, only these production plans can be matched. Thus, linear prices as a method of control perform suboptimal. However, controlling the ESS with a  $L^1$ -norm optimization improves the matching. Furthermore, this approach can be re-formulated as a linear programming problem and can be interpreted economically as penalty pricing.

We claim that  $L^1$ -norm optimization offers the possibility to value flexibility in a promising way.

- [1] ] N. G. Paterakis, O. Erdinc, and J. P. Catalão. An overview of demand response: Key-elements and international experience. *Renewable and Sustainable Energy Reviews*, 69:871–891, 2017.
- [2] T. Lübker, M. Venzke, N.-V. Vo, V. Turau. Understanding price functions to control domestic electric water heaters for demand response: A bilevel approach to adapt power consumption to availability. *Computer Science - Research and Development*, 33:81–92, 2017.

## Optimal control of coupled ordinary and partial differential equations

Sven-Joachim W. Kimmerle (1),

(1)Department of Mathematics and Computer Application, Bundeswehr University Munich, Neubiberg, Munich, Germany

We present several examples for optimal control problems subject to coupled systems of ordinary differential equations (ODEs) and partial differential equations (PDEs), among other things an elastic crane-trolley-load system [1] and a truck with a fluid container [2]. There are two approaches: on one hand the ODE may be treated as a PDE, yielding an optimal control problem for a coupled system of PDE, on the other hand the PDE may be considered as an ODE in function spaces. The class of optimal control problems for coupled ODEs and PDEs is heterogeneous that is obvious since different PDEs alone require different theories and methods. We discuss further aspects of our class of problems like the reversal of the coupling structure in the adjoint equations or structure-exploiting algorithms [3].

- [1] S.-J. Kimmerle, M. Gerdt, and R. Herzog: Optimal control of an elastic crane-trolley-load system - a case study for optimal control of coupled ode-pde systems. *MCMDS*, 24(2):182-206, 2018.

- [2] S.-J. Kimmerle and M. Gerds: Necessary optimality conditions and a semi-smooth Newton approach for an optimal control problem of a coupled system of Saint-Venant equations and ordinary differential equations, *Pure Appl. Funct. Anal.*, 1(2):231–256, 2016.
- [3] J.-H. Weibert, P.E. Gill, S.-J. Kimmerle, and M. Gerds: A study of structure-exploiting sqp algorithms for an optimal control problem with coupled hyperbolic and ordinary differential equation constraints. Accepted by *DCDS-S* in 2017.

## 34. Real options 2

11:30 – 12:45

*Chair:* P.M. Kort

FH HS 4

### Exit game with information externalities

Svetlana I. Boyarchenko (1),

(1) University of Texas at Austin, Austin, U.S.A.

I analyze a two-player stopping time game with pure informational externalities. While the players are in the game, they receive deterministic revenues and incur stochastic costs. Each player incurs the cost at random times. Times of arrival of costs are modeled as Poisson processes with unknown parameters. The costs are assumed to be i.i.d. random variables for each state of a continuous time Markov chain that models the evolution of the nature. The characteristics of the cost process are common to both players. As a result, players may remain active longer than a single player would do. For some observations of costs, the current state of the Markov chain cannot be uniquely inferred, therefore, there is space for a stochastic evolution of two-dimensional beliefs about the current state of the Markov chain and about the parameters of the Poisson process. Each player learns about the current value of the cost both when she incurs the cost, and when the other player incurs the cost. Thus, each player benefits if the other player stays in the game longer, because this increases the frequency of observations and the value of staying in the game. I demonstrate that if the players are heterogeneous, there is an equilibrium, where they exit the game sequentially, and the order of exit is determined endogenously.

The optimal stopping time is the first time the two-dimensional beliefs enter the exit region. I formulate general conditions on the evolution of beliefs near the boundary of the exit region, which ensure that the value function is smooth at a part of the boundary (absorbing part), and the condition that ensure that the value function has a kink at a part of boundary (reflecting part).

### Dynamic investment with endogenous prices and capital depreciation

Thomas Dangl (1), Hamed Ghoddusi (2),

(2) Technische Universität Wien, Vienna, Austria (2) School of Business, Stevens Institute of Technology, Hoboken, USA

We present a continuous-time model of optimal dynamic capacity investment under demand uncertainty when the spot price of a depreciating capital asset is determined in a market equilibrium. Output prices are endogenous and competitive firms optimize their instantaneous investment decision under full consideration of the equilibrium price dynamics. We derive closed-form solutions for the optimal instantaneous investment policies, the value of the firm, endogenous output price dynamics, and their stationary



distribution. Investment and output prices are path-dependent, the net present value of new investment is always equal to zero. We find that lower-quality (shorter-lived) capital, which is cheaper to purchase but depreciates faster acts like a put option for the firm value in a competitive market. The less the market power of the firm, the higher the value of capital depreciation in bad times is. More expensive productive capital moves the mode of the stationary price distribution towards lower prices but increases expected output prices. Demand volatility has a nonlinear influence on output prices, such that expected prices are highest for intermediate demand-volatility.

### On some real options on two risky assets

Pavel V. Gapeev (1), Goran Peskir (2),

(1) Department of Mathematics, London School of Economics, London, United Kingdom (2) School of Mathematics, The University of Manchester, Manchester, United Kingdom

We present some closed-form solutions to the problems of rational pricing of some real options on two risky assets with finite investment times. It is assumed that the dynamics of prices of these risky assets are described by two geometric Brownian motions driven by constantly correlated standard Brownian motions. The optimal investment times are shown to be the first passage times of one risky asset price process on stochastic boundaries depending on the running value of the other asset price process. We derive explicit expressions for the value functions and the optimal investment boundaries for the so-called standard basket, rainbow, traffic-light, compound, and switching currency put and call options.

## 35. Stochastic control and optimization in finance

14:00 – 15:40

*Chair:* S. Federico, M. Maggis

FH HS 7

### Continuous time superhedging on prediction sets

Daniel Bartl (1), Michael Kupper (1), Ariel Neufeld (2),

(1) Math Department, University of Konstanz, Germany (2) Math Department, ETH Zürich, Switzerland

We provide a pricing-hedging duality for the model-independent superhedging price with respect to a prediction set  $\Xi \subset C[0, T]$ , where the superhedging property needs to hold pathwise, but only for paths lying in  $\Xi$ : For any upper/lower semicontinuous claim  $\Xi$  which is bounded from below, the superhedging price coincides with the supremum over all pricing functionals  $E_Q[\Xi]$  with respect to martingale measures  $Q$  concentrated on the prediction set  $\Xi$ . We further discuss applications to robust stochastic analysis.

### Optimal liquidation under partial information with price impact

Katia Colaneri (1), Zehra Eksi (2), Rüdiger Frey (2), Michaela Szölgényi (3),

(1) School of Mathematics, University of Leeds, Leeds, UK (2) Institute for Statistics and Mathematics, Vienna University of Economics and Business, Vienna, Austria (3) Department of Mathematics, ETH Zurich, Zurich, Switzerland

We study an optimal liquidation problem for a large investor having an impact on stock prices, in a market model driven by a pure jump process with (stochastic) jump intensity and jump size distribution

depending on an unobservable risk source. From the mathematical point of view, this results in a stochastic control problem for piecewise deterministic Markov processes (PDMPs) under partial information. In order to solve the problem we follow a two-step procedure. First, we derive an equivalent control problem under full information via stochastic filtering. In this way we obtain a control problem where unobservable state variables are replaced by their filtered estimates. Second, the resulting control problem has a state process which is piecewise deterministic Markov processes in the sense of [1]. We provide a detailed mathematical analysis of this problem. Precisely, we establish the dynamic programming equation for the value function and we derive conditions on the data of the problem that guarantee the continuity of the value function and the existence of optimal relaxed controls. For this we need a careful analysis of the behaviour of the value function close to the boundary. As a further step, using the approach by [2] suitably extended to our setting, we characterize the value function as continuous viscosity solution of the Hamilton Jacobi Bellman (HJB) partial integro-differential equation associated with the problem. Moreover, we prove a novel comparison theorem for the HJB equation which is valid in more general setups. In order to gain intuition on the form of the resulting optimal liquidation rate we carry out a numerical study, based on discretization of the HJB equation.

[1] M. Davis. *Markov models & optimization*. CRC Press. 1993.

[2] M. Davis and M. Farid. Piecewise-deterministic processes and viscosity solutions. *Stochastic analysis, control, optimization and applications*, 249–268, 1999. Birkh user, Boston, MA.

### The value of informational arbitrage

Claudio Fontana (1), Huy N. Chau (2), Andrea Cosso (3),

(1) LPSM, Universit  Paris Diderot (Paris VII), Paris, France (2) Hungarian Academy of Sciences, Budapest, Hungary (3) Dipartimento di Matematica, Universit  di Bologna, Italy

In the context of a general semimartingale model of a complete market, we aim at answering the following question: How much is an investor willing to pay for learning some inside information that allows to achieve arbitrage? If such a value exists, we call it the value of informational arbitrage. In particular, we are interested in the case where the inside information yields arbitrage opportunities but not unbounded profits with bounded risk. In the spirit of Amendinger et al. (2003, *Finance Stoch.*), we provide a general answer to the above question by relying on an indifference valuation approach. To this effect, we establish some new results on models with inside information and study optimal investment-consumption problems in the presence of initial information and arbitrage. We characterize when the value of informational arbitrage is universal, in the sense that it does not depend on the preference structure. Our results are illustrated with several explicit examples.

### Model-independent bounds for Asian options: a dynamic programming approach

Sigrid K llblad (1), Alexander M.G. Cox (2),

(1) Mathematical Stochastics, Vienna University of Technology, Vienna, Austria (2) Department of Mathematical Sciences, University of Bath, Bath, U. K..

We consider the problem of finding model-independent bounds on the price of an Asian option, when the call prices at the maturity date of the option are known. Our methods differ from most approaches to model-independent pricing in that we consider the problem as a dynamic programming problem, where

the controlled process is the conditional distribution of the asset at the maturity date. By formulating the problem in this manner, we are able to determine the model-independent price through a PDE formulation. Notably, this approach does not require specific constraints on the payoff function (e.g. convexity), and would appear to generalise to many related problems.

### 36. Model order reduction in control and optimization 1

14:00 – 15:40

*Chair:* M. Falcone, V. Simoncini

FH 8 Nöbauer HS

#### Model order reduction for vibrations

Karl Meerbergen (1),

(1) KU Leuven, Department of Computer Science, Leuven, Belgium

Model order reduction techniques are often used to speed up computations of finite element analyses of vibrations. In this talk, we explain why Krylov methods are often the preferred methods for such problems. We present a trust region and penalty function approach for design optimization of vibration problems. Recent models include advanced damping properties which lead to nonlinear frequency dependencies. We show how Krylov methods can be used for such applications.

#### Greedy controllability of reduced-order linear dynamical systems

Stefan Volkwein (1), Laura Iapichino (2), Giulia Fabrini (1),

(1) Universität Konstanz, Department of Mathematics and Statistics, Germany (2) Technische Universiteit Eindhoven, Department of Mathematics and Computer Science, The Netherlands

Often a dynamical system is characterized by one or more parameters describing physical features of the problem or geometrical configurations of the computational domain. As a consequence, by assuming that the system is controllable, corresponding to different parameter values, a range of optimal controls exists. The goal of the proposed approach is to avoid the computation of a control function for any instance of the parameters. The greedy controllability consists in the selection of the most representative values of the parameter set that allows a rapid approximation of the control function for any desired new parameter value, ensuring that the system is steered to the target within a certain accuracy. By proposing the Reduced Basis method in this framework, the computational costs are drastically reduced and the efficiency of the greedy controllability approach is significantly improved.

[1] G. Fabrini, L. Iapichino, and S. Volkwein. Reduced-order greedy controllability of finite dimensional linear systems. Submitted, 2017.

[2] M. Lazar and E. Zuazua. Greedy controllability of finite dimensional linear systems. *Automatica*, 74:327?340, 2016.

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### $H_2$ -model reduction for stabilizable systems

Tobias Breiten (1), Chris Beattie (2), Serkan Gugercin (2),

(1) Institute for Mathematics and Scientific Computing, University of Graz, Graz, Austria (2) Department of Mathematics, Virginia Tech, Blacksburg, USA

For an asymptotically stable linear time-invariant systems, locally  $H_2$ -optimal reduced-order models are known to satisfy Hermite type interpolation conditions. A numerical approach for computing such minimizers is provided by the iterative rational Krylov algorithm (IRKA). While generalizations to unstable systems exist, they typically require an explicit decomposition of the spectrum and thus are not feasible in a large-scale setting. Inspired by the method of LQG-balanced truncation, for stabilizable systems, we define a generalized  $H_2$ -error measure based on the solution of a Riccati equation. We discuss a modification of IRKA with respect to this generalized error measure and show that its computation is independent of the underlying Riccati equation. Based on numerical examples the performance of the method is studied.

### Combining POD model order reduction with adaptivity

Michael Hinze (1, 2), Carmen Gräßle (1),

(1) Fachbereich Mathematik, Universität Hamburg, Hamburg, Germany (2) Lothar Collatz Center for Computing in Science, Universität Hamburg, Hamburg, Germany

A crucial challenge within snapshot-based POD model order reduction for time-dependent systems lies in the input dependency. In the 'offline phase', the POD basis is computed from snapshot data obtained by solving the high-fidelity model at several time instances. If a dynamical structure is not captured by the snapshots, this feature will be missing in the ROM solution. Thus, the quality of the POD approximation can only ever be as good as the input material. In this sense, the accuracy of the POD surrogate solution is restricted by how well the snapshots represent the underlying dynamical system. If one restricts the snapshot sampling process to uniform and static discretizations, this may lead to very fine resolutions and thus large-scale systems which are expensive to solve or even can not be realized numerically. Therefore, offline adaptation strategies are introduced which aim to filter out the key dynamics. On the one hand, snapshot location strategies detect suitable time instances at which the snapshots shall be generated. On the other hand, adaptivity with respect to space enables us to resolve important structures within the spatial domain. Motivated from an infinite-dimensional perspective, we explain how POD in Hilbert spaces can be implemented. The advantage of this approach is that it only requires the snapshots to lie in a common Hilbert space. This results in a great flexibility concerning the actual discretization technique, such that we even can consider r-adaptive snapshots or a blend of snapshots stemming from different discretization methods. Moreover, in the context of optimal control problems adaptive strategies are crucial in order to adjust the POD model according to the current optimization iterate. In this talk, recent results in this direction from [1-3] are discussed and illustrated by numerical experiments.

- [1] A. Alla, C. Gräßle, M. Hinze: A-posteriori snapshot location for POD in optimal control of linear parabolic equations. arXiv:1608.08665v1 (2016), accepted for publication in ESAIM: Mathematical Modelling and Numerical Analysis (M2AN).
- [2] A. Alla, C. Gräßle, M. Hinze: A residual based snapshot location strategy for POD in distributed optimal control of linear parabolic equations. IFAC-PapersOnLine 49:13-188, 2016.
- [3] C. Gräßle, M. Hinze. POD reduced order modeling for evolution equations utilizing arbitrary finite element discretizations. arXiv:1701.05054 (2017). arXiv-file

### 37. Spatial resource and environmental economics and dynamic games 3

14:00 – 15:40

*Chair:* S. Behringer, T. Upmann

FH HS 3

**Convex risk measures for the aggregation of multiple information sources and their applications in natural resources management**

Georgios I. Papayiannis (1), Athanasios N. Yannacopoulos (1),

(1) Department of Statistics & Stochastic Modeling and Applications Laboratory, Athens University of Economics & Business, Athens, Greece

A novel class of convex risk measures is proposed, based on the concept of the Fréchet mean, designed in order to handle uncertainty which arises from multiple information sources regarding the risk factors of interest. The proposed risk measures robustly characterize and quantify hazards, by filtering out appropriately the partial information available in individual sources into an aggregate model for the risk factors of interest. Importantly, the proposed risks can be expressed in closed analytic forms allowing for interesting qualitative interpretations as well as comparative statics and thus facilitate their use in the everyday risk management process. A concrete application of the above framework as a decision tool in harvesting is illustrated.

**Quantifying the benefits of spatial fisheries management – an ecological-economic optimization approach**

Martin F. Quaas (1), Rudi Voss (1), Jörn O. Schmidt (1), Max T. Stoeven (1),

(1) Department of Economics, Kiel University, Kiel, Germany

Improving fisheries management is a key challenge to address the United Nations Sustainable Development Goal 2 (Zero Hunger) and also support goals 1 (No Poverty) and 14 (Life Below Water). However, sustaining the ocean's living resources has important dimensions beyond food security, such as cultural values, which might be of equal importance in some settings. Fisheries management faces special challenges when there is a mismatch between biological units and management units, e.g. when ecological spatial structures are not reflected in how catch limits are set. This might result in overexploitation and even the loss of sub-stocks. We use a spatially structured ecological-economic model parameterized for a pelagic schooling ('herring-like') fishery to examine how the benefits of implementing spatially differentiated fisheries management depend on biological parameters. We prove that in theory an ideally differentiated spatial management could be implemented without the need to exactly understand recruitment behavior. For imperfectly differentiated spatial management, however, we find that knowledge on spatial recruitment behavior becomes key to avoid economic losses and to sustain stock structuring, especially when there is large spatial heterogeneity in biological parameters. Knowledge on variability in site-specific productivity determines the expectation of achievable sustainable harvest levels.

## Hopf bifurcation in infinite time horizon distributed optimal control problems

Hannes Uecker (1),

(1) Institut für Mathematik, Carl von Ossietzky Universität Oldenburg, Oldenburg, Germany

In [1], an infinite time horizon optimal control problem for emissions  $v_1(t)$  of some firms and pollution stock  $v_2(t)$  as state variables and the firms abatement policy  $k(t)$  as control was set up as a model showing Hopf bifurcations for the associated 4-dimensional canonical system. Here we extend the model to a PDE setting with  $v_{1,2} = v_{1,2}(t, x)$  and  $k = k(t, x)$  with diffusive coupling. We formally derive the canonical PDE system, which we then study numerically using the continuation and bifurcation software `pde2path` [2,3]. We find that in certain parameter regimes there occur Hopf bifurcations from a spatially homogeneous canonical steady state to branches of time-periodic spatially homogeneous and spatially inhomogeneous solutions. From their Floquet spectrum we find that some of these solutions have the saddle-point property and are thus candidates for optimal solutions.

- [1] Fr. Wirl, Optimal accumulation of pollution: Existence of limit cycles for the social optimum and the competitive equilibrium, *Journal of Economic Dynamics and Control*, 24(2):297-306, 2000
- [2] H. Uecker, `pde2path` homepage, [www.staff.uni-oldenburg.de/hannes.uecker/pde2path](http://www.staff.uni-oldenburg.de/hannes.uecker/pde2path), 2018
- [3] H. Uecker, Hopf bifurcation and time periodic orbits with `pde2path` – algorithms and applications, *Comm. in Comp. Phys*, to appear, 2018

## Optimal coastal fishery with constraints

Dieter Grass (1), Hannes Uecker (2), Thorsten Upmann (3,4,5),

(1) TU Wien, Institut für Stochastik und Wirtschaftsmathematik, Operations Research and Control Systems (ORCOS), Austria (2) Universität Oldenburg, Institut für Mathematik, Oldenburg, Germany (3) Helmholtz-Institute for Functional Marine Biodiversity at the University of Oldenburg (HIFMB), Oldenburg, Germany (4) Bielefeld University, Faculty of Business Administration and Economics, Bielefeld, Germany (5) CESifo, München, Germany

In many spatial resource models the agent is able to determine the harvesting activity over the complete spatial domain. However, agents frequently have only access to a resource at particular locations at which the moving biomass, such as fish or game, may be caught or hunted. In this paper, we analyse such an optimal control model with boundary harvesting and constraints on the controls. Using Pontryagin's Maximum Principle, we derive the associated canonical system, consisting of a forward-backward diffusion system with boundary controls, and numerically compute the canonical steady states and the optimal time dependent paths. We thus characterise the optimal control and the associated stock of the resource, and study the dependence of the optimal policies on the cost parameters. We begin with simple one-species models, and then extend the analysis to a predator-prey model of the Lotka-Volterra type, and show how the presence of two species enriches the results of our basic model.

These models are rather generic, and structurally similar problems exist in other economic domains. Therefore, our methods are applicable to a large class of economic models with boundary controls.

**38. Model based control: analysis and modelling 4**

**14:00 – 15:40**

*Chair:* K. Worthmann, K. Chudej

**FH HS 2**

**Euler discretization for a class of nonlinear optimal control problems with control appearing linearly**

Walter Alt (1), Ursula Felgenhauer (2), Martin Seydenschwanz (3),

(1) Institut für Mathematik, Friedrich-Schiller-Universität Jena, Germany (2) Institut für Mathematik, Brandenburgische Technische Universität Cottbus-Senftenberg, Cottbus, Germany (3) Siemens AG, Research in Digitalization and Automation, Munich, Germany

We investigate Euler discretization for a class of optimal control problems with a nonlinear cost functional of Mayer type, a nonlinear system equation with control appearing linearly and constraints defined by lower and upper bounds for the controls. Under the assumption that the cost functional satisfies a growth condition we prove for the discrete solutions Hölder type error estimates w.r.t. the mesh size of the discretization. If a stronger second-order optimality condition is satisfied the order of convergence can be improved. Numerical experiments confirm the theoretical findings.

**Asymptotic controllability via infinite horizon optimal control and an application to an epidemic model**

Katharina Kolo (1), Sabine Pickenhain (1),

(1) BTU Cottbus - Senftenberg, Cottbus, Germany

We consider an epidemic model in the form of a SEIR-system. The aim is to find an exponentially stable vaccination strategy that prevents the spreading of the epidemic. We construct a control, which stabilizes the dynamical system asymptotically by solving an infinite horizon optimal control problem. This problem is formulated in weighted Sobolev spaces as state spaces and weighted Lebesgue spaces as control spaces. For the class of problems proposed, we are able to derive a related dual program in form of a variational problem in weighted spaces. A polynomial approximation for the dual variables is used to solve the dual problem numerically.

**Markov-chain based scenario tree generation for robust NMPC**

Conrad Leidereiter (1), Dimitris Kouzoupis (2), Moritz Diehl (2), Andreas Potschka (1),

(1) IWR, Heidelberg University, Heidelberg, Germany (2) IMTEK, University of Freiburg, Freiburg, Germany

We consider Nonlinear Model Predictive Control (NMPC) of fault-tolerant systems with redundant components. The probability of failure is modelled by a Markov chain. Due to the uncertainty we employ a robustification approach for NMPC based on a scenario tree formulation. The commonly used approach for scenario tree generation is to choose realizations of the uncertainty, a robust horizon and then couple the scenarios according to the stochastic principle of non-anticipativity. A major challenge of scenario tree NMPC is the exponentially growing number of scenarios. This exponential growth in the length of the robust horizon with the number of realizations as base quickly becomes a bottleneck for the computational

costs, which need to stay within bounds that permit real-time applicability. Therefore the robust horizon is usually short (one to three stages).

Our novel scenario tree generation method does not depend on a robust horizon as in the usual scenario tree generation described above. Every possible dynamical evolution of the Markovian uncertainty is interpreted as a scenario. After coupling all scenarios according to the non-anticipativity we obtain large trees with  $10^{24}$  scenarios for the application. We present an efficient algorithm to enumerate all scenarios of the complete tree in the order of non-increasing scenario probabilities. For practical application of scenario tree NMPC we stop the algorithm when the subtree meets prescribed criteria. We conclude our presentation with numerical results for controlling a system of masses connected by spring packets with inherent Markovian fault tolerances. Our open-source implementation treeQP (available on <https://github.com/dkouzoup/treeQP>) provides a collection of efficient tree-structure exploiting QP solvers based on the linear algebra library BLASFEO.

### Adaptive tracking control for Port-Hamiltonian boundary control systems

Timo Reis (1), Thomas Berger (1), Marc Puche (1), Felix L. Schwenninger (1),

(1) Fachbereich Mathematik, Universität Hamburg, Hamburg, Germany

We consider abstract boundary control systems of the form

$$\begin{aligned}\dot{x}(t) &= \mathfrak{U}x(t), \\ u(t) &= \mathfrak{B}x(t), \\ y(t) &= \mathfrak{C}x(t),\end{aligned}$$

with operators  $\mathfrak{U}, \mathfrak{B}, \mathfrak{C}$  acting on (infinite-dimensional) spaces. We further assume that our system is port-Hamiltonian, that is, all trajectories fulfill

$$\int_0^t u^*(\tau)y(\tau)d\tau \geq \|x(t)\|^2 - \|x(0)\|^2.$$

Our aim is to design a simple controller  $u(t) = -k(t)(y(t) - y_{\text{ref}}(t))$  that stabilizes the system and achieves that the output  $y$  approximately tracks a give reference signal  $y_{\text{ref}}$ . We show that our problem leads to the consideration of nonlinear evolution equations whose solvability will be discussed.

## 39. Application of optimal control to problems in biomedicine 1

14:00 – 15:40

*Chair:* U. Ledzewicz, M.R. de Pinho

FH HS 4

Constant versus periodic control under integral constraint on the input – applications to populations models

Terence Bayen (1), Alain Rapaport (2), Fatima Tani (2),

(1) IMAG, Univ Montpellier, CNRS, Montpellier, France (2) MISTEA, Univ Montpellier, INRA, Montpellier SupAgro, Montpellier, France

This presentation is about periodic optimal control problems governed by a system, linear w.r.t. the control  $u$ , under an integral constraint on  $u$ . In the one-dimensional setting, we give conditions for which



the value of the cost function at steady state with a constant control  $\bar{u}$  can be improved by considering periodic controls  $u$  with average value equal to  $\bar{u}$ . This leads to the so-called *over-yielding* met in several applications such as in resource-consumer models (see *e.g.* [1,2]). With the use of the Pontryagin Maximum Principle, we provide the optimal synthesis of periodic strategies under the integral constraint. The results are based on [1] and will be illustrated on a single population model in order to study the effect of periodic inputs on the utility of the stock of resource.

- [1] T. Bayen, A. Rapaport, F.-Z. Tani, *Optimal periodic control for scalar dynamics under integral constraint on the input*, submitted 2018, preprint <https://hal.archives-ouvertes.fr/hal-01700128>
- [2] F. Wang, G. Pang, *Competition in a chemostat with Beddington DeAngelis growth rates and periodic pulsed nutrient*, Journal of Mathematical Chemistry, vol. 44, 3, pp. 691–710, 2008.

### Applications of infinite horizon optimal control problems in bio-medicine

Valeriya Lykina (1), Dieter Grass (2),

(1) Department Optimization, Brandenburg University of Technology Cottbus-Senftenberg, Cottbus, Germany (2) Research Unit ORCOS, Vienna University of Technology, Vienna, Austria

In the presented talk we discuss the opportunities to apply infinite horizon optimal control problems to bio-medical issues such as problems of finding low-dosed long-term cancer treatment strategies or problems of controlling the spread of infectious diseases. We mainly investigate cancer treatment problems as optimal control problems, cf. [1], with the aim to figure out whether the considering of an infinite horizon setting leads to principally different solution strategies in contrast to a fixed finite horizon setting. An another important question is whether it is possible to achieve an adequate modeling for describing the so called metronomic chemotherapy cancer treatment strategy via an infinite horizon optimal control setting. Such a setting corresponds to consideration of cancer as a chronic disease, which will be treated over the whole remaining future life time of the particular patient. It is worth of mentioning that through minimizing the expectation value of the cost functional the optimal control problem becomes stochastic. Nevertheless, it can easily be transformed to a purely deterministic control problem with infinite horizon.

Mathematically viewed we consider optimal control problems with integral objective of Lagrange type and analytical setting in weighted functional spaces, cf. [3]. Combining theoretical analysis of models with numerical analysis by means of software OCMat (Software for solution of nonlinear deterministic infinite horizon optimal control problems, cf. [2]) we arrive at final results.

- [1] Schättler, H.; Ledzewicz, U.: *Optimal Control for Mathematical Models of Cancer Therapies. An Application of Geometric Methods*, Interdisciplinary Applied Mathematics 42, Springer, 2015.
- [2] [https://orcocos.tuwien.ac.at/research/ocmat\\_software/](https://orcocos.tuwien.ac.at/research/ocmat_software/).
- [3] Lykina, V.; Pickenhain, S.: *Weighted functional spaces approach in infinite horizon optimal control problems: a systematic analysis of hidden advantages and opportunities*. J. math. Anal. Appl. **454**, pp. 195 – 218 (2017).

## Numerical approach for epidemiology multi-objective optimal control problem

Zahra Foroozandeh (1), Maria do Rosário de Pinho (1), Mostafa Shamsi (2),

(1) SYSTEC, Faculdade de Engenharia da Universidade do Porto, Portugal (2) Faculty of Mathematics and Computer Sciences, Amirkabir University of Technology, Tehran, Iran

Recently, different costs for optimal control problems involving compartmental models for epidemiology have been proposed; the aim is, in all the cases, the control of the spread of diseases in a certain population. The chosen costs reflect in different ways the social costs of the infection. Multi-Objective Optimal Control Problems (MOOCs) are particular useful to study and compare such different costs. However, they are computationally heavy, a fact that may explain why they have not deserved much attention in this biomath area. Our aim is to contribute to remedy such situation by proposing an efficient and fast numerical approach to solve such problems.

We consider MOOCs for controlled systems with control functions appearing linearly where the controls are bang-singular. We first reformulate the MOOC into a sequence of single-objective optimal control problems (SOOCs) using the *epsilon scalarization* (see, e.g., [1]). The Pareto front is then computed solving the SOOCs for various values of the scalar parameter. In order to capture switching times without a priori information of the structure of each SOOCs, we apply a mixed-binary non-linear programming approach (MBNLP), developed previously in [2]. We illustrate our method using a numerical implementation of the method on SIMR model in [3].

[1] Matthias Ehrgott, *Multicriteria Optimization*, Springer, 2015.

[2] Z. Foroozandeh, M. Shamsi and MdR de Pinho, *A mixed-binary non-linear programming approach for the numerical solution of a family of singular optimal control problems*, *International Journal of Control*, Vol. 86, 2018.

[3] MdR de Pinho, H. Maurer and H. Zidani, *Optimal Control of Normalized SIMR Models with Vaccination and Treatment*, *DCDS - Series B*, Vol. 23 (1) p. 79-99, 2018.

This work has the support of project PTDC/EEIAUT/ 2933/2014, TOCCATTA, funded by FEDER funds through COMPETE2020 - POCI and by national funds through FCT - Fundação para a Ciência e a Tecnologia.

## Some applications of multiobjective optimal control

C. Yalçın Kaya (1),

(1) School of Information Technology and Mathematical Sciences, University of South Australia, Adelaide, Australia

Pareto minimization of multiple objective functionals/costs in optimal control is the process of finding a compromise solution, referred to as a Pareto minimum, where any of the costs cannot be improved (i.e., reduced) further, without making the values of some of the other costs worse (i.e., higher). The set of all such compromise solutions form the *Pareto set*, or the *Pareto front*. In this talk, methods will be described to obtain the Pareto fronts of optimal control problems. Optimization over the Pareto front will also be considered. The latter is especially useful in the instances when construction of the Pareto front is costly or the viewing of the Pareto front is not easy, if not impossible. We will discuss examples, including tumour anti-angiogenesis, problems involving minimization of the total control variation, and trajectory planning

for search-and-rescue operations. This talk contains joint work with Regina Burachik, Henri Bonnel and Helmut Maurer.

#### 40. Sub-optimal solutions in games and control 1

16:00 – 17:40

*Chair:* Y. Averboukh, D. Gromov

FH HS 7

##### Approximate public-signal correlated equilibria for nonzero-sum differential games

Yurii Averboukh (1, 2),

(1) Krasovskii Institute of Mathematics and Mechanics UrB RAS, Yekaterinburg, Russia (2) Ural Federal University, Yekaterinburg, Russia

In the talk we examine the nonzero-sum differential game of two players with the dynamics given by

$$\frac{d}{dt}x(t) = f(t, x(t), u(t)) + g(t, x(t), v(t)), \quad t \in [0, T], \quad x(t) \in \mathbb{R}^d, \quad u(t) \in U, \quad v(t) \in V$$

and the objective function of the  $i$ -th player determined by  $\sigma_i(x(T))$ . It is well-known that the corresponding system of the Hamilton-Jacobi equation for this game is ill-posed.

We assume that the players choose their strategies in the class of public-signal correlated stochastic strategies with memory and construct an approximate Nash equilibrium using an auxiliary nonzero-sum continuous-time stochastic game. In particular, one can construct a near Nash equilibrium in the differential game based on a solution to stochastic differential game approximating the original game. Furthermore, we study the limit of approximate equilibrium outcomes in the case when the auxiliary stochastic games tend to the original deterministic one. It is shown that this limit lies in the convex hull of the set of equilibrium values provided by deterministic punishment strategies.

##### On Tauberian theorem for stationary Nash equilibria

Dmitry V. Khlopin (1),

(1) Krasovskii Institute of Mathematics and Mechanics, Yekaterinburg, Russia

The discussion is devoted to  $n$ -player nonzero-sum dynamic games. We consider a general enough framework, which is not limited to e.g. differential games and could accommodate both discrete and continuous time. Assuming common dynamics, we study two game families with total payoffs that are defined either as the Cesaro average (long run average game family) or Abel average (discounting game family) of the running costs. We analyze asymptotic Nash equilibria—strategy profiles that are approximately optimal if the planning horizon tends to infinity in long run average games and if the discount tends to zero in discounting games. Moreover, we also assume that this strategy profile is stationary. Under a mild assumption on players' strategy sets, we prove a uniform Tauberian theorem for stationary asymptotic Nash equilibrium. If a stationary strategy profile is an asymptotic Nash equilibrium and the corresponding Nash value functions converge uniformly for one of the families (when discount goes to zero for discounting games, when planning horizon goes to infinity in long run average games), then for the other family this strategy profile is also an asymptotic Nash equilibrium, and its Nash value functions converge uniformly to the same limit.

This study was supported by the Russian Science Foundation (project no. 17-11-01093).

[1] D.V. Khlopin. Tauberian Theorem for Value Functions. *Dyn. Games Appl.* (in print)

**Approximate equilibria for a class of stochastic differential games**

J. Daniel López-Barrientos (1), Héctor Jasso-Fuentes (2), Ekaterina V. Gromova (3),

(1) Facultad de Ciencias Actuariales, Universidad Anáhuac México, México (2) Departamento de Matemáticas, CINVESTAV-IPN, México (3) St. Petersburg State University, St. Petersburg, Russia

It is widely known that, in the context of dynamic games, it is necessary to look for Nash equilibria in the set of randomized (mixed) strategies. However, sometimes, this approach lacks a practical economic interpretation because we would like to be able to apply a pure strategy. This fact entails the need of making strong assumptions on the structure of the dynamics and the cost/reward functions (see [1, 2 and 3]). When there are, for instance, transferences between the pay-offs of the players, a plausible alternative for this problem is the use of the notion of  $\epsilon$ -equilibria (see, for instance, Chapter 5.4 in [5]). In this talk, we use standard dynamic programming techniques to present an extension of the algorithms studied in [4] to find approximate equilibria in a class of non-zero sum stochastic differential games for the cases of the rates of extraction of non-renewable resources (see [3]), and the price-setting oligopoly model of Bertrand-Edgeworth (see [6]).

- [1] B.A. Escobedo-Trujillo, J.D. López-Barrientos. Nonzero-sum stochastic differential games with additive structure and average payoffs. *J. Dynamics & Games*, 1(4), 555–578, 2014.
- [2] H. Jasso-Fuentes, J.D. López-Barrientos, B.A. Escobedo-Trujillo. Infinite-horizon non-zero-sum stochastic differential games with additive structure. *IMA J. Mathematical Control and Information*, 34(1), 283–309, 2015.
- [3] S. Kostyunin, A. Palestini, E. Shevkoplyas. On a Nonrenewable Resource Extraction Game Played by Asymmetric Firms. *J. Optim. Theory Appl.*, 163(2), 660–673, 2014.
- [4] H.J. Kushner. Numerical Approximations for Nonzero-Sum Stochastic Differential Games. *SIAM J. Control Optim.*, 46(6), 1942–1971, 2007.
- [5] L.A. Petrosyan, N.A. Zenkevich, E.V. Shevkoplyas. *Teoriya igr*. BHV-Peterburg, Saint-Petersburg, 2016. (In Russian language.)
- [6] P. Roy-Chowdhury. Bertrand-Edgeworth equilibrium with a large number of firms. *International J. Industrial Organization* 26(3), 746–761, 2008.

**McKean-Vlasov SPDEs for Mean Field games based on stable-like processes with common noise**

Marianna S. Troeva (1), Vassili N. Kolokoltsov (2, 3),

(1) Research Institute of Mathematics, North-Eastern Federal University, Yakutsk, Russia (2) Department of Statistics, University of Warwick, Coventry, UK (3) Faculty of AMCP, Saint-Petersburg State University, Saint-Petersburg, Russia

In this talk we will consider the nonlinear McKean-Vlasov SPDE arising in Mean Field games based on nonlinear stable-like processes with common noise. The MFG limit is specified by a single quasi-linear deterministic infinite-dimensional partial differential second order backward equation. Using the method of stochastic characteristics, McKean-Vlasov equation turns into a non-stochastic equation of the second order with random coefficients. We show the regularity and sensitivity with respect to the initial conditions

Wednesday, July 4<sup>th</sup>

of the solution to the nonlinear McKean-Vlasov SPDE, as well as the  $1/N$ -rate convergence for interacting stable-like processes to the limiting measure-valued stable-like process.

**41. Numerical analysis for PDE constrained optimization 3** **16:00 – 17:40**

*Chair:* A. Rösch, J. Pfefferer

**FH 8 Nöbauer HS**

**A priori error estimates for optimal control with functions of bounded variation**

Florian Kruse (1),

(1) University of Graz, Graz, Austria

We derive a priori error estimates for the variational discretization of a PDE-constrained optimal control problem that involves univariate functions of bounded variation as controls. We prove  $L^2$  error order  $h$  for the state and  $L^\infty$  error order  $h$  for the adjoint state. Under the structural assumption that the control is piecewise constant and that the adjoint state has nonvanishing first derivative at the points where the control exhibits jumps, we improve the error estimate for the state and the adjoint state to  $h^2$  and show that the  $L^1$  error of the control behaves like  $h^2$ .

**Accelerated conditional gradient methods for PDE-constraint optimization**

Daniel Walter (1),

(1) Technical University of Munich, Munich, Germany

We present a generalized version of the well-known Frank-Wolfe method for composite minimization problems

$$\min_{u \in \mathcal{M}} f(u) + g(u),$$

where  $f$  is a smooth function and  $g$  is in general nonsmooth but convex. The control space  $\mathcal{M}$  is given as the dual space of a separable, generally non-reflexive, Banach space  $\mathcal{C}$ . As a prototype example one might think of  $\mathcal{C} = C_0(\Omega)$ , the space of continuous functions with zero trace on an open and bounded set  $\Omega$ , and  $\mathcal{M} = \mathcal{M}(\Omega)$ , the space of Radon measures on  $\Omega$ . We discuss theoretical properties of the method, such as worst-case convergence rates and mesh-independence properties. Subsequently, the method is applied to two PDE-constrained optimal control problems with different choices of  $\mathcal{M}$ . Using structural properties of the specific control space we investigate possible strategies to accelerate the convergence. The theoretical results are confirmed by numerical experiments which show the practical efficiency of the proposed method

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## Second order optimality conditions for optimal control problems with quasilinear parabolic PDEs

Ira Neitzel (1), Lucas Bonifacius (2),

(1) Institute for Numerical Simulation, Universität Bonn, Bonn, Germany (2) Centre for the Mathematical Sciences, Technische Universität München, Garching, Germany

In this talk we analyze a class of optimal control problems governed by quasilinear parabolic partial differential equations. We focus on presenting second order sufficient conditions without two-norm discrepancy. The problem setting discussed includes problems with distributed control in two and three space dimensions, as well as Neumann boundary control in two dimensions. If the control depends on time, only, three dimensions can be handled as well. In the second part of the talk, we discuss higher regularity of the adjoint state that can be used for e.g. stability results for the control with respect to perturbations.

## Numerical approximation of rate-independent evolutions

Christian Meyer (1), Michael Sievers (1),

(1) TU Dortmund, Faculty for Mathematic, Dortmund, Germany

We present a discretization of a rate-independent evolution governed by a non-convex energy functional. While standard continuous and piecewise linear finite elements are used for the discretization in space, we employ a tailored local minimization algorithm for the discretization w.r.t. time. It is shown that sequences of discrete solutions converge so called parametrized solutions, as the mesh size tends to zero. This solution concept, that also arise via a vanishing viscosity analysis, allows for solutions which are discontinuous in time. A numerical example shows that our algorithm is able to approximate solutions that provide a time discontinuity.

## 42. Variational analysis and optimal control problems 1

16:00 – 17:40

*Chair:* P. Wolenski, H. Zidani

FH HS 3

### Discontinuous time-dependent optimal control problems and Hamilton-Jacobi equations

Piernicola Bettiol (1), Julien Bernis (1),

(1) LMBA Laboratoire de Mathématiques, Université de Bretagne Occidentale, Brest, France

We consider a class of optimal control problems in which the dynamic constraint is expressed in terms of a differential inclusion and an integral term appears in the cost functional to minimize. The velocity set and the Lagrangian are supposed time-dependent and discontinuities (w.r.t. the time variable) are allowed on a zero-measure set. In this context we provide a characterization of the value function as the unique generalized solution to the Hamilton Jacobi Equation satisfying a suitable boundary condition. Problems with state constraints are also investigated.

[1] P. Bettiol and R. Vinter. The Hamilton Jacobi Equation For Optimal Control Problems with Discontinuous Time Dependence. *SIAM J. Control Optim.*, 55(2), 1199–1225, 2017.

- [2] J. Bernis and P. Bettiol. *Discontinuous time-dependent optimal control problems with an integral cost and Hamilton-Jacobi equations*. Preprint.

### Strong tangential transversality

Mira I. Bivas (1, 2), Mikhail I. Krastanov (1, 2), Nadezhda K. Ribarska (1, 2),

- (1) Faculty of Mathematics and Informatics, Sofia University, Sofia, Bulgaria  
(2) Institute of Mathematics and Informatics, Bulgarian Academy of Sciences, Sofia, Bulgaria

We propose the concept of strong tangential transversality in Banach spaces (see [3]). The definition involves uniform tangent sets (introduced in [5] and discussed in [1]) and generalises the classical definitions of transversality of manifolds and transversality of cones.

It is shown that strong tangential transversality is a sufficient condition for tangential transversality (see [2]). Strong tangential transversality implies an intersection property for the Clarke tangent and normal cones, and a rather general sum rule for the Clarke subdifferential. The obtained results incorporate the classical theorems concerning epi-Lipschitz (c.f. [6]) and epi-Lipschitz-like sets and functions (c.f. [4], [7]).

- [1] M. Bivas, N. Ribarska, M. Valkov, Properties of uniform tangent sets and Lagrange multiplier rule, <https://arxiv.org/abs/1712.01540>
- [2] M. Bivas, M. Krastanov, N. Ribarska, On tangential transversality, preprint, 2018.
- [3] M. Bivas, M. Krastanov, N. Ribarska, On strong tangential transversality, preprint, 2018.
- [4] J.M. Borwein, H.M. Strojwas, The hypertangent cone, *Nonlinear Analysis: Theory, Methods & Applications*, Volume 13, Issue 2 (1989), 125-144.
- [5] M. Krastanov and N. Ribarska, Nonseparation of Sets and Optimality Conditions, *SIAM J. Control Optim.* (2017), 55(3), 1598-1618.
- [6] R.T. Rockafellar, Generalized directional derivatives and subgradients of nonconvex functions, *Canad. J. Math.*(1980), 32, 257-280.
- [7] A. Jourani and L. Thibault, Extensions of subdifferential calculus rules in Banach spaces, *Canad. J. Math.* (1996), 48, 834-848.

### Optimal control problems in Wasserstein spaces

Benoît Bonnet (1), Francesco Rossi (2),

- (1) Aix Marseille Université, CNRS, ENSAM, Université de Toulon, LIS, Marseille, France (2) Dipartimento di Matematica "Tullio Levi-Civita" Università degli Studi di Padova, Padova, Italy

The ever increasing attention devoted to the study of multi-agents systems during the past decade has progressively brought its corresponding modelling tools and problems into the realm of control and optimization theory. During this talk, we will focus on the so-called family of *mean-field optimal control problems*, describing how an external policy maker can achieve a desired goal which is written in the form of an optimization problem on a large assembly of interacting particles.

As it shall be emphasized, these many-body systems are mostly out of computational grasp in their discrete forms. Thus, they are usually approximated through the well-known *mean-field* procedure by infinite-dimensional problems. In this setting, the resulting dynamics is formulated as a *conservation law* on the *density* of agents.

With this modelling motivations in mind, we will focus on optimal control problems of the form

$$\begin{cases} \min_{u \in \mathcal{U}} \left[ \int_0^T L(\mu(t), u(t)) dt + \varphi(\mu(T)) \right] \\ \text{s.t.} \begin{cases} \partial_t \mu(t) + \nabla \cdot ((v[\mu(t)](t, \cdot) + u(t, \cdot))\mu(t)) = 0, \\ \mu(0) = \mu^0 \in \mathcal{P}_c(\mathbb{R}^d), \end{cases} \end{cases}$$

studied in the so-called *Wasserstein space of probability measures*. After introducing some concepts and tools from optimal transportation, we will discuss classical questions arising in the study of these problems: existence of solutions, algorithms designed to solve them, etc. We will finally describe a result obtained jointly with F. Rossi concerning first-order Pontryagin optimality conditions.

### Dynamical programming of a chemotherapy preventing drug resistance for in vitro heterogeneous tumours

Cécile Carrère (1), Hasnaa Zidani (2),

(1) LJLL, Sorbonne University, Paris, France (2) UMA, Ensta ParisTech, Palaiseau, France

Resistance to chemotherapy is a major cause of treatment failure for tumours. Several observations currently suggest that it is often due to heterogeneity in the cancer cells, even in the initial tumour before beginning the treatment[1]. Taking into account this phenomenon is thus important in the conception of new treatment protocols.

We base our study on an *in vitro* experiment done by M.Carré<sup>1</sup>. Two cancer lineages are cocultivated in a Petri dish, and are subject to a treatment, one lineage being sensitive to it and the other one resistant. Using the competition between the two lineages, it is possible to reduce the tumour volume without letting the resistant population emerge.

To propose better treatment schedules, we design based on previous work[2] an ODE model of these experiments, with uncertainties on some parameters. The objective we set is, given a certain threshold, to determine a treatment maintaining the tumour size below the threshold. If this objective cannot be attained, whether the tumour is initially too big or too resistant, we want to bring it to an admissible size as fast as possible. These two problems can be expressed mathematically in terms of controllability problems, which can be solved by the study of Hamilton Jacobi Bellman equations[3]. The numerical resolution of said equation is studied, and we present convergence results that allow the reconstruction of trajectories and treatment for an actual situation.

[1] Chisholm, R.H., Lorenzi, T., Clairambault, J. Cell population heterogeneity and evolution towards drug resistance in cancer: Biological and mathematical assessment, theoretical treatment optimisation. *Biochimica et Biophysica Acta (BBA) - General Subjects* 1860, 2627–2645, 2016.

[2] Carrère, C. Optimization of an in vitro chemotherapy to avoid resistant tumours. *Journal of Theoretical Biology* 413, 24–33, 2017.

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<sup>1</sup>Centre de Recherche en Oncobiologie et Oncopharmacologie, Aix-Marseille University



- [3] Altarovici, A., Bokanowski, O., Zidani, H. A general Hamilton-Jacobi framework for non-linear state-constrained control problems. *ESAIM: Control, Optimisation and Calculus of Variations* 19, 337–357, 2013.

### 43. Turnpike properties for ODEs and PDEs: theory and application 3

16:00 – 17:40

Chair: L. Grüne

FH HS 2

#### Turnpike in optimal control, and shape turnpike

Emmanuel Trélat (1),

(1) Sorbonne Université, Université Paris-Diderot SPC, CNRS, Inria, Laboratoire Jacques-Louis Lions, équipe CAGE, Paris, France

The turnpike property emerged in the 50's, after the works by the Nobel prize Samuelson in econometry. It stands for the general behavior of an optimal trajectory solution of an optimal control problem in large time. This trajectory tends to behave as the concatenation of three pieces: the first and the last arc being rapid transition arcs, and the middle one being in large time, almost stationary, close to the optimal value of an associated static optimal control problem.

In collaboration with Can Zhang and Enrique Zuazua, we have established the turnpike property in a very general framework in finite and infinite dimensional nonlinear optimal control. We prove that not only the optimal trajectory is exponentially close to some (optimal) stationary state, but also the control and the adjoint vector coming from the Pontryagin maximum principle. Our analysis shows an hyperbolicity phenomenon which is intrinsic to the symplectic feature of the extremal equations. We infer a very simple and efficient numerical method to compute optimal trajectories in that framework, in particular with an appropriate variant of the shooting method.

In recent works with Gontran Lance and Enrique Zuazua, we address the issue of the shape turnpike, where for instance the control in a PDE also consists of choosing the time-varying control domain, and we show how to obtain a turnpike result on time-varying shapes.

#### Sensitivity analysis of optimal control problems and an exponential turnpike property

Lars Grüne (1), Manuel Schaller (1), Anton Schiela (1),

(1) Chair of Applied Mathematics, Department of Mathematics, University of Bayreuth, Bayreuth, Germany

The first order optimality conditions of optimal control problems (OCPs) governed by parabolic partial differential equations (PDEs) are given as an infinite dimensional linear system. After elimination of the control, this system can be interpreted as two coupled PDEs running forward and backward in time.

In the context of sensitivity analysis of linear quadratic optimal control problems it has proven very useful to analyze the norm of the solution operator of this system of equations. This linear operator maps  $L_2$  source terms and initial data to the solution of the first order optimality conditions. In the case of stabilizable and detectable dynamics it can be shown that the norm of this operator is bounded by a constant independent of the end time of the OCP. The consequences are twofold. First, this implies that

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the  $L_2$  norm on the interval  $[0, T]$  of the solution's distance to a steady state, the turnpike, is bounded by a constant independent of  $T$ . This intuition can be rigorously quantified in the form of an exponential turnpike property.

Secondly, the bound on the operator norm can be used to show that perturbations of the extremal equations decay exponentially in time. These theoretical considerations will be accompanied by numerical examples for partial differential equations.

### The turnpike property in mean field games

Alessio Porretta (1),

(1) Department of Mathematics, University of Rome Tor Vergata, Rome, Italy

The turnpike property of optimal control problems raised new interest in the last few years, in connection with stabilization effects and long time behavior of evolutionary optimality systems. In this talk I will present a turnpike result which appears in mean field game theory; in the optimal control interpretation, this corresponds to the control of a Fokker-Planck equation through the action of the drift. I will especially address how the turnpike result appears by mixing global convexity, linearization techniques and decoupling methods, in which the so-called master equation (a PDE in infinite dimensions) plays a major role. All the three steps seem to be relevant in many other problems where the turnpike property is expected to hold.

### Several turnpike properties of optimal control problems for distributed parameter systems

Can Zhang (1, 2),

(1) Wuhan University, China (2) UPV/EHU, Spain

In this talk, we introduce three kinds of turnpike properties for the optimal control problem of evolution system arising in the context of infinite dimensional cases: integral-turnpike, measure-turnpike, and periodic-turnpike. We develop two approaches to analyze these turnpike theorems: one is from the perspective of the dissipativity of the control system; and another is from the view point of Pontryagin maximum principle as well as the saddle point theory of Hamiltonian system.

## 44. Application of optimal control to problems in biomedicine 2 16:00 – 17:40

*Chair:* U. Ledzewicz, M.R. de Pinho

FH HS 4

### Optimal control problems with time delays: necessary conditions, numerical treatment and case studies in biomedicine

Laurenz Göllmann (1), Helmut Maurer (1),

(1) Dept. of Mech. Engin., Münster University of Applied Sciences, Steinfurt, Germany (2) Institute of Analysis and Numerics, Westfälische Wilhelms-Universität, Münster, Germany

We consider optimal control problems with multiple time delays in state and control variables and present two applications in biomedicine. In the general setting the problem is to determine a pair of functions  $(x, u) \in W^{1,\infty}([0, t_f], \mathbb{R}^n) \times L^\infty([0, t_f], \mathbb{R}^m)$  that minimizes a functional  $J(u, x) = g(x(t_f))$  in Mayer

form subject to a delayed differential equation, boundary conditions and mixed control-state inequality constraints

$$\begin{aligned} \dot{x}(t) &= f(t, x(t - \tau_0), \dots, x(t - \tau_d), u(t - \tau_0), \dots, u(t - \tau_d)), \quad \text{a.e. } t \in [0, t_f], \\ x(t) &= x_0(t), \quad t \in [-\tau_d, 0], \quad u(t) = u_0(t), \quad t \in [-\tau_d, 0], \\ \psi(x(T)) &= 0, \\ 0 &\geq C(t, x(t - \tau_0), \dots, x(t - \tau_d), u(t - \tau_0), \dots, u(t - \tau_d)), \quad \text{a.e. } t \in [0, t_f]. \end{aligned}$$

After discussing necessary optimality conditions, we propose several discretization methods by which the delayed control problem is transformed into a large-scale nonlinear programming problem. The first case study is concerned with the delay differential model in [1] for tumour-immune response with chemoimmunotherapy. Assuming a more realistic  $L_1$ -type objective that is linear in control we obtain optimal controls of bang-bang type. In the second case study, we introduce a control variable in the delay differential model of hepatitis B virus infection developed in [2]. Again, we consider  $L_1$ -type objectives and show that optimal controls are bang-bang.

- [1] F. Rihan, D. H. Abdelrahman, F. Al-Maskari, F. Ibrahim, and M. A. Abdeen. Delay differential model for tumour-immune response with chemoimmunotherapy and optimal control. *Computational and Mathematical Methods in Medicine*, Hindawi Publishing Corporation, Vol. 2014, Article ID 982978, (2014).
- [2] S. Eikenberry, S. Hews, J. D. Nagy, and Y. Kuang. The dynamics of a delay model of Hepatitis B virus infection with logistic hepatocyte growth. *Mathematical Biosciences*, 6 (2009), pp. 283–299

### Control time delay in optimal control problems arising in combined anticancer therapies

Andrzej Swierniak (1), Helmut Maurer (2),

- (1) Silesian University of Technology, Department of Automatic Control, Akademicka, Gliwice, Poland  
 (2) University of Munster, Institute of Computational and Applied mathematics, Münster, Germany

In this work we study an effect of multiple control time delays in optimization of treatment protocols in combined anticancer therapy. The delays are related to PK/PD effects and some clinical recommendations taking into account advantages of particular sequencing of treatments. As an example we consider a two compartmental model of response to combination of cytotoxic and antiangiogenic drugs based on the Hahnfeldt et al. model. The optimized protocols are found using necessary conditions of optimality for optimal control problems with delays and numerical procedures based on nonlinear programming algorithms and arc parametrization method. We discuss structural sensitivity of the optimal solutions. Yet another example of the combined therapy takes into account concurrent or sequential chemo-radiation. In this case we assume a Gompertz model of tumor growth, the linear quadratic model of radiation effects and chemotherapy model based on Skipper assertion.

The study is partially supported by National Science Committee, Poland, Grant no.2016/21/B/ST7/02241 (AS)

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## Hopf bifurcation and optimal control of a delayed HIV model with state constraints

Cristiana J. Silva (1), Helmut Maurer (2), Delfim F.M. Torres (1),

(1) CIDMA, Department of Mathematics, University of Aveiro, Aveiro, Portugal (2) Institute of Computational and Applied Mathematics, University of Münster, Münster, Germany

We propose and analyze a delayed HIV infection model based in [1, 2] where the time-delay represents the incubation period, that is, the time between the new infection of a CD4+T cell and the time it becomes infectious. The stability of the equilibrium points is analyzed. Using the time delay as a bifurcation parameter, we derive necessary and sufficient conditions for the occurrence of Hopf bifurcation. Due to the importance of the pharmacological delay in the HIV treatment, we introduce a control variable into the previous model and a discrete time-delay in the control, which represents the delay that occurs between the administration of drug and its appearance within cells, due to the time required for drug absorption, distribution, and penetration into the target cells. In this work we introduce state constraints, representing positive bounds on the concentration of uninfected CD4+T cells at each instant of time. We formulate and solve an optimal control problem with state-control delays and state constraints, where the objective is to find a treatment strategy that maximizes the number of CD4+T cells as well as the number of CTL immune response cells, keeping the cost, measured in terms of chemotherapy strength and a combination of duration and intensity, as low as possible and the concentration of uninfected CD4+T cells between the given positive lower and upper bounds. The optimal control problem is solved analytical and numerically and optimal strategies are derived.

Acknowledgements: Research supported by FCT within projects UID/MAT/04106/2013 (CIDMA) and PTDC/EEI-AUT/2933/2014 (TOCCATA). Silva is also supported by the post-doc fellowship SFRH/BPD/72061/2010.

- [1] R. Culshaw, S. Ruan and R. Spiteri. Optimal HIV treatment by maximising immune response. *J. Math. Biol.*, 48, 545–562, 1992.
- [2] D. Rocha, C. J. Silva and D. F. M. Torres. Stability and Optimal Control of a Delayed HIV Model *Mathematical Methods in the Applied Sciences*, in press. DOI: 10.1002/mma.4207.

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45. Plenary

08:40 – 09:30

*Chair:* F. Gozzi

FH HS 1

Sparse and mean-field optimal control

Massimo Fornasier (1),

(1) Department of Mathematics, Technical University of Munich, Munich, Germany

In the past decade there has been a large scope of studies on mathematical models of social dynamics. Self-organization, i.e., the autonomous formation of patterns, has been so far the main driving concept. Usually first or second order models are considered with given predetermined nonlocal interaction potentials, tuned to reproduce, at least qualitatively, certain global patterns (such as flocks of birds, milling school of fish or line formations in pedestrian flows etc.). It is common experience that self-organization of a society does not always spontaneously occur. In the first part of the talk we address the question of whether it is possible to externally and parsimoniously influence the dynamics, to promote the formation of certain desired patterns. In particular we address the issue of finding the sparsest control strategy for finite agent models in order to lead the dynamics optimally towards a given outcome. In the second part of the talk we address the rigorous limit process connecting finite dimensional sparse optimal control problems with ODE constraints to an infinite dimensional sparse mean-field optimal control problem with a constraint given by a PDE of Vlasov-type, governing the dynamics of the probability distribution of the agent population. We discuss solvability of the resulting mean-field optimal control problems.

46. New trends in theory of stochastic control 2

10:00 – 11:15

*Chair:* H. Frankowska, M. Quincampoix

FH HS 7

Stochastic dynamic systems with switching and applications

George Yin (1),

(1) Department of Mathematics, Wayne State University, Detroit, USA

Many problems arising in control and optimization involve random noise influence as well as interactions of continuous and discrete events. In the past decade, much effort was devoted to studying switching diffusions where the switching depends on the continuous state and takes values in a finite set. In this talk, we present recent progress that the switching process take values in a countable set and the associate operator could be past dependent. We study recurrence, ergodicity, and stability of the system. This is a joint work with Dang Nguyen.

Invariance for quasi-dissipative systems in Banach spaces

Piermarco Cannarsa (1), Giuseppe Da Prato (2), Helene Frankowska (3),

(1) Department of Mathematics, University of Rome Tor Vergata, Rome, Italy (2) Scuola Normale Superiore di Pisa, Pisa, Italy (3) CNRS, Institut de Mathématiques de Jussieu, Paris, France

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This talk will be focussed on the study of the invariance of a closed subset  $K$  of a separable Banach space, under the action of dynamics associated with a maximal dissipative linear operator perturbed by a quasi-dissipative nonlinear term. This classical property has been widely investigated in different settings from the viewpoint of dynamical systems and control theory. In the recent work [1], necessary and sufficient conditions for invariance have been obtained in terms of some generalized derivatives of the distance function from  $K$ . Such results will be discussed in detail as well as applications to various partial differential equations, including 2-D Navier-Stokes equations with periodic boundary conditions and nonlocal terms. Finally, we will address stochastic quasi-dissipative systems in Hilbert spaces, where new difficulties arise because the lack of smoothness of the distance function poses restrictions to the use of Itô's formula.

- [1] P. Cannarsa, G. Da Prato, H. Frankowska. Invariance for quasi-dissipative systems in Banach spaces. *J. Math. Anal. Appl.*, 457:1173–1187, 2018.

### Viability of an open set for stochastic control systems

Marc Quincampoix (1), Rainer Buckdahn (1), Helene Frankowska (2),

(1) Laboratoire de Mathématiques, Université de Brest, Brest, France (2) Institut Mathématiques de Jussieu, Université Paris VI, Paris, France

The problem of compatibility of a stochastic control system and a set of constraints - the so called viability property - has been widely investigated during the last decade. The question is to characterize sets  $A$  such that for any initial condition belonging to  $A$  there exists a control ensuring that the associated process remains forever almost surely in  $A$  (this is called the viability property of the constrained set). When  $A$  is closed and the dynamics is continuous, the viability property has been characterized in the literature through several equivalent geometrical conditions involving the set  $A$ , the drift and the diffusion of the control system. In this article we give a necessary and sufficient geometrical condition on the boundary of an open set  $A$  ensuring the viability property of  $A$ . For this we only need to assume that  $A$  has a  $C^{2,1}$  boundary and that the dynamics is Lipschitz. When we assume moreover a classical convexity condition on the control dynamics we obtain that the viability property of the open set  $A$  of constraints is equivalent to the viability of the closure of  $A$ . This result is rather surprising, because several very elementary examples in the deterministic framework show that this equivalence is, in general, wrong for a general open set  $A$ . We will also discuss examples showing that the above equivalence is wrong when either the set  $A$  does not have enough regularity, or the coefficients of dynamics are not Lipschitz continuous.

### 47. Contributed session: optimal control 2

10:00 – 11:15

Chair: F. Rampazzo

FH 8 Nöbauer HS

### *hp*-finite elements for elliptic optimal control problems with control constraints

Lothar Banz (1), Michael Hintermüller (2), Andreas Schröder (1),

(1) Department of Mathematics, University of Salzburg, Salzburg, Austria (2) Institut für Mathematik, Humboldt-Universität zu Berlin, Berlin, Germany

We consider a distributed elliptic control problem with control constraints formulated as a three field problem. The latter consists of two variational equations for the state and the co-state variables as well

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as of a variational inequality over a convex set for the control variable. The adjoint control is associated with the residual of the variational inequality but does not appear in the weak formulation. Each of the three variables are discretized independently by standard  $hp$ -finite element techniques, in particular the non-penetration condition of the control variable is relaxed from the entire domain to a finite set of quadrature points.

Under the condition that the regularization parameter is sufficiently large we prove an a priori error estimate and guaranteed convergence rates in the mesh sizes and in the polynomial degrees under assumed regularity. Moreover, we derive a family of reliable a posteriori error estimators for all positive regularization parameters allowing  $hp$ -adaptivity.

Several numerical experiments demonstrate the practicability of our proposed  $hp$ -method, the efficiency of our a posteriori error estimate and the improved (optimal) order of convergence obtained by adaptivity. In particular, the  $hp$ -adaptive scheme shows superior convergence rate.

### Fractional Variational Calculus containing a derivative with a non-singular kernel

Nuno R. O. Bastos (1, 2),

(1) Department of Mathematics, School of Technology and Management of Viseu, Polytechnic Institute of Viseu, Viseu, Portugal (2) Center for Research and Development in Mathematics and Applications, University of Aveiro, Aveiro, Portugal

In this talk we present certain problems of calculus of variations with a Lagrangian depending on a fractional derivative that have a non-singular kernel. Sufficient and necessary conditions of the first and second order, as well the cases of isoperimetric problem and holonomic constraints, will be presented.

[1] N.R.O. Bastos, Calculus of variations involving Caputo-Fabrizio fractional differentiation. *Stat. Optim. Inform. Comput.* (6), 12-21, 2018.

### Singular solutions in the calculus of variations and optimal control

Gerardo Sánchez Licea (1),

(1) UNAM, Universidad Nacional Autónoma de México, Ciudad de México, México

In the classical calculus of variations the most important first order necessary condition is Euler's condition. Solutions of Euler's equation are called extremals. The most important second order necessary condition is Jacobi's condition. Unfortunately, Jacobi's condition is only applicable for nonsingular smooth extremals. However, it is worthwhile mentioning that the verification of the conditions above is a hopeless task. On the other hand, the nonnegativity of the second variation over the set of admissible variations, is also a second order necessary condition which does not require nonsingularity or smoothness assumptions. Nevertheless, this condition has the undesirable feature that, in general, its verification has the same degree of difficulty as solving the problem directly. Due to this issue, in general, the classical calculus of variations second order necessary conditions give a poor information when the extremals are nonsmooth and singular. Since the classical calculus of variations sufficient conditions are obtained by making a slight strengthening to the most important necessary conditions, implying in particular the fulfillment of smoothness and nonsingularity assumptions, the classical calculus of variations sufficiency theory gives no information for singular nonsmooth extremals. It is important to mention that these issues are inherited in the classical optimal control theory. In this talk, we present some new sufficient calculus of variations and

optimal control theorems which diminish the gap between the necessary and sufficient conditions. These theorems are illustrated by examples.

#### 48. Dynamic games in economics 1

10:00 – 11:15

*Chair:* S. Wrzaczek

FH HS 3

#### Spatial vs. non-spatial transboundary pollution control in a class of cooperative and non-cooperative dynamic games

Javier De Frutos (1), [Guíomar Martín-Herrán](#) (1),

(1) IMUVA, Universidad de Valladolid, Valladolid, Spain

We analyze a transboundary pollution differential game where, in addition to the standard time dimension, a spatial dimension is introduced to capture the different geographical relationships among regions. Each region behaves strategically and aims to maximize its welfare net of environmental damage caused by the stock of pollution. The emission-output ratio in each region can be reduced by investment in clean technology which is region specific and evolves over time. The spatio-temporal dynamics of the stock of pollution is described by a parabolic partial differential equation. Using aggregate variables for the environmental variables of the model we study the feedback Nash equilibrium of a discrete-space model which could be seen as a space discretization of the continuous-space model. The discrete-space model still presents the three main features of the original formulation: first, the model is truly dynamic; second, the decision agents behave strategically; third, the model incorporates spatial aspects. For special functional forms previously used in the literature of transboundary pollution dynamic games we analytically characterize the feedback Nash equilibrium and evaluate the impact of the introduction of the spatial dimension in the economic-environmental model. We show that our spatial model is a generalization of the model that disregards the spatial aspects in the sense that the behavior of the environmental variables at the equilibrium in the non-spatial setting can be reproduced as a limit case of the spatial setting. In particular, this link is obtained when the parameter describing how pollution diffuses among regions tends to infinity and the stocks of pollution in the regions are instantaneously mixed, which is the main hypothesis made in the non-spatial differential game.

#### Cooperation with asymmetric environmental valuation and responsibility in a dynamic setting

[Francisco Cabo](#) (1), [Mabel Tidball](#) (2),

(1) IMUVA, Universidad de Valladolid, Valladolid, Spain (2) INRA, UMR Lameta, Montpellier, France

When an environmental agreement between two countries is regarded from a dynamic perspective, it is very often observed that cooperation does not lead to an immediate reward. More to the contrary, an agreement to reduce the emissions of pollutants is usually associated with lower flows of production income. However in a profitable agreement the current costs are more than compensated by a future cleaner environment. While this is true globally (for the two countries), neither the costs from lower emissions nor the value of a cleaner environment need to be identical for the two parts. Because the uneven benefits from cooperation are delayed, it is the cost of compliance what needs to be distributed between the signing countries. This paper analyzes a sharing mechanism satisfying two main properties.



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Firstly, a benefit-pay-principle or fairness axiom: the greater the benefit one country gets from cooperation, the greater must be its share of the costs. And secondly, assuming that the responsibility from the initial environmental problem is not even across countries, a responsibility axiom requires that a country's share of the costs increases with its responsibility. Moreover, the sharing scheme must be defined to guarantee time consistency. At any intermediate instant of time, no country can do better by deviating from cooperation with the sharing mechanism presented in the paper.

#### Selection of a Markov perfect Nash equilibrium in a class of differential games

Javier De Frutos (1), Guiomar Martín-Herrán (1),

(1) IMUVA, Universidad de Valladolid, Valladolid, Spain

This paper revisits the problem of how to select an equilibrium in a differential game in the case of multiplicity of Nash equilibria. Most of the previous applied dynamic games literature has considered pre-play negotiations between players, implicitly or explicitly, with the aim of reaching an agreement on the selection of the pair of strategies. The main objective of this paper is to determine what would be the equilibrium to be played without pre-play communications. We study the linear and nonlinear Markov perfect Nash equilibria for a class of well-known models in the literature if pre-play communications are eliminated. We analyze both symmetric and nonsymmetric strategies. We show that the nonlinear strategies are not always the optimal strategies implemented when pre-play communications are removed. We conclude that in the presence of multiple equilibria and without pre-play communications the equilibria actually implemented are symmetric piecewise linear Markov perfect Nash equilibria at least for a range of initial values of the state variable.

#### 49. Infinite horizon optimal control and applications 1

10:00 – 11:15

*Chair:* N. Hayek, S. Pickenhain

FH HS 2

#### Growth without private property

Bertrand Crettez (1), Naila Hayek (1), Lisa Morhaim (1),

(1) Université Panthéon-Assas, Paris, France

This paper revisits Strulik model of growth [1] with insecure property rights. In this model different social groups both accumulate capital and devote some effort to control a part of the sum of the accumulated capital. We show that a slight variation in the model of strategic interactions results in the coexistence of savings and efforts to control a share of the available capital. We also study the effects of a change in the number of social groups on growth. We show that an increase in the number of social groups may lead to less effort to control the available capital and to a higher growth rate.

[1] Strulik, Holger 2008, Social composition, social conflict and economic development, *Economic Journal*, 118, july, 1145-1170

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## On optimality of investments at the persistent zero interest rate

Anton O. Belyakov (1, 2),

(1) Moscow School of Economics, Lomonosov Moscow State University, Moscow, Russia (2) Krasovskii Institute of Mathematics and Mechanics, Yekaterinburg, Russia

We consider “q-theory” of investment under adjustment costs and constant zero interest rate. Although the obtained condition is also valid for negative constant interest rates  $r$ , such that  $r > -\delta$ , where  $\delta > 0$  is the constant norm of capital depreciation. Necessary optimality conditions in the form of the maximum principle for control problems with infinite time horizon are applied with a new formula, developed by S.M. Aseev and A.V. Kryazhimskiy for adjoint variable, see, e.g., [1]. Transversality condition for current value adjoint variable (Tobin’s  $q$ )

$$\lim_{t \rightarrow \infty} e^{-(r+\delta)t} q(t) = 0, \quad (1)$$

derived from the new formula, completes conditions of maximum principle and extends its applicability to the case of not positive interest rate, when transversality conditions usually used in the literature do not hold, see, e.g., the transversality condition in section 7.8 in [2] and compare it with (1).

This work was supported by the Russian Science Foundation (project no. 17-11-01093).

[1] S.M. Aseev and V.M. Veliov. Needle variations in infinite-horizon optimal control. *Contemporary Mathematics*, 916:1–17, 2014.

[2] D. Acemoglu. *Introduction to Modern Economic Growth*. Princeton University Press, 2009.

## Infinite horizon and dichotomy: control constraints and the neutral component

Pavel Brunovský (1),

(1) Department of Applied Mathematics and Statistics, Comenius University, Bratislava, Slovakia

In [1], we have shown that for the unconstrained infinite horizon discrete time OC problem dichotomy of the linearized dynamics along the tested trajectory is sufficient for the Lagrange mechanism of the derivation of the variational (Pontryagin maximum principle type) necessary condition of optimality to be applicable. In the talk several enhancements of this result will be presented. In particular, control constraints of common type will be admitted. Under the mild assumption of asymptotic autonomy of the dynamics the assumption of dichotomy will be relaxed - a “controlled” neutral component will be admitted. By these enhancements the Lagrange formalism will be brought closer to realistic applications.

[1] P. Brunovský and M. Holeciová. Optimal control, dichotomy and closed range: *SIAM J. Control Opt.* in press

50. Application of optimal control to problems in biomedicine 3 10:00 – 11:15

Chair: U. Ledzewicz, M.R. de Pinho

FH HS 4

Optimization for the intensive treatment of non-invasive bladder cancer

Svetlana Bunimovich-Mendrazitsky (1),

(1) Department of Mathematics, Ariel University, Ariel, Israel

Intravesical Bacillus Calmette-Guerin (BCG) vaccine is the preferred first level treatment for non-invasive bladder cancer (BC) in order to prevent recurrence and progression of cancer.

We propose a new optimal control approach applied to improved BCG treatment model which describe the tumor-immune interactions after the injection of the BCG into the bladder. The improved model uses the cytotoxic T lymphocyte differentiation as an integral element of the delayed immune response. This model has been obtained from the first BCG model according to biological and clinical data accumulated during the last decade.

The main goal of this research is to find an optimal dosage amount required in each instillation of BCG for the immune system stimulating and tumor cells eradicating during a given treatment period. For this purpose, we introduce a control function, which represents the dose of BCG immunotherapy procedure. Afterward, we solve an optimal control problem, providing the minimum of the tumor cells.

**Enhancement of chemotherapy using oncolytic virotherapy: Mathematical and optimal control analysis**

Rachid Ouifki (1), Joseph Malinzi (1), Amina Eladdadi (2), Delfim F.M. Torres (3), Jane White (4),

(1) Department of Mathematics and Applied Mathematics, University of Pretoria, Hatfield, South Africa

(2) Department of Mathematics, The College of Saint Rose, Albany, New York, USA (3) Department of Mathematics, University of Aveiro, Aveiro, Portugal (4) Centre for Research and Development in Mathematics and Applications, University of Bath, Claverton Down, Bath, UK

Oncolytic viruses has been emerging as a promising novel immunotherapy strategy for cancer treatment, which may be further combined with the existing therapeutic modalities to enhance their effects. In this talk, we aim to determine the optimal combination of chemotherapy and oncolytic virotherapy for the elimination of tumour cells in the body tissue.

We propose an ODE based mathematical model and an optimal control problem that describe the interactions between the tumour cells, the immune response, and a treatment combination with chemotherapy and oncolytic viruses.

The stability analysis results of the model with constant chemotherapy treatment rates show that without any form of treatment, a tumour would grow to its maximum size and chemotherapy is capable of clearing tumour cells provided that the drug efficacy is greater than intrinsic tumour growth rate. Virotherapy may not be able to clear tumour cells from the body tissue but would enhance chemotherapy if viruses with high viral potency are used.

To assess the combined effect of virotherapy and chemotherapy, we use the forward sensitivity index to perform a sensitivity analysis, with respect to chemotherapy key parameters, of the virus basic reproductive number and the tumour endemic equilibrium. The results from this sensitivity analysis indicate the existence of a “critical” dose of chemotherapy above which one no longer observe any further significant reduction in the tumour population.

The optimal control problem was solved using the Pontryagin's Maximum Principle. Numerical solutions to the optimal control problem were carried out to identify the optimal concentrations for the minimization of the chemo-viro combination. Numerical results show that a successful combinational therapy of drugs and viruses is mostly dependent on virus burst size, infection rate and the amount of drugs supplied into a patient's body, which are in agreement with the stability analysis and sensitivity index of the model.

**An optimal control problem for chemotherapy based on selection-mutation PDE models for resistance**

Camille Pouchol (1,2), Jean Clairambault (2,1), Alexander Lorz (1,2,3), Antoine Olivier (1), Emmanuel Trélat (1),

(1) Sorbonne Université, Laboratoire Jacques-Louis Lions (2) INRIA, Mamba Team (3) King Abdullah University of Science and Technology, CEMSE Division

In this presentation, I will first introduce on some basic examples the typical asymptotic behaviour of some phenotype-structured equations: the density of individuals converges to some Dirac masses, which can be understood as the selection of the fittest phenotypes.

I will then enter into the detail of the initial motivation of these models, which is an optimal control problem. The goal is to minimise the number of cancer cells at the end of a given time-window thanks to chemotherapy. The model takes into account drug resistance, the level of which is the structuring phenotype in this problem. I will give the optimal strategy, as computed numerically.

I will then discuss a further complication of the model (addition of mutations) which makes the optimal control significantly harder to solve. I will present a new numerical approach which first consists in deforming the problem to a simpler one, for which significant information can be obtained by a Pontryagin Maximum Principle. Direct methods and a homotopy are then combined to solve the initial problem.

**51. New trends in theory of stochastic control 3**

**11:30 – 12:45**

*Chair:* H. Frankowska, M. Quincampoix

**FH HS 7**

**Optimal control of two scale stochastic systems in infinite dimensions using BSDE**

Giuseppina Guatteri (1),

(1) Dipartimento di Matematica, Politecnico di Milano, Milan, Italy

We study, by probabilistic techniques, the convergence of the value function for a two-scale, infinite-dimensional, stochastic controlled system as the ratio between the two evolution speeds diverges. The value function is represented as the solution of a *backward stochastic differential equation* (BSDE) that it is shown to converge towards a *reduced* BSDE.

The state equation is the following

$$\begin{cases} dX_t = AX_t^{\varepsilon,\alpha} + b(X_t^{\varepsilon,\alpha}, Q_t^{\varepsilon,\alpha}, \alpha_t)dt + RdW_t^1, & X_0^{\varepsilon,\alpha} = x_0, \\ \varepsilon dQ_t^{\varepsilon,\alpha} = (BQ_t^{\varepsilon,\alpha} + F(X_t^{\varepsilon,\alpha}, Q_t^{\varepsilon,\alpha}))dt + G\rho(\alpha_t)dt + \varepsilon^{1/2}G dW_t^2, & Q_0^{\varepsilon,\alpha} = q_0, \end{cases}$$

where the state processes  $X$  and  $Q$  are Hilbert valued,  $A$  and  $B$  are unbounded linear operators,  $\alpha$  represents the control and  $(W_t^1)_{t \geq 0}$ ,  $(W_t^2)_{t \geq 0}$  are infinite dimensional cylindrical Wiener processes. The

cost functional is of the form:

$$J^\varepsilon(x_0, q_0, \alpha) := \mathbb{E} \left( \int_0^1 l(X_t^{\varepsilon, \alpha}, Q_t^{\varepsilon, \alpha}, \alpha_t) dt + h(X_1^{\varepsilon, \alpha}) \right)$$

and we set

$$v^\varepsilon(x_0, q_0) := \inf_{\alpha} J^\varepsilon(x_0, q_0, \alpha),$$

then we prove that

$$v^\varepsilon(x_0, q_0) \rightarrow \bar{Y}_0$$

where  $(X, \bar{Y}, \bar{Z})$  is the unique solution of the following decoupled forward backward system of stochastic differential equations

$$\begin{cases} dX_t = AX_t dt + R dW_t^1, \\ -d\bar{Y}_t = \lambda(X_t, \bar{Z}_t) dt - \bar{Z} dW_t^1, \\ X_0 = x_0, \quad \bar{Y}_1 = h(X_1). \end{cases}$$

The function  $\lambda$  can itself be interpreted as the optimal cost of an ergodic optimal control problem.

### A numerical method for solving linear quadratic stochastic optimal control problems with bounded convex control constraints

Haisen Zhang (1),

(1) School of Mathematics and Statistics, Southwest University, Chongqing, China

We consider a linear quadratic stochastic optimal control problem with bounded convex control constraint. In stead of reformulating the original problem into a fully coupled nonlinear forward-backward stochastic differential equation, we shall use the variational inequality theory to establish a iterative algorithm for solving the stochastic optimal controls. The main advantage of our approach is that, in each step, we only need to solve numerically a uncoupled forward-backward linear stochastic differential equation.

### Stochastic optimal control problems with initial-final states constraints

Helene Frankowska (1), Haisen Zhang (2), Xu Zhang (3),

(1) CNRS & UPMC (Paris 6), Paris, France (2) School of Mathematics and Statistics, Southwest University, Chongqing, China (3) School of Mathematics, Sichuan University, Chengdu, China

We investigate the first and second order necessary optimality conditions for the Mayer type stochastic optimal control problem

$$\inf \mathbb{E} \phi(x(T))$$

over trajectories of the (SDE)

$$\begin{cases} dx(t) = b(t, x(t), u(t))dt + \sigma(t, x(t), u(t))dW(t), & t \in [0, T] \\ x(0) = x_0, \end{cases}$$

satisfying end points constraints  $x_0 \in K_0, \quad \mathbb{E} g^i(x(T)) \leq 0, \quad \forall i = 1, \dots, k.$

Here  $W(\cdot)$  is a standard  $d$ -dimensional Wiener process,  $u(\cdot)$  is progressively measurable with values in a given closed nonempty subset  $U \subset \mathbb{R}^m$  such that  $\mathbb{E} \int_0^T |u(t, \cdot)|^2 dt$  is finite,  $x(\cdot)$  is the corresponding solution of (SDE) and  $K_0 \subset \mathbb{R}^n$ .

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We provide a weak form of the maximum principle and a second order necessary condition in the integral form. When some convexity assumptions on  $b$ ,  $\sigma$  hold true, then we get also the true maximum principle by using only the first order adjoint equation. In the difference with the existing literatures, the second order variations of the control set are used to derive the second order necessary conditions. This leads to stronger results under less restrictive, than usual, assumptions.

## 52. Spatially distributed harvesting

11:30 – 12:45

*Chair:* S. Behringer, T. Upmann

FH 8 Nöbauer HS

### Voluntary management of fisheries under an uncertain background legislative threat

H. Stahn (1), A.-S. Chiambretto (1),

(1) AMSE, Aix-Marseille University, Marseille, France

We investigate the possibility for governance authorities to avoid a large part of regulatory costs, by simply backing up social norms with a threat of collective punishment. Specifically, we consider the case of fisheries in which the regulatory cap is to sustain an optimal conservation level. We identify a mandatory regulation such that, when it is used as a threat, it ensures that the cap is voluntarily implemented. The mandatory scheme is based on an incentive mechanism which secures the returns of the harvester, and a tax on potential capacity. From the status of mere threat, this mandatory regulation takes time to be enforced though. We show that such a tax scheme, even if it is applied randomly after the first occurrence of a deviation from the optimal conservation level, ensures voluntary compliance, provided a suitable choice of the capacity tax. We study the properties of this tax scheme and build an example using data on the scallop fishery in the Saint-Brieuc Bay (France) to illustrate our point.

### Modelling of growth and collapse of empires

Yuri Yegorov (1),

(1) Department of Business Administration, University of Vienna, Vienna, Austria

The paper models the dynamics of empires using spatio-temporal economic approach. The model focuses on the effects of economic geography in a highly stylized form. It is shown in what range of sizes empires can expand and what are the forces that can stop this expansion and lead to collapse. While this model is more applicable to historical empires, some of its elements can be useful for current state of the world.

### On optimal harvesting of a resource on a circle

Lev V. Lokutsievskiy (1),

(1) Steklov Mathematical Institute of Russian Academy of Sciences, Russia

The talk is devoted to optimality conditions in the problem of cyclic harvesting of a resource distributed on a circle with a certain prescribed density. The velocity of motion of the collecting device and the portion of the resource being harvested at a given time play the role of controls.

The problem is to choose controls maximizing a given functional of quality.

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I will present a result that solves the most concrete problems of the described type. One essential restriction is used: we assume that the device always moves only in one direction.

- [1] M. I. Zelikin, L. V. Lokutsievskiy, S. V. Skopintcev, “On Optimal Harvesting of a Resource on a Circle”, *Mat. Zametki*, 102:4 (2017), 565–578; *Math. Notes*, 102:4 (2017), 521–532.

### 53. Contributed session: economic dynamics 2

11:30 – 12:45

*Chair:* F. Privileggi

FH HS 3

#### Public debt, sustainability and economic growth

Alfred Greiner (1),

(1) Department of Business Adm. and Economics, Bielefeld University, Germany

In this paper we present an endogenous growth model with productive public spending. The government levies an income tax rate and issues government bonds to finance its spending, but, it must stick to its inter-temporal budget constraint. The latter leads to a feedback effect in the sense that a higher debt to GDP ratio implies that the primary surplus relative to GDP must rise, see e.g. [1]. We analyze the implications of three public deficit scenarios: (i) a balanced government budget, (ii) a slight deficit where public debt grows less than GDP and (iii) a scenario with permanent deficits where public debt grows at the same rate as GDP. The analysis of the model shows that the scenarios (i) and (ii) give rise to a unique saddle-point stable balanced growth path that goes along with a higher growth rate than the scenario with permanent deficits, scenario (iii). Further, using the reaction coefficient of the government to higher debt ratios as the bifurcation parameter, we can show that the dynamic system in scenario (iii) may undergo a Hopf bifurcation leading to stable limit cycles around the balanced growth path. Next, assuming that public spending as a flow affects aggregate output, scenario (iii) may generate two saddle-point stable balanced growth paths implying that an underdevelopment trap can arise, depending on the initial debt to GDP ratio. The results with regard to the balanced budget, scenario (i), and with regard to the slight deficit, scenario (ii), remain unchanged.

- [1] A. Greiner and B. Fincke. *Public Debt, Sustainability and Economic Growth. Theory and Empirics*. Springer, Heidelberg, 2015.

#### Bubbles and cycles in the Solow-Swan model

Gerhard Sorger (1),

(1) Department of Economics, University of Vienna, Vienna, Austria

We modify the Solow-Swan model by introducing a second asset (which is unproductive, cannot be consumed, and does not pay dividends) and by assuming arbitrage-free pricing. Then we study under which conditions the intrinsically useless asset can have a positive price. The analysis is conducted once under the assumption of a constant consumption-to-income ratio and once under the assumption of a constant investment-to-income ratio. We find that the relation between dynamic inefficiency (overaccumulation of capital) and the existence of bubbles (overpricing) is more subtle than one would expect on the basis of Tirole’s treatment of the overlapping generations model in [1]. Finally, we demonstrate that asset price bubbles can lead to non-monotonic and even periodic capital accumulation paths.

[1] J. Tirole. Asset bubbles and overlapping generations. *Econometrica*, 53:1071–1100, 1985.

A two-sector growth model with endogenous technical progress: when Romer meets Uzawa Harutaka Takahashi (1),

(1) Department of Economics, Meiji Gakuin University, Tokyo, Japan

We will introduce different R and D sectors into the Uzawa two-sector optimal growth model with Cobb-Douglas technologies. In other words, each sector has its intermediate good sector where a new technology is invented through learning-by-doing process. This is a sharp contrast to the model by [1], where they assume that a part of labor of the knowledge-intensive sector will be used as a kind of effort for invention of a new technology. Before considering two-sector case, let us consider one of two sectors. Solving the profit maximization problem of the sector and the market equilibrium conditions yields the integrated final good production function. We can apply the exact same argument to the remaining sector and obtain the similar integrated production function of the other sector. Using these two integrated functions, we set up the optimal growth problem similar to the Uzawa two sector growth model. We will show the existence of optimal steady states, the saddle-path stability around the optimal steady state.

[1] C. Ghiglino, K. Nishimura and A. Venditti. Non-balanced endogenous growth and structural change: when Romer meets Kaldor and Kuznets. *mimeo AMSE*, 2016.

## 54. Infinite horizon optimal control and applications 2

11:30 – 12:45

Chair: N. Hayek, S. Pickenhain

FH HS 2

Pseudospectral methods for infinite horizon optimal control problems

Angie Burtchen (1), Sabine Pickenhain (1),

(1) Mathematical Institute, Brandenburg University of Technology Cottbus-Senftenberg, Cottbus, Germany

In this talk we address numerical techniques for solving optimal control problems with infinite horizon. We study a linear-quadratic regulator (LQR) problem with infinite horizon embedded in a natural space setting, that is characterized by a weight function  $\mu_\beta(t) = e^{\beta t}$  with  $\beta > 0$ . With given matrices  $W \in \mathbb{R}^{n \times n}$ ,  $R \in \mathbb{R}^{m \times m}$ ,  $A \in \mathbb{R}^{n \times n}$  and  $B \in \mathbb{R}^{m \times n}$  the problem formulation reads as follows: Minimize

$$J(x, u) = \frac{1}{2} \int_0^\infty \{x^T(t)Wx(t) + u^T(t)Ru(t)\} \mu_\beta(t) dt$$

subject to all pairs  $(x, u) \in W_2^{1,n}(\mathbb{R}_+, \mu_\beta) \times L_2^m(\mathbb{R}_+, \mu_\beta)$  satisfying the state equations

$$\dot{x}(t) = Ax(t) + Bu(t)$$

and the initial conditions in  $x(0) = x_0$  a.e. on  $\mathbb{R}_+$ . In this setting our problem becomes a LQR in Hilbert Spaces where questions of existence and regularity of optimal solutions can be dealt with classical tools of convex analysis. Using a Pontryagin's type Maximum Principle as a necessary criteria for optimality as well as transversality conditions for the adjoints, we construct an indirect pseudospectral method using generalized Laguerre polynomials for solving the canonical equation system numerically. The convergence of the proposed method is proved and finally an example illustrates its applicability.



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### A Condition of optimality for convex functions in infinite dimension

Mohammed Bachir (1), Adrien Fabre (1),

(1) Laboratoire SAMM, Université Paris 1 Panthéon-Sorbonne, Paris, France

We give a necessary and sufficient condition such that a convex function (in infinite dimension) attains its minimum on a convex set, by replacing the classical Gâteaux-differentiability assumption by a weaker notion of derivatives in the directions of a fixed basis. Applications to discrete-time and infinite horizon problems are given.

### Infinite-dimensional infinite-horizon multiobjective optimal control in discrete time

Naila Hayek (1),

(1) CRED EA 7321, Panthéon-Assas University Paris 2, Paris, France

This paper studies multiobjective optimal control problems in the discrete time framework and in the infinite horizon case when the space of states and the space of controls are infinite-dimensional. The paper generalizes to the multiobjective case existing results for single-objective optimal control problems in that framework. The dynamics are governed by difference equations. Necessary conditions of Pareto optimality are presented namely Pontryagin maximum principles in the weak form.

[1] M. Bachir and J. Blot, Infinite Dimensional Infinite-horizon Pontryagin Principles for Discrete-time Problems, *Set-Valued Var. Anal.* 23, 2015, 43-54.

[2] N. Hayek, Infinite horizon multiobjective optimal control problems in the discrete time case, *Optimization*, 60, 2011, 509-529.

## 55. Application of optimal control to problems in biomedicine 4 11:30 – 12:45

*Chair:* U. Ledzewicz, M.R. de Pinho

FH HS 4

### Optimal control problems under the Norton-Simon hypothesis in chemotherapy

Luis A. Fernández (1), Cecilia Pola (1),

(1) Dep. de Matemáticas, Estadística y Computación, University of Cantabria, Santander, Spain

We study some problems associated with the optimization of cancer chemotherapy treatments, under the assumptions of Gompertzian-type tumor growth and the Norton-Simon hypothesis ([2], i. e. the drug killing effect is proportional to the rate of growth for the untreated tumor). Classical pharmacokinetics and different pharmacodynamics are considered, together with a toxicity limit or the penalization of the accumulated drug effect. Existence and uniqueness of the optimal control is proved in some cases, while in others the existence of an infinite number of optimal controls is shown. Explicit expressions for the solutions are derived in terms of the problem data [1]. Finally, numerical results of illustrative examples are presented together with a comparison with previous works.

[1] L. A. Fernández and C. Pola. Optimal control problems for the Gompertz model under the Norton-Simon hypothesis in chemotherapy. Submitted.

- [2] L. Norton and R. Simon. Tumor size, sensitivity to therapy, and design of treatment schedules, *Cancer Treat Rep.*, 61:1307–1317, 1977.

### On the role of pharmacometrics in optimizing drug administration

Urszula A. Ledzewicz (1,2), Maciej Leszczyński (2), Helen Moore (3), Heinz M. Schättler (4),

(1) Dept. of Mathematics and Statistics, Southern Illinois University Edwardsville, Edwardsville, USA  
(2) Institute of Mathematics, Lodz University of Technology, Lodz, Poland (3) Bristol-Myers Squibb, Princeton, USA (4) Dept. of Electrical and Systems Engr., Washington University, St. Louis, USA

We consider the optimization of drug administration schedules with the aim to minimize an objective functional that takes into account both the tumor burden and pharmacologically relevant quantities which measure side effects of the drugs. Depending on whether a pharmacokinetic model (PK) for the drug action is included in the dynamics or not, the control represents the dosage, respectively the concentration of the agent. The effects of the drugs are modelled by either a log-kill or a saturating Hill-functions (based on Michaelis-Menten type kinetics) pharmacodynamic relation (PD). Theoretical results about the structure of optimal controls are presented. For example, if PD is modelled by a Michaelis-Menten relation, then, and in agreement with an interpretation of the controls as concentrations, optimal controls are continuous functions of time that change between full or no dose segments with connecting pieces that take values in the interior of the control set. On the other hand, optimal controls may be discontinuous for a log-kill model in line with an interpretation of controls as dose rates.

As a specific example, we give results for the treatment of chronic myeloid leukemia (CML) through a combination of tyrosine kinase inhibitors and immuno-modulatory therapies. We also compare optimal solutions with best-in class solutions that only allow for a limited range of dosages and timing changes which are specified a priori. The latter is a common limitation in the practical administration of drug schedules. We show that excellent approximations of optimal protocols can be achieved even within very limited scheduling options.

### Prevention of drug resistance as a goal of chemotherapy scheduling

Piotr Bajger (1, 2), Mariusz Bodzioch (3), Urszula Foryś (2),

(1) Inter-Faculty Individual Doctoral Studies in Natural Sciences and Mathematics, University of Warsaw, Warsaw, Poland (2) Faculty of Mathematics, Informatics and Mechanics, University of Warsaw, Warsaw, Poland (3) Faculty of Mathematics and Computer Science, University of Warmia and Mazury, Olsztyn, Poland

When the optimal control theory framework is applied to the problem of chemotherapy scheduling, the usual practice is to search for protocols which minimise tumour size. One of the major obstacles in therapy planning, however, is the tumour cells developing resistance to chemotherapy over the course of treatment. The aim of this talk is to investigate how optimal control theory may be used to delay the onset of chemotherapy resistance. The usual objective functional is modified to include a term explicitly penalising the chemoresistant tumour phenotype. Based on a simple compartmental model of tumour growth it is shown how this approach leads to locally optimal singular controls. A numerical method for solving the formulated optimal control problem is proposed. The singular portion of the interval is shown to be crucial in preventing the early onset of drug resistance.

## 56. Modeling and computational methods for financial applications 3

14:00 – 15:40

*Chair:* A. Picarelli, C. Reisinger

FH HS 7

### Strategic interactions and uncertainty in decisions to curb greenhouse gas emissions I: A tragedy of the commons

Margaret C. Insley (1), Peter A. Forsyth (2), Tracy Snoddon (3),

(1) Department of Economics, University of Waterloo, Waterloo, Canada (2) Cheriton School of Computer Science, University of Waterloo, Waterloo, Canada (3) Department of Economics, Wilfrid Laurier University, Waterloo, Canada

This paper examines the optimal choice of carbon emissions for two asymmetric regions, both contributing to rising atmospheric carbon stocks which damage the economy. Optimal decisions are modeled as a differential Stackelberg pollution game with closed loop strategies. The global average temperature is modeled as a mean reverting stochastic process driven by the stock of atmospheric carbon. A numerical solution of a coupled system of HJB equations is implemented. In a numerical example, we examine the trade-offs for regions making strategic decisions about greenhouse gas emissions in the face of the uncertainty and compare the results to the case of a Social Planner. We demonstrate a classic tragedy of the commons, which is made worse if regions experience asymmetric damages or if temperature volatility increases. We also consider the effect of asymmetric preferences over emissions reduction.

### Strategic interactions and uncertainty in decisions to curb greenhouse gas emissions II: Numerics

Peter A. Forsyth (1), Margaret C. Insley (2), Tracy Snoddon (3),

(1) Cheriton School of Computer Science, University of Waterloo, Waterloo, Canada (2) Department of Economics, University of Waterloo, Waterloo, Canada (3) Department of Economics, Wilfrid Laurier University, Waterloo, Canada

This paper examines the optimal choice of carbon emissions for two asymmetric regions, both contributing to rising atmospheric carbon stocks which damage the economy. The global average temperature is modelled as a mean reverting stochastic process driven by the stock of atmospheric carbon. Emissions provide short term benefits to the economy (i.e. increased production) but increase global carbon stock, with resulting long-term damage. Each region (player) chooses their own emission level at periodic intervals. The optimal choice of emission level for each player is determined via a coupled system of HJB equations, which is solved numerically.

We discuss the numerical issues involved in computing the solution to the coupled system of HJB equations. We consider three types of possible games: Stackelberg, Nash, and leader-leader. In a Stackelberg game, there is a leader who chooses first, and a follower who chooses second. A Nash equilibrium exists if neither player can improve their strategy by changing only their own strategy. A leader-leader strategy occurs when both players assume that they are the leaders (which will be a sub-optimal policy). Perhaps a more evocative nomenclature for a leader-leader strategy is “Trumpian”, i.e. each region assumes they “can be great again” without regard to the competing region.

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We solve the HJB equations using a fully implicit finite difference technique. Even if a positive coefficient condition holds, we require a timestep condition to be satisfied in order to ensure that the finite difference solution does not generate spurious non-monotone results.

### A fully discrete scheme for systems of non linear Fokker-Planck-Kolmogorov equations and applications to Mean Field Games

Elisabetta Carlini (1), Francisco J. Silva (2),

(1) Sapienza, Università di Roma, Rome, Italy (2) Université de Limoges, Limoges, France

We consider a system of Fokker-Planck-Kolmogorov (FPK) equations, where the dependence of the coefficients is nonlinear and nonlocal. We propose a fully discrete scheme of semi-Lagrangian type for a single and for a system of FPK equations. We show a convergence result under large time steps. The main assumptions to obtain the convergence result are that the coefficients are continuous and satisfy a suitable linear growth property with respect to the space variable. We apply the scheme to solve a new Hughes-type model, for which we prove an existence result by applying the convergence analysis, and to a two populations Mean Field Games.

### Importance sampling for McKean-Vlasov SDEs

Gonçalo dos Reis (1), Greig Smith (1), Peter Tankov (2),

(1) University of Edinburgh, United Kingdom (2) CREST-ENSAE, Palaiseau, France

We deal with the Monte-Carlo methods for evaluating expectations of functionals of solutions to McKean-Vlasov Stochastic Differential Equations (MV-SDE) with drifts of super-linear growth. We assume that the MV-SDE is approximated in the standard manner by means of an interacting particle system and propose two importance sampling (IS) techniques to reduce the variance of the resulting Monte Carlo estimator. In the *complete measure change* approach, the IS measure change is applied simultaneously in the coefficients and in the expectation to be evaluated. In the *decoupling* approach we first estimate the law of the solution in a first set of simulations without measure change and then perform a second set of simulations under the importance sampling measure using the approximate solution law computed in the first step. For both approaches, we use large deviations techniques to identify an optimisation problem for the candidate measure change. It turns out that the decoupling approach is far easier to implement than the complete measure change. Moreover, the variance of the decoupling approach in our examples is up to 3 orders of magnitude smaller than that of the standard Monte Carlo, with a computational overhead which is only a factor of 2–3. We also estimate the propagation of chaos error and find that this is dominated by the statistical error by one-order of magnitude.

57. Numerical analysis for PDE constrained optimization 4 14:00 – 15:40

Chair: A. Rösch, J. Pfefferer

FH 8 Nöbauer HS

Error estimates for numerical approximation of semilinear elliptic control problems with bang-bang controls

Eduardo Casas (1), Daniel Wachsmuth (2), Gerd Wachsmuth (3),

(1) Department of Applied Mathematics and Computer Sciences, University of Cantabria, Santander, Spain  
 (2) Institute of Mathematics, University of Würzburg, Würzburg, Germany (3) Technical University of Chemnitz, Faculty of Mathematics, Chemnitz, Germany

In this talk we consider the numerical approximation of a control problem of a semilinear elliptic equation. The controls are subject to box constraints and the cost functional does not involve the control itself. In this situation the optimal controls are typically bang-bang. However, in some situations this property is not fulfilled. In both cases we analyze the convergence of numerical discretizations. In particular, we provide some error estimates for the controls in the bang-bang case and for the states in the other case. To prove these estimates we use some second order conditions obtained in [1] and [2].

- [1] E. Casas. Second order analysis for bang-bang control problems of PDEs. *SIAM J. on Control & Optimization*, 50(4):2355–2372, 2012.
- [2] E. Casas, D. Wachsmuth, G. Wachsmuth. *Sufficient second-order conditions for bang-bang control problems*. *SIAM J. on Control & Optimization*, 55(5):3066–3090, 2017.

Numerical analysis of optimal control problems related to quasi-linear parabolic pdes

Eduardo Casas (1), Konstantinos Chrysafinos (2),

(1) Departamento de Matemática Aplicada y Ciencias de la Computación, E.T.S.I. Industriales y de Telecomunicación, Universidad de Cantabria, Santander, Spain (2) Department of Mathematics, National Technical University of Athens, Athens, Greece

An optimal control problem related to quasi-linear parabolic pdes is considered. The controls are of distributed type and satisfy pointwise constraints. After presenting some results regarding the solvability of the control to state mapping, we discuss results related to the existence of optimal solutions, as well as to first and second order necessary and sufficient conditions. The fully-discrete scheme is based on the lowest order discontinuous (in time) Galerkin approach (piecewise constants in time), combined with standard conforming finite element spaces (piecewise linears in space). Error estimates are proved for the difference between the locally optimal controls and their discrete approximations. Our focus will be on the key ingredient of our proof which is a novel superconvergence estimate for the fully-discrete approximation of the control to state mapping in  $L^\infty(0, T; L^2(\Omega))$  under low regularity assumptions.

Optimal error estimates for parabolic optimal control problems with moving point controls

Dmitriy Leykekhman (1, 2), Boris Vexler (1),

(1) University of Connecticut, Storrs, USA  
 (2) Technical University of Munich, Munich, Germany

In this paper we consider a parabolic optimal control problem with a Dirac type control with moving point source in two space dimensions. We discretize the problem with piecewise constant functions in time and continuous piecewise linear finite elements in space. For this discretization we show optimal order of convergence with respect to the time and the space discretization parameters modulo some logarithmic terms. The main ingredients of our analysis are the global and local error estimates on a curve, that have an independent interest.

- [1] D.Leykekhman and B. Vexler. Optimal a priori error estimates of parabolic optimal control problems with a moving point control. *Solvability, Regularity, Optimal Control of Boundary Value Problems for PDEs*. Springer Verlag, pp.327–356, 2017.

### Numerical analysis of sparse initial data identification for parabolic problems

Boris Vexler (1), Dmitriy Leykekhman (2),

(1) Technical University of Munich, Munich, Germany (2) University of Connecticut, USA

We consider a problem of identification of initial data for a homogeneous parabolic equation from an observation of the final state. The unknown initial condition is assumed to be sparse. Based on this assumption the problem is formulated as a PDE-constrained optimal control problem on a space of regular Borel measures for the control variable. For this problem we discuss a finite element discretization and prove a priori error estimates. Our error analysis is based on sharp smoothing type pointwise finite element analysis for homogeneous parabolic equations.

### 58. Variational analysis and optimal control problems 2

14:00 – 15:40

*Chair:* P. Wolenski, H. Zidani

FH HS 3

On the regularity of solutions to a class of variational problems, including the p-Laplace equation for  $2 \leq p < 4$

Arrigo Cellina (1),

(1) Dipartimento di Matematica e Applicazioni, Università degli Studi di Milano-Bicocca, Milan, Italy

We consider the classical problem of the calculus of variations, i.e., in the problem of minimising a functional of the kind

$$I(u) = \int_{\Omega} [L(|\nabla u(x)|) + f(x)u(x)] dx$$

with prescribed boundary conditions. A problem that has been of interest to me is to investigate the properties of its solution, in particular the (possible) *higher differentiability* of a solution. We minimise an integral functional over a subset of the space of functions having (weak) first order derivatives. The solution  $\tilde{u}$  simply gives a value to the integral that is the smallest among the values computed along the competing functions.

A strange phenomenon might appear: under certain conditions, *the solution  $\tilde{u}$ , instead of having only first order derivatives, has, in addition, second order derivatives.*

This is well known, in particular, for the problem of minimising

$$\int_{\Omega} \left[ \frac{1}{2} |\nabla u(x)|^2 + f(x)u(x) \right] dx.$$

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I have been interested in understanding what happens if, under the integral sign, we have  $\frac{1}{p}|\nabla u(x)|^p$  instead of  $\frac{1}{2}|\nabla u(x)|^2$ , for  $p$  close to 2 (for instance:  $p = 2.01$ ). This will be discussed in the talk.

### Applications of optimal multiprocess problems

Maria do Rosário de Pinho (1),

(1) SYSTEC, Faculdade de Engenharia da Universidade do Porto, Portugal

We focus on a particular class of optimal multiprocess problems described by a family of continuous control systems paired with state constraints. To keep the exposition simple, we consider three different control systems acting on adjacent regions,  $\Omega_1$ ,  $\Omega_2$  and  $\Omega_3$  with  $\partial\Omega_1 = \partial\Omega_3 = \Omega_2$ . The control systems are coupled by boundary constraints with the switching between them determined by state constraints. For such family we consider the problem of driving the system from an initial position in  $\Omega_1$  to a target point in  $\Omega_3$  while minimizing a certain cost. A key feature of these problems is that the switching times between regions are not fixed; they are variables to be determined.

For problems with data Lipschitz w.r.t. the time variable, necessary conditions in the form of a maximum principle have recently been derived in [1]. Here, after discussing the importance of such optimal multiprocess problems for applications, we use an auxiliary problem, defined in [1], to design computational schemes to solve these problems numerically. As an illustration we solve numerically the problem of determining the optimal path for an Autonomous underwater vehicle (AUV) to go from a point on the surface to a rendez-vous point in situations where deep horizontal marine currents are present. Moreover, we confront optimal multiprocess problems with specific sweeping optimal control problems.

[1] MdR de Pinho and Hasnaa Zidani, A Maximum Principle for a Special Optimal Multiprocess Problem with State Constraints, 11th Asian Control Conference (ASCC), Australia December 17-20, 2017.

This work has the support of project PTDC/EEIAUT/ 2933/2014, TOCCATTA, funded by FEDER funds through COMPETE2020 - POCI and by national funds through FCT - Fundação para a Ciência e a Tecnologia.

### Pareto front characterization for multi-objective optimal control problems using HJB approach

Anna Désilles (1), Hasnaa Zidani (1),

(1) Unité de Mathématiques Appliquées (UMA), Ensta ParisTech, Palaiseau Cedex, France

In this talk we present some recent results about the characterization of the Pareto front for multi-objective optimal control problems. Our approach is based on the HJB (Hamilton-Jacobi-Bellman) framework. We define an auxiliary optimal control for an augmented dynamical system and show that the Pareto front is a subset of the zero level set of the corresponding augmented value function  $w$ . The proposed characterization allows to deduce an efficient numerical procedure for computing the entire Pareto optimal front and the corresponding optimal trajectories. Our approach allows also to consider objective functions of different kinds (minimum time cost, Bolza cost and infinite horizon cost function). Some numerical examples are considered to show the relevance of this approach.

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## Route planning problems and hybrid control

Simone Cacace (1), Adriano Festa (2), Roberto Ferretti (1),

(1) Roma Tre University, Mathematics and Physics Department, Roma, Italy (2) INSA Rouen, Rouen, France

In its simplest formulation, the so-called *route planning problem* for sailing boats consists in minimizing the expected time to reach a given target for a vessel sailing in a partly stochastic wind field. A change of direction (especially when *tacking*) might be associated to a time loss, which is in fact a crucial point in short-course races. This transition cost makes it natural to formulate the problem in term of *stochastic hybrid control* (see [1, 2]). The related numerical dynamic programming techniques have been studied in [3] for the case of deterministic systems, and extended in [2] to the the specific framework of route planning.

In this talk, we will discuss a detailed hybrid model to formulate the optimal route planning in the case of both fleet races and match races, and provide a convergent numerical approximation. We will also present numerical examples showing the good agreement between the proposed model and the heuristically known features of the optimal strategy.

- [1] A. Bensoussan and J.L. Menaldi. Hybrid control and dynamic programming. *Dynam. Contin. Discrete and Impuls. System*, 3:395–442, 1997.
- [2] A. Festa and R. Ferretti. A hybrid control approach to the route planning problem for sailing boats. submitted, 2017.
- [3] R. Ferretti and H. Zidani. Monotone numerical schemes and feedback construction for hybrid control systems. *J. Optim. Theory Appl.*, 165(2):507–531, 2015.

## 59. Infinite horizon optimal control and applications 3

14:00 – 15:40

*Chair:* N. Hayek, S. Pickenhain

FH HS 2

### Optimal control of a global model of climate change with adaptation and mitigation

Helmut Maurer (1), Manoj Atolia (2), Prakash Loungani (3), Willi Semmler (4),

(1) University of Münster, Institute of Analysis and Numerics, Münster, Germany.

(2) Department of Economics, Florida State University, Tallahassee, FL, USA. (3) Research Department, International Monetary Fund, Washington, DC, USA. (4) Department of Economics, New School of Research, New York, NY, USA.

The Paris 2015 agreement on climate change is aiming at reducing the temperature increase to below 2° C. This implies that effective mitigation policies need to be pursued that not only prevent the CO<sub>2</sub> emission from rising further but reduce the annual emission substantially. The modeling strategy we pursue attempts to answer three questions: First, what are the best strategies to keep the CO<sub>2</sub> emission bounded by a predefined upper bound. Second, what resources should be allocated to the adaptation effort when climate risk, due to a lack of emission reduction, is rising and future economic, social, and ecological damages can be expected. A third issue is of how the efforts of mitigation and adaptation are funded and how the funds should efficiently be allocated between traditional infrastructure investment, mitigation and adaptation efforts.



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We have developed a dynamic global model with 5 state and 8 control variables that allows to consider the specific policies of infrastructure investment, mitigation and adaptation. There are two sources of energy: non-renewable (brown) energy produced by an extractive resource sector and renewable (green) energy produced with private physical and green capital. The emissions from brown energy use are a source of negative externality that directly enters the (instantaneous) welfare functional. A numerical challenge arises from the fact that the optimal control model involves a nonlinear mixed control-state constraint. We discuss the necessary optimality conditions and determine stationary points of the canonical system. Discretization and nonlinear programming methods then allow us to determine optimal control policies for various initial conditions and terminal constraints.

### Optimal control of DAEs from an ODE point of view

Achim Ilchmann (1), Jonas Witschel (1), Karl Worthmann (1),

(1) Institute for Mathematics, Technische Universität Ilmenau, Ilmenau, Germany

We consider a linear quadratic Optimal Control Problem (OCP) governed by a Differential-Algebraic Equation (DAE). The key questions are the regularity of the input, the characterization of the space of consistent initial values and the optimal value of the OCP. To this end, the concept of an input index is introduced, which is used to reformulate the DAE as an augmented system of ordinary differential equations. This equivalent representation allows to characterize the optimal value and to calculate the optimal control.

### Necessary optimality conditions for global minimizers of a class of infinite horizon optimal control problems with dynamics, affine-linear with respect to the control

Torsten Ziemann (1),

(1) Mathematical Institute, Brandenburg University of Technology Cottbus – Senftenberg, Cottbus, Germany

In this talk, we address a class of infinite horizon optimal control problems involving the Lebesgue integral in the objective and a dynamics, which is non-linear in the state and affine-linear in the control. These problems arising in many economic, biological and technical models. Often, more complicated optimal control problems can be relaxed to this problem setting, as well.

The following abstract problem is studied: Minimize the objective function

$$J(x, u) = \int_0^{\infty} r(t, x(t), u(t)) dt$$

w.r.t.  $x \in \mathbb{X}, u \in \mathbb{U}$

fulfilling the differential equation

$$\dot{x}(t) = A(t, x(t)) + B(t, x(t))u(t), \quad x(0) = x_0.$$

Usually, for  $\mathbb{X}$  the space of locally absolutely continuous functions  $AC_{loc}((0, \infty))$  is chosen. The key idea in our approach is to embed  $AC_{loc}$  into an appropriate weighted Sobolev space  $W_2^1((0, \infty), \mu)$ . Thus the optimization becomes a formulation in the space  $\mathbb{X} \times \mathbb{U} = W_2^1((0, \infty), \mu) \times L_2((0, \infty), \mu)$ .

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Using a weak variation of the form

$$u(t; \lambda) = u_*(t) + \lambda(u(t) - u_*(t)), \quad u, u_* \in L_2^m((0, \infty), \mu)$$

we prove a Pontryagin-type maximum principle as a main result. We observe that the arising co-state in this principle belongs to the space  $W_2^1((0, \infty), \mu^{-1})$ . This implies a natural transversality condition, which brings advantages for numerical calculations, especially indirect pseudospectral methods.

#### On existence and boundedness of optimal controls in infinite-horizon problems

Sergey M. Aseev (1, 2),

(1) Steklov Mathematical Institute, Moscow, Russia (2) International Institute for Applied Systems Analysis, Laxenburg, Austria

A class of infinite-horizon optimal control problems with unbounded set of control constraints is considered. A result on existence of optimal solutions is established and the uniform local boundedness of the optimal controls is shown (see [1]). A non-concave model of optimal economic growth with a renewable resource (see [2]) is considered as an illustrative example.

- [1] S.M. Aseev. Existence of an optimal control in infinite-horizon problems with unbounded set of control constraints. *Proc. Steklov Inst. Math.*, 297 (suppl. 1): 1–10, 2017.
- [2] S.M. Aseev, T. Manzoor. *Optimal growth, renewable resources and sustainability*. Laxenburg, Austria, WP-16-017, 2016.

## 60. Application of optimal control to problems in biomedicine 5 14:00 – 15:40

*Chair:* U. Ledzewicz, M.R. de Pinho

FH HS 4

### Optimal control of allergy

Ellina V. Grigorieva (1), Evgenii N. Khailov (2),

(1) Department of Mathematics and Computer Sciences, Texas Woman's University, Denton, USA  
(2) Faculty of Computational Mathematics and Cybernetics, Lomonosov Moscow State University, Moscow, Russia

One defining characteristic of the modern world is the increasing of immune disorders and an absence of cure or their resistance to existing treatment. An acute allergic reaction is immune disorder that changes the code in action of T-helper cells. It was found that people showing allergy symptoms have bigger ratio of Th2/Th1-cells than those without symptoms. The main objective of this study is to create realistic control models of different types of allergy, and find possible way to prevent its symptoms by optimal treatment. Our control models consist of a set of nonlinear differential equations describing the dynamic behavior of four variables: the concentrations of Th1-, Th2-cells, the concentration of naive T-helper-cells, and the concentration of allergen presented by antigen-presenting cells. These models include two bounded control functions reflecting two possible types of treatment. The first type of treatment is related to the intake of antihistamine that suppresses the dominance of Th2-cells. Depending of the type of the drug intake, one of the following would happen: blocking histamine receptors, increasing the ability of

serum to bind histamine, and inhibiting the release of histamine from mast cells. The second type of treatment is the allergen specific immunotherapy that consists of injections of a small amount of allergen. Minimization of the ratio of Th2/Th1-cells and the cost of the treatment over a given time interval is our objective function. We will first proceed analytically, determine properties of the minimization problem and its solutions, subsequently turn to numerical programs and simulate the behavior of various parametric versions of the models.

### Analysis of optimal control problems for SIR models with vaccination

Filipa N. Nogueira (1), Maria do Rosário de Pinho (1),

(1) SYSTEC, DEEC, Faculdade de Engenharia da Universidade do Porto, Porto, Portugal

We study the control of the spread of an infectious diseases via vaccination using a SIR model with time varying population. The aim is to drive the number of infected individuals to a residual quantity, called the target, and to propose residual feedback controls to avoid future outbursts of the disease.

It is well known that for highly contagious diseases the choice of the target is crucial since the disease may reappear sometime after stopping the vaccination policy. To prevent future outbursts of the disease, it is important to choose a target point for which there exists feedback control strategies to keep the system in a neighborhood of it. Here we analyze the dynamical system in order to choose such point. Since any model is a rough approximation of the real system, we consider several different targets and we determine feedback controls for all of them. In order to keep the analysis as simple as possible we use a normalized version of the SIR model similar to that developed in [1]. The main advantage is the reduction of the dimension of the system to two differential equations.

To drive the system to target points we study a free time problem minimizing the societal costs and we compare such results with those obtained for the minimal time optimal control problem using computational simulations.

This work has the support of project PTDC/EEIAUT/ 2933/2014, TOCCATTA, funded by FEDER funds through COMPETE2020 - POCI and by national funds through FCT - Fundação para a Ciência e a Tecnologia.

[1] MdR de Pinho, Filipa N. Nogueira, *On application of optimal control to SEIR normalized models: Pros and cons*, Mathematical Biosciences and Engineering 14(1):111-126 Å October 2016 DOI: 10.3934/mbe.2017008.

### Analysis of control for a free boundary problem of steady plaques in the artery

Andrzej Nowakowski (1,2), Alicja Miniak-Gorecka (1),

(1) Lodz University, Lodz, Poland (2) Faculty of Math & Computer Sciences, Lodz University, Lodz, Poland

In the earlier paper of A. Friedman et al. a simplified model of plaque growth involving LDL and HDL cholesterol, macrophages and foam cells is considered and they satisfy a coupled system of PDEs with a free boundary. The paper adds some control function to that model, allowing the controlled growth of LDL, HDL and plaque. Next, the new dual dynamic programming approach for free boundary problem is developed to formulate sufficient optimality conditions for the optimal steering of drugs. Finally an approximate optimality and numerical calculations are presented.

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### Modelling of cortical waves with integro-differential equations

A. Beuter (1,2), A. Balossier (3), S. Trofimchuk (4), V. Volpert (5),

(1) Bordeaux INP, Bordeaux, France (2) Equipage Innovation SARL, Plérin, France (3) AP-HM La Timone Aix-Marseille, University Marseille, Provence-Alpes-Côte d'Azur, France (4) Instituto de Matematica y Fisica, Universidad de Talca, Talca, Chile (5) Institut Camille Jordan, University Lyon, Villeurbanne, France

We study the propagation of waves of electric potential in the cortical tissue with integro-differential equations arising in neural field models. Existence, stability and the speed of propagation of such waves will be discussed.

Various regimes of wave propagation will be illustrated with numerical simulations.

### 61. Modeling and computational methods for financial applications 4

16:00 – 17:40

*Chair:* A. Picarelli, C. Reisinger

FH HS 7

#### Variational setting for some financial option problems

J. Frédéric Bonnans (1), Axel Kröner (1,2),

(1) CMAP, Ecole Polytechnique, CNRS, Université Paris Saclay, and Inria, France (2) Department of Mathematics, Humboldt University of Berlin, Berlin, Germany

The talk, based on [2], performs a variational analysis for a class of European or American options with stochastic volatility models, including those of Heston and Achdou-Tchou. Taking into account partial correlations and the presence of multiple factors, we obtain the well-posedness of the related partial differential equations, in some weighted Sobolev spaces. This involves a generalization of the commutator analysis due to [2].

[1] Y. Achdou and N. Tchou. Variational analysis for the Black and Scholes equation with stochastic volatility. *M2AN Math. Model. Numer. Anal.*, 36(3): 373–395, 2002.

[2] J.F. Bonnans and A. Kröner. Variational analysis for options with stochastic volatility and multiple factors. *SIAM Journal on Financial Mathematics*, to appear.

#### Numerical approximation of quantile hedging problem

J.-F. Chassagneux (1),

(1) LPSM, Université Paris Diderot, Paris, France

In this talk, I consider the problem of hedging European and Bermudan option with a given probability. This question is more generally linked to portfolio optimisation problems under weak stochastic target constraints. I will recall, in a Markovian framework, the characterisation of the solution by non-linear PDEs. I will then discuss a numerical algorithm to compute in practice the quantile hedging price.

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This presentation is based on joint works with B. Bouchard (Université Paris Dauphine), G. Bouveret (University of Oxford) and ongoing work with C. Benezet (Université Paris Diderot) and C. Reisinger (University of Oxford).

### $\mathcal{E}^g$ -pricing of American options in financial markets with default

Agnès Sulem (1, 2), Roxana Dumitrescu (3), Myriana Grigorova (4), M.-Claire Quenez (5),

(1) INRIA Paris, Paris, France (2) Université Paris-Est, Paris, France (3) Department of Mathematics, King's College London, Strand, London, United Kingdom (4) Center for Mathematical Economics, University Bielefeld, Bielefeld, Germany (5) Université Paris 7 Denis Diderot, Paris, France

We study American options in financial markets with default and imperfections taken into account via nonlinear wealth dynamics. The payoff is given by an RCLL adapted process  $(\xi_t)$ . We first consider the case of a complete market. We define the price of an American option as the minimum initial wealth which allows the seller to be superhedged. We prove that it coincides with the value function of an optimal stopping problem with nonlinear expectation  $\mathcal{E}^g$  (induced by a Backward SDE), which corresponds to the solution of a nonlinear reflected BSDE with obstacle  $(\xi_t)$ . Moreover, we show the existence of a superhedging portfolio strategy, defined in terms of the solution of this reflected BSDE. We then address the case of an incomplete market. We characterize the seller's price as the value of a mixed stochastic control/optimal stopping problem with nonlinear expectation, and prove that it admits a representation as the minimal solution of a constrained reflected BSDE with lower obstacle.

- [1] R. Dumitrescu, M.C. Quenez, A. Sulem. American options in an imperfect complete market with default. *ESAIM: Proceedings and Surveys*, to appear, 2018.
- [2] M. Grigorova, M.C. Quenez, A. Sulem.  $\mathcal{E}^g$ -pricing of American options in incomplete markets with default, *Preprint 2018*.

## 62. Model order reduction in control and optimization 2

16:00 – 17:40

*Chair:* M. Falcone, V. Simoncini

FH 8 Nöbauer HS

### LQG and $H_\infty$ balanced truncation for active flow control

Peter Benner (1, 2), Jan Heiland (1), Steffen W.R. Werner (1, 2),

(1) Max Planck Institute for Dynamics of Complex Technical Systems, Magdeburg, Germany (2) Otto-von-Guericke University Magdeburg, Magdeburg, Germany

Recent theoretical and simulation results have shown that Riccati-based feedback can stabilize flows at moderate Reynolds numbers [1]. Nevertheless, the resulting regulators may be of too high order to be implemented as digital controllers. Therefore, we discuss suitable model reduction (MOR) techniques enabling to compute low-order controllers. Two balancing-related MOR methods directly aiming at observer-based designs are suitable for this task: *LQG balanced truncation* and  *$H_\infty$  balanced truncation*. We introduce output feedback controllers using these techniques. Also, we provide very low dimensional observers so that the control actuation can be computed in an online fashion. This work extends the work presented in [2] by robustifying the LQG-based controller considered there and by, for the first time, discussing a controller based on the  *$H_\infty$  balanced truncation* reduced-order model for incompressible Navier-Stokes equations.

- [1] E. Bänsch, P. Benner, J. Saak, and H.K. Weichelt. Riccati-based boundary feedback stabilization of incompressible Navier-Stokes flow. *SIAM Journal on Scientific Computing*, 37(2):A832–A858, 2015.
- [2] P. Benner and J. Heiland. LQG-balanced truncation low-order controller for stabilization of laminar flows. In R. King (ed.), *Active Flow and Combustion Control 2014*. Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 127, pp. 365–379. Springer, Heidelberg, 2014.

## Optimization within and by the Reduced Basis Method

Karsten Urban (1),

(1) Ulm University, Germany

The Reduced Basis Method (RBM) is nowadays a well-established model reduction technique for parameterized partial differential equations (PPDEs) within realtime and/or multi-query context. Such a multi-query context is relevant for iterative optimization schemes. For PDE-constrained optimization problems with elliptic or parabolic problems, the floor is well settled, The situation is more involved for problems involving e.g. Hamilton-Jacobi-Bellman (HJB) equations.

On the other hand, the RBM itself is subject to optimization, e.g. when considering a best possible reduced model (in which sense ever).

We will discuss recent results for both aspects, namely optimization by and within the RBM.

## Low-rank techniques for PDE-constrained optimization problems and statistical inverse problems

Martin Stoll (1), Peter Benner (2), Tobias Breiten (3), Yue Qiu (2),

(1) Scientific Computing, Department of Mathematics, TU Chemnitz, Chemnitz, Germany (2) Computational Methods in Systems and Control Theory, MPI Magdeburg, Magdeburg, Germany (3) Institute for Mathematics and Scientific Computing, University of Graz, Graz, Austria

The solution of PDE-constrained optimization problems is a challenging task as it requires the numerical solution of the first order optimality system. These conditions are characterized by a coupled system of partial differential equations running forward and backward in time. An all-at-once discretization of the coupled system in both space and time can be tackled if the dimensionality of the discretized system can be handled efficiently. For this we propose the use of a low-rank in time technique that allows a dramatic reduction of the storage requirements but also the need for PDE solves. The approach is based on the implementation of a low-rank Krylov method coupled with robust preconditioning techniques.

Such a low-rank Krylov method is in fact quite general and we show that it can be applied in statistical inverse problems both for the maximum a posteriori point and also in the computation of the posterior covariance matrix.

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### Basis generation for feedback control problems

A. Alla (1), B. Haasdonk (2), A. Schmidt (2), V. Simoncini (3),

(1) PUC-Rio, Rio de Janeiro, Brazil (2) University of Stuttgart, Stuttgart, Germany (3) University of Bologna, Bologna, Italy

We consider numerical approximation of feedback control for linear and nonlinear PDEs. Since control problems are computationally very expensive, we use model order reduction techniques to reduce its complexity. The general idea is to find some *basis functions*, which allow to project our dynamical system into a low-dimensional system. It is crucial that the basis functions have information about the underlying control problem. In this talk, we will focus on recent advances in the computation of the basis functions. We explore order reduction techniques for solving the algebraic Riccati equation (ARE), and investigating the numerical solution of the linear-quadratic regulator problem (LQR). We note that a classical approach is to build a surrogate low dimensional model of the dynamical system, for instance by means of e.g. POD, and then solve the corresponding ARE. Alternatively, iterative methods can be used to directly solve the ARE and use its approximate solution to estimate quantities associated with the LQR. We propose a class of Petrov-Galerkin (see [3]) strategies that simultaneously reduce the dynamical system while approximately solving the ARE by projection. This basis functions will directly benefit information upon the value function which is fundamental to compute feedback control. We will also use this technique to compute feedback control for nonlinear problems (see [1,2]).

Finally, we present numerical tests to illustrate our approach and show the effectiveness of the proposed methods in comparison to existing approaches.

- [1] A. Alla, B. Haasdonk, A. Schmidt. Feedback control of parametrized PDEs via model order reduction and dynamic programming principle, submitted, 2017.
- [2] A. Alla, A. Schmidt, B. Haasdonk. Model order reduction approaches for infinite horizon optimal control problems via the HJB equation. In: Benner P., Ohlberger, M., Patera A., Rozza G., Urban K. (eds) *Model Reduction of Parametrized Systems. MS&A (Modeling, Simulation and Applications)*, vol 17. Springer, Cham, 2017, 333-347.
- [3] A. Alla, V. Simoncini. *Order reduction approaches for the algebraic Riccati equation and the LQR problem*, submitted, 2017.

### 63. Variational analysis and optimal control problems 3

16:00 – 17:40

*Chair:* P. Wolenski, H. Zidani

FH HS 3

#### Set of sustainable thresholds

Pedro Gajardo (1),

(1) Departamento de Matemática, Universidad Técnica Federico Santa María, Valparaíso, Chile

What is the ability of a natural resource to satisfy some constraints (objectives), usually in conflict, from now over time? (e.g., to sustain a minimal level of biomass and to get a minimum profit due to harvesting). What is the minimal percentage of infected people that a city can sustain as upper bound for a given healthcare budget? The viability theory has addressed this type of problems for more than

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30 years. In general, given a controlled dynamical system under state and control constraints, the idea is to find the initial conditions (e.g., current state of a natural resource or current percentage of infected people), for which it can be assured there exists a future viable trajectory, that is, a way to manage the associated dynamical system over time in order to satisfy the desired constraints. The set of these (initial) states is called the viability kernel, a key concept in the mentioned theory.

During last years we have analyzed a different problem but strongly related: given an initial condition, what are the constraints (parametrized by thresholds) that can be satisfied from now on? We call the set of these constraints the *set of sustainable thresholds*, which actually is the inverse mapping of the viability kernel.

In this talk I will present some interpretations of the set of sustainable thresholds, advantages with respect the viability kernel, methods for computing this set, and applications related to fishery management and epidemiology.

**Theory and numerical practice for optimization problems involving  $\ell^p$ -functionals, with  $p \in [0, 1)$**

Daria Ghilli (1), Karl Kunisch (1,2),

(1) Institute of Mathematics and Scientific Computing, Karl-Franzens University, Graz, Austria (2) RICAM Johan Radon Institute for Computational and Applied Mathematics, Linz, Austria

Nonsmooth nonconvex optimization problems involving the  $\ell^p$  quasi-norm,  $p \in [0, 1)$ , of a linear map are considered. A monotonically convergent scheme for a regularized version of the original problem is developed and necessary optimality conditions for the original problem in the form of a complementary system amenable for computation are given. Then an algorithm for solving the above mentioned necessary optimality conditions is proposed. It is based on a combination of the monotone scheme and a primal-dual active set strategy. The performance of the two schemes is studied and compared to other existing algorithms by means of a series of numerical tests in different cases, including optimal control problems, fracture mechanics and microscopy image reconstruction.

**Generalized characteristic method for fully convex impulsive systems**

Cristopher Hermosilla (1), Peter Wolenski (2),

(1) Departamento de Matemática, Universidad Técnica Federico Santa María, Valparaíso, Chile (2) Department of Mathematics, Louisiana State University, Baton Rouge, USA

The aim of this talk is to present some new results on the value function of a Fully Convex optimal control problem with state constraints. Problems of this kind have been widely investigated by Rockafellar and collaborators if the Lagrangian is coercive and no state constraints are considered. A lack of coercivity implies the dual has nontrivial state constraints, and vice versa (that is, they are dual concepts in convex analysis). The novelty of this work is that no coercive assumptions are made, which leads to optimal control problems whose trajectories are of bounded variation rather than merely absolutely continuous. Our approach is based on classical convex analysis, and we establish a Legendre-Fenchel type equality between the value function of the optimal control problem and its dual. The main result we present in this talk is a characteristic method that allows us to describe the evolution of the subgradients of the value function.



Thursday, July 5<sup>th</sup>

## Program-predicting control of systems with evolving dynamics

Yuri S. Ledyae (1),

(1) Department of Mathematics, Western Michigan University, Kalamazoo, USA

This talk is dedicated to new problems of optimal control systems under uncertainty. We start with problems of optimal control of systems in which uncertainty is modelled in terms of some scenarios of evolution of system's dynamics. The main difficulty in study of such problems lies in the fact that bifurcating structure of possible scenarios requires an application of non-anticipating (causal) control procedures or feedback control.

We describe optimization theory of characterization of such optimal non-anticipating strategies. Assuming that the set of possible evolution scenarios is finite and is known along with probabilities of realization of such scenarios, we derive necessary conditions for optimal non-anticipating strategies in terms of some non-standard maximum principle. The main feature of this maximum principle is new extended adjoint system which is significantly different from the one in classical Pontryagin maximum principle.

We demonstrate that these new optimality conditions can be used for a construction of optimal discontinuous feedback control. Robustness properties of this feedback with respect to small measurement errors of state vector and small perturbations of the dynamics are also studied.

We show that this approach can be used for study of a variety of more difficult control problems under uncertainty including some problems in differential games theory.

## 64. Model based control: analysis and modelling 5

16:00 – 17:40

*Chair:* K. Worthmann, K. Chudej

FH HS 2

### Optimal control of an optical system for material testing

Walter Alt (1), Christopher Schneider (1), Martin Seydenschwanz (2),

(1) Faculty of Mathematics and Computer Science, Friedrich Schiller University Jena, Jena, Germany

(2) Research in Digitalization and Automation, Siemens AG, Munich, Germany

In this talk, we consider the process of automatic optical material testing in the manufacturing of glass panels. To model this problem, we use an optimal control approach with a discontinuous cost functional and box constraints for both, the control and the state variables. We implement a prototype for this application which aims for computing the optimal control at run time. The algorithm will be demonstrated and tested with the help of an illustrative example where it turns out that the optimal control is of bang-bang or bang-zero-bang type, depending on the state constraints.

### Optimal control of switched DAEs

Stephan Trenn (1),

(1) SCAA @ JBI, FSE, University of Groningen, Netherlands

Switched systems are used to model continuous dynamics subject to sudden structural changes. These changes are formalized by introducing a discrete-valued switching signal. The switching signal can be

seen as externally given, which altogether results in a time-varying system with a piecewise-constant time-dependence. The switching signal can also be viewed as being state-dependent (i.e. internally given), which then results in a discontinuous nonlinear system. Finally, the switching signal can be treated as an input signal and is therefore a design variable. This talk will give an overview of already existing methods to solve optimal control problems for switched systems, taking into account the different roles of the switching signal. Furthermore, the challenges are highlighted when considering switched systems with algebraic constraints, i.e. when switched differential-algebraic equation (DAEs) should be controlled in an optimal way.

### Backward-forward reach set splitting for differential games

Mario E. Villanueva (1), Xuhui Feng (1), Boris Houska (1),

(1) School of Information Science and Technology, ShanghaiTech University, Shanghai, China

In 1960, Rufus Isaacs initiated the investigation of differential game theory. Since then, differential games—which model decision making problems for systems described by differential equations—have found a plethora of application areas, ranging from operations research and economics to control.

This talk focuses on the class of two-player zero-sum non-cooperative Stackelberg differential games, under open- and closed-loop control policies. We present a novel formulation of the game in the form of an optimal control problem with set-valued states under the assumption that both players have to satisfy state and control constraints, or, else, lose the game. We discuss differences and similarities to standard robust optimal control problems. Moreover, we outline a numerical solution strategies for analyzing and solving the considered class of differential games designing algorithms that are based on a backward-forward reachable set propagation strategy.

### Stabilization of a population balance model governed by integro-differential equations

Alexander Zuyev (1), Peter Benner (1),

(1) Max Planck Institute for Dynamics of Complex Technical Systems, Magdeburg, Germany

In this talk, we consider a control system governed by the population balance equation

$$\frac{\partial w(x, t)}{\partial t} + G(c) \frac{\partial w(x, t)}{\partial x} = F(x)w(x, t), \quad x \in [0, L], \quad (1)$$

subject to the boundary condition  $w(0, t) = B(c)/G(c)$ , where  $c = c(t)$  satisfies the following integro-differential equation:

$$\frac{dc}{dt} = (c_0 - c) \left( v + \frac{d}{dt} \ln \varepsilon \right) - \frac{\rho v}{\varepsilon} \left( 1 + k \int_0^L \psi(x)w(x, t)dx \right) + u. \quad (2)$$

Here  $B(c)$ ,  $G(c)$ ,  $F(x)$  are given functions,  $\varepsilon = 1 - k \int_0^L x^3 w(x, t)dx$ , and  $c_0$ ,  $k$ ,  $v$ ,  $\rho$  are positive constants. Control system (1), (2) is a mathematical model of a continuous crystallizer [1], whose state  $(w(\cdot, t), c(t))$  describes the crystal size distribution and the solute concentration at time  $t$ , respectively, and the control  $u$  corresponds to manipulating the solute concentration in the feed. We assume that there is an equilibrium  $(\bar{w}, \bar{c})$  of the system (1), (2) with some constant control  $u = \bar{u}$ .

It will be shown that the above equilibrium can be stabilized by a state feedback law under additional assumptions on the system parameters. Our stability proof extends the construction of a Lyapunov functional, proposed in [2], for the case of coupled partial and integro-differential equations.

Thursday, July 5<sup>th</sup>

- [1] U. Vollmer and J. Raisch.  $H_\infty$ -Control of a continuous crystallizer. *Control Engineering Practice*, 9: 837–845, 2001.
- [2] A. Zuyev, A. Kienle, and P. Benner. Construction of a Lyapunov functional for a class of controlled population balance models. *PAMM*, 17(1): 827–828, 2017.

## 65. Dynamics of health and health care

16:00 – 17:40

*Chair:* M. Kuhn

FH HS 4

### Quality competition in healthcare services with regional regulators: a differential game approach

Michele Bisceglia (1), Roberto Cellini (2), Luca Grilli (3),

(1) Dipartimento di Scienze Aziendali, Economiche e Metodi Quantitativi, Università di Bergamo, Bergamo, Italy (2) Dipartimento di Economia e Impresa, Università di Catania, Catania, Italy (3) Dipartimento di Economia, Università di Foggia, Foggia, Italy

This article proposes a differential game model, in order to analyze markets in which regional regulation is operative and competition is based on quality. The case we have in mind is healthcare public service, where consumers (patients) choose the provider mainly basing on the providers location and the quality of services, while prices play a more limited role. In most European countries, within the same State, regional (or local) providers compete on quality to attract demand. Market regulation is set at national and/or regional level. Our model highlights the features of equilibrium in such a framework and specifically investigates how the differences in product quality evolve among regions and how inter-regional demand flows behave. Differently from some available similar models, that do not take into account the regional dimension of the decision process, we find that quality differentials among regions may persist in equilibrium.

### A theory of education, health and longevity

Titus J. Galama (1,2), Hans van Kippersluis (2),

(1) University of Southern California, Dornsife College Center for Economic and Social Research, Los Angeles, USA (2) Erasmus School of Economics, Erasmus University Rotterdam, Rotterdam, The Netherlands

This paper presents a unified theory of human capital with both health capital and, what we term, skill capital endogenously determined within the model. By considering joint investment in health capital and in skill capital, the model highlights similarities and differences in these two important components of human capital. Health is distinct from skill: health is important to longevity, provides direct utility, provides time that can be devoted to work or other uses, is valued later in life, and eventually declines, no matter how much one invests in it (a dismal fact of life). The theory provides a conceptual framework for empirical and theoretical studies aimed at understanding the complex relationship between education, health and longevity, and generates new testable predictions on (i) the effect of health on skill formation, and (ii) the powerful effect of longevity gains on health and economic inequality.

Thursday, July 5<sup>th</sup>

### The impact of medical innovations on longevity inequality

Michael Kuhn (1, 2), Ivan Frankovic (1, 2),

(1) Vienna Institute of Demography, Vienna, Austria (2) Wittgenstein Centre, Vienna, Austria

We study medical progress and skill-biased productivity growth as drivers of longevity inequality from a theoretical life-cycle as well as from a macroeconomic perspective. To do so, we develop an overlapping generation model populated by heterogeneous agents subject to endogenous mortality. We model two groups of individuals for whom differences in skills translate into differences in income and in the ability to use medical technology effectively in curbing mortality. We derive the age-specific individual demand for health care based on the value of life, the level of medical technology and the market prices. Calibrating the model to the development of the US economy and the longevity gap between the skilled and unskilled, we study the impact of rising effectiveness of medical care in improving individual health and examine how disparities in health care demand and mortality emerge as a consequence. Furthermore, we explore the role of differential income growth. We pay particular attention to the macroeconomic feedback from price changes, especially to medical price inflation.

### Medical and nursery care for the oldest old

Johannes Schünemann (1), Holger Strulik (1), Timo Trimborn (2),

(1) University of Göttingen, Göttingen, Germany (2) Vienna University of Technology, Vienna, Austria

For the oldest old, nursing home expenditures constitute on average the largest share in health investments. In this paper, we distinguish between medical care, intended to improve one's state of health, and personal care required for daily routine. In our model, personal care can be either carried out autonomously or by a third party. In the course of aging, autonomous personal care is eventually substituted by nursery care. We set up a life-cycle model in which individuals are subject to physiological aging, calibrate it with data from gerontology, and analyze the interplay between medical and nursery care. Interestingly, nursing homes are not covered by Medicare, implying that most of the expenditures have to be paid out of pocket. In this light, we also contribute to the discussion on public health insurance in the U.S.

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66. Plenary

08:40 – 09:30

*Chair:* G. Feichtinger

FH HS 1

**Integrating finance into the macroeconomic modelling of climate change – a multi-phase policy problem**

Willi Semmler (1),

(1) New School for Social Research, New York, USA

The talk will first cover some work on the empirics of the economics-climate interaction with respect to the cause of the atmospheric CO<sub>2</sub> concentration, temperature rise, tipping points and damages through extreme weather events. Although models have been designed to appropriately deal with mitigation and adaptation policies, yet those policies need financing. Carbon tax and bond issuing, as financing sources of climate policies, have recently been suggested. We will study the financing issue first in the context of the Nordhaus' IAM model, following up a proposal Jeff Sachs (2015) and others in a finite horizon optimization framework with fixed switching times. Scaling up the issuing of long-maturity green bonds, that is paid back later, are believed to be able to distribute the burdens over generations more evenly. In a joint work with Orlov et al. (2016), we examine whether green bonds can indeed resolve the intergenerational inequity challenge in a model of a multi-phase control problem with optimal switching times. To do so, we employ the IAM model and supplement it with green bonds and green taxes through which future generations repay the bonds. We show that bonds can reduce the intergenerational inequities leading to a Pareto improvement as Sachs indicates. The full integration of finance (taxes and bonds) is then studied in a large-scale model, see Maurer et al. (2017), where a standard IAM methodology is extended to find the optimal allocation of infrastructure expenditure to carbon-neutral physical capital, climate change adaptation, and emissions mitigation. We demonstrate that the endogenously selected infrastructure, mitigation, and adaptation out-perform fixed allocations by increasing consumption, private capital and tax revenue while reducing public debt and CO<sub>2</sub> emissions. Further, the homotopic analysis is conducted on unobservable parameters. The model also displays two regime switches and entails that the integration of bond issuing gives superior welfare results when first large-scale bond financing for climate policies is pursued and subsequently the debt is reduced through a tax levy on future generations. This multi-phase model is solved through AMPL with fixed switching times but smoothing out the control variables when a regime change occurs. Finally, building on Chiarella et al. (2016) a more generic approach is indicated that links a dynamic asset pricing and portfolio theory to the real side of the economy when the return on assets and the portfolio performance are affected by the efforts and effects of climate change on the real side.

**67. Contributed session: optimal control 3****10:00 – 11:15***Chair: F. Pereira***FH HS 7****An optimal control problem with a sparsity constraint**Giulia Cavagnari (1), Antonio Marigonda (2), Benedetto Piccoli (3),

(1) Department of Mathematics “F. Casorati”, University of Pavia, Pavia, Italy (2) Department of Computer Science, University of Verona, Verona, Italy (3) Department of Mathematical Sciences, Rutgers University-Camden, Camden, U.S.A.

The interest in the study of optimal control problems in measure spaces is motivated by its numerous applications from biology to economics and social sciences. Measures can indeed represent the statistical distribution of a mass with a huge number of particles.

We present the study of an optimal control problem in Wasserstein spaces, where the dynamics is given by a (controlled) continuity equation. The interaction considered is encoded in the cost functional, dealing with a *control sparsity constraint*, i.e. we impose an upper-bound to the magnitude of control that we are allowed to use to drive the mass.

We prove a Dynamic Programming Principle and existence of optimal trajectories for a generic value function. Finally, we provide an HJB equation solved in a suitable viscosity sense by the value function, building a definition of sub/super-differential in the spirit of [1]. An important tool used, coming from Transport Theory, is the Superposition Principle [1]. We provide its extension to the Differential Inclusion setting.

[1] L. Ambrosio, N. Gigli, G. Savaré. *Gradient flows in metric spaces and in the space of probability measures*. Lectures in Mathematics ETH Zürich, 2nd ed., Birkhäuser Verlag, Basel, 2008.

**Computing reachable sets of nonlinear systems with isoperimetric constraints**Mikhail I. Gusev (1),

(1) N.N.Krasovskii Institute of Mathematics and Mechanics, Ekaterinburg, Russia

We study a reachability problem for a continuous-time affine-control system under isoperimetric constraints. The constraints are defined by a finite system of integral inequalities with quadratic in control variables integrands. The initial state of the system is not fixed, but belongs to a given set of initial states. Under controllability assumptions it is proved that any admissible control that steers the control system to the boundary of its reachable set is a local solution to some auxiliary optimal control problem with vector-valued cost functional and terminal constraints on a trajectory. The last leads to necessary optimality conditions in the form of Pontryagin’s maximum principle for boundary trajectories. We propose a numerical algorithm for computing the reachable set boundary based on the maximum principle and provide some numerical examples.

The research is supported by Russian Science Foundation, project 16-11-10146.

Friday, July 6<sup>th</sup>

### The expected hitting time approach to optimal adjustment problems

Hamed Ghoddusi (1), Chihoon Lee (1), Yiyang Cheng (2), Yaozhong Hu (3),

(1) School of Business, Stevens Institute of Technology, Hoboken, USA (2) Department of Mathematics, University of Kansas, USA (3) Department of Mathematical and Statistical Sciences, University of Alberta, USA

We offer an alternative approach for solving optimal adjustment problems with fixed costs (i.e. impulse control problems), when the underlying process is a Geometric Brownian Motion (GBM) process. Our approach relies on characterizing the cumulative cost of deviation from the optimal target until the first hitting time of the lower or upper barriers as well as the expected cost of adjusting the process at barriers. Using this approach, we are able to derive an analytical expression for the cost function of the planner. This cost function can be solved using standard optimization methods and does not require solving a PDE or running Monte-Carlo simulations. Thus, we convert a stochastic control problem into a simple two-variable optimization problem. Our problem can be classified as a mean field optimal stopping time problem. In the absence of stopping time mean field stochastic control has been studied very recently by [1]. However, mean field optimal stopping time problem has not been formulated and/or solved earlier. The advantages of our approach include flexibility in specifying the cost function, computational robustness, and the explicit calculation of the adjustment period. We apply our framework to the real world problem of adjusting domestic energy prices in countries that adopt administratively-set energy price rules. Our toolbox code in Matlab can be easily modified to be used to calculate optimal policies in a wide range of topics in finance, operations management, economics, and natural resource management.

[1] Hu, Yaozhong and Øksendal, Bernt and Sulem, Agnès. Singular mean-field control games *Stochastic Analysis and Applications*, 35(5):823–851, 2017.

### 68. Shape optimization 1

10:00 – 11:15

*Chair:* R. Kovacevic

FH 8 Nöbauer HS

#### A diffuse interface approach for topology optimization and a global convergent solver

Luise Blank (1), Christoph Rupprecht (1),

(1) Faculty of Mathematics, University of Regensburg, Germany

One possibility of modelling interfaces between several phases employs diffuse interfacial layers. Here one assumes that the interfaces have a width of order  $\varepsilon$  where  $\varepsilon > 0$  is small. The governing partial differential equation, given by a sharp interface model are extended appropriately to the diffuse interfaces, where so called phase fields  $\phi_i$  describe at each point the fraction of the  $i$ -th phase (material). The necessary regularization of the cost function with the perimeter is replaced by the Ginzburg-Landau energy. The phase field approach allows the optimization with respect to multiple phases and without knowing in advance the topology of the minimizer. We introduce the problem formulation in particular for multi-material structural topology optimization including the choice of the involved obstacle potential and the choice of the elasticity tensor on the interface.

For the resulting nonlinear optimization problem in function spaces with inequality constraints we deduce a solver-called V(ariable)M(etric)P(rojection)T(ype)-method- to take into account that the cost

functional is only differentiable in  $L^\infty$ . In this solver second order information can be included and we can prove global convergence. This provides a fast, mesh independent solver.

With computational experiments we demonstrate the independence of the mesh size and of the interface thickness in the number of iterations as well as its efficiency in time. We present numerical results for mean compliance problems, compliance mechanism, drag minimization and an inverse problem of discontinuous diffusion coefficients.

### Shape optimization of a layer by layer mechanical constraint for additive manufacturing

Grégoire Allaire (1), Charles Dapogny (2), Rafael Estevez (3), Alexis Faure (3),  
Georgios Michailidis (3),

(1) Centre de Mathématiques Appliquées, École Polytechnique, France (2) Laboratoire Jean Kuntzmann, Université Grenoble-Alpes, France (3) SIMaP, Institut Polytechnique de Grenoble

In this presentation, we introduce a new constraint functional for shape optimization problems, which enforces the constructibility by means of additive manufacturing processes, and helps in preventing the appearance of *overhangs* - large regions hanging over void which are notoriously difficult to assemble using such technologies.

The proposed constraint relies on a simplified model for the construction process: it involves a continuum of shapes, namely the *intermediate shapes* corresponding to the stages of the construction process where the total, *final* shape is erected only up to a certain level.

The shape differentiability of this constraint functional is analyzed - which is not a standard issue because of its peculiar structure. Several numerical strategies and examples are then presented.

[1] G. ALLAIRE, C. DAPOGNY, R. ESTEVEZ, A. FAURE, AND G. MICHAILIDIS, *Structural optimization under overhang constraints imposed by additive manufacturing technologies*, Journal of Computational Physics, 351 (2017), pp. 295–328.

[2] I. GIBSON, D. W. ROSEN, B. STUCKER, ET AL., *Additive manufacturing technologies*, vol. 238, Springer, 2010.

### A stochastic gradient algorithm for shape optimization

Caroline Geiersbach (1), Georg Pflug (1),

(1) Department of Statistics and Operations Research, University of Vienna, Vienna, Austria

Models incorporating uncertain inputs, such as loading or material properties, have been of increasing interest in PDE constrained optimization. Such models may yield more robust solutions, but also come with the cost of additional complexity. Optimization techniques from stochastic approximation have been largely unexploited in this field. We explore an iterative algorithm using a stochastic gradient, which has the appeal of being straightforward to implement alongside deterministic solvers. Questions of convergence are addressed, which rely on finding directions of sufficient decrease and stepsize rules that take advantage of the structure inherent in Hilbert spaces. The algorithm's complexity is reviewed. The approach will be demonstrated for a model problem in linear elasticity using a phase field representation for shapes.



## 69. Variational analysis and optimal control problems 4

10:00 – 11:15

Chair: P. Wolenski, H. Zidani

FH HS 3

## Necessary optimality conditions for average cost minimization problems subject to a state constraint

Nathalie Khalil (1), Piernicola Bettiol (2),

(1) Université de Paris Nanterre, Paris, France (2) Université de Bretagne Occidentale, Brest, France

Parameter-dependent control systems appear a natural framework for applications in which the model design has to take into account various uncertainties. In these circumstances the performance criterion can be given in terms of an average cost. In this talk, we describe an optimal control problem subject to a state constraint in which unknown parameters intervene in the data, and we provide necessary optimality conditions in the form of the Maximum Principle. This is an extension of an earlier work on necessary conditions for state-constraint free average cost minimization problems.

- [1] P. Bettiol and N. Khalil. Necessary optimality conditions for average cost minimization problems. *Submitted*.
- [2] I.M. Ross, M. Karpenko, R.J. Proulx. A Lebesgue-Stieltjes framework for optimal control and allocation. *American Control Conference IEEE*, 5599–5604, 2015.
- [3] R.B. Vinter. Minimax optimal control. *SIAM journal on control and optimization*, 44(3):939–968, 2015.
- [4] J. Warga. *Optimal control of differential and functional equations*. Academic press, 1972.

## Mean-field optimal control of multi-agent systems

Antonio Marigonda (1),

(1) Department of Computer Science, University of Verona, Italy

Recently, there has been an increasing interest from the community in real-life complex system modeling. The most popular example is provided by systems where the number of agents is so large, that only a statistical description (reminiscent to the statistical mechanics description of systems in thermodynamics) turns out to be viable. The usual way to model such kind of systems is to choose a measure space over the underlying Euclidean space as new state space: the measure of a set will give an estimate of the agent present in that set. The peculiarity of such and infinite-dimensional space, and the connection with optimal transport theory, lead to a very rich mathematical structure. In this talk we provide some recent results obtained in optimal control of multi-agent systems, among which we mention a characterization of the value function for some optimal control problems by means of a suitable infinite-dimensional Hamilton-Jacobi equation. Applications will be presented, together with planned future developments.

Friday, July 6<sup>th</sup>

## A geometric perspective on “Infimum Gap” conditions

Michele Palladino (1), Franco Rampazzo (2),

(1) Penn State University, Mathematics Department, USA (2) University of Padova, Department of Mathematics “Tullio Levi-Civita”, Italy

Tonelli’s Direct Method provides a general framework for solving calculus of variations and optimal control problems. Generally, its first step consists in proving the existence of a minimizer. This might not directly follow from the hypotheses satisfied by the problem under consideration: in this case, one can embed the “original” problem into a new, “minimally extended” class of problems for which existence of a solution can be proved. In optimal control and calculus of variations, such a requirement is often achieved by “extending” the class of minimizers, in order to guarantee the existence of a solution. It is then natural to identify the cases in which the original problem and its extended counterpart exhibit a different cost. We refer to this as “Infimum Gap” phenomenon. In this talk, we will show a general, geometric structure that appears in a wide class of optimal control and calculus of variations problems when an “Infimum Gap” phenomenon occurs. In particular, we will recover some of the well-known “Infimum Gap” conditions (see, e.g. [1]-[7]) and we will be able to extend them to other classes of optimal control problems.

- [1] M. Motta, F. Rampazzo and R. B. Vinter, “Normality and Gap Phenomena in Optimal Impulsive Control”, *submitted*
- [2] M. Palladino and R. B. Vinter, “Minimizers that are not also Relaxed Minimizers”, *SIAM J. Control and Optim.*, 52, 4, 2014, pp. 2164 - 2179.
- [3] M. Palladino and R. B. Vinter, “When are Minimizing Controls Also Minimizing Relaxed Controls?”, *Discr. and Cont. Dyn. Syst. - Ser. A* , 52, 4, 2014, pp. 2164 - 2179.
- [4] J. Warga, “Normal Control Problems have no Minimizing Strictly Original Solutions”, *Bulletin of the Amer. Math. Soc.*, 77, 4, 1971, pp. 625-628.
- [5] J. Warga, *Optimal Control of Differential and Functional Equations*, Academic Press, New York, 1972.
- [6] J. Warga, “Controllability, extremality, and abnormality in nonsmooth optimal control”, *J. Optim. Theory and Applic.*, 41, 1, 1983, pp. 239-260.
- [7] J. Warga, “Optimization and Controllability Without Differentiability Assumptions”, *SIAM J. Control and Optim.*, 21, 6, 1983, pp. 837-855.

## 70. Contributed session: applications of optimal control 3

10:00 – 11:15

*Chair: J. Haunschmied*

FH HS 2

### An agent negotiation approach to distributed optimal control

João M. Lemos (1),

(1) INESC-ID, Instituto Superior Técnico, Univ. of Lisbon, Portugal

This work addresses the distributed optimal control of complex systems made of a network of process agents that interact among them in a way described by a graph that defines a process layer. Furthermore,

it is assumed that this interaction occurs only through the manipulated variable. Each process node  $i$ ,  $i = 1, \dots, N$ , is described by the finite dimensional state model in discrete time

$$x_i(k+1) = f_i(x_i(k), u_i(k), v_i(k)),$$

where  $k$  is an integer that denotes discrete time,  $x_i \in \mathbb{R}^{n_i}$  is the state of the agent  $\mathcal{A}_i$ ,  $f_i(x_i) \in \mathbb{R}^{n_i}$  is the corresponding vector field,  $u_i$  is the manipulated vector of node  $i$ , and  $v_i$  is the vector of the signals from neighbor process agents that affect  $\mathcal{A}_i$  which is assumed to be available for measurement.

A corresponding control layer is made of control agents  $\mathcal{K}_i$ ,  $i = 1, \dots, N$ , each one interconnected with a process agent through sensors and actuators. Each control agent  $\mathcal{K}_i$  optimizes a cost  $J_i$  that is a function of the manipulated variables of  $\mathcal{K}_i$  as well as of the ones of its neighbors (*i. e.* the control agents with which it interacts). The goal is that the different control agents cooperate while interchanging local control decisions so as to optimize the global cost

$$J = \sum_{i=1}^N J_i.$$

In order to reach a consensus among neighbor control agents on what the value of the manipulated variable of each one should be, distributed optimization algorithms that rely on the alternating direction method of multipliers (ADMM) or cooperative game concepts are employed. A detailed presentation is made for the linear quadratic problem, including the derivation of the algorithm and a case study on the control of a water delivery canal divided in different sections associated to gates.

This work has been supported by Fundação para a Ciência e a Tecnologia, Portugal, under contracts UID/CEC/50021/2013 and PTDC/EEIPRO/0426/2014 (project SPARSIS)

### Fertility, mortality and emission policy

Tapio K. Palokangas (1,2,3), Ulla Lehmijoki (1,3),

(1) HECER, University of Helsinki, Helsinki, Finland (2) IIASA, Laxenburg, Austria (3) IZA, Bonn, Germany

In this paper, we examine an economy with endogenous fertility, emissions-related mortality, and clean and dirty sectors that produce output from labor and capital. Technically, we integrate the Heckscher-Ohlin-Samuelson two-sector model into Becker's [2] model with capital accumulation and population growth. We solve the dynamics of the economy by maximizing the representative family's welfare by Pontryagin's maximum principle. Consequently, there are two predetermined variables (population, capital) and one non-predetermined jump variable (consumption per head).

Our main results are the following. Assume that the government strives against mortality by emission caps or taxes. This reduces the relative size of the dirty sector, shifting labor and capital to the clean sector. Because the dirty sector has traditionally been relatively capital intensive, emissions-restricting policy hampers fertility through higher wages, which supports its goals. However, the policy faces two dangers – overpopulation and factor intensity reversal – that reverse the direction of population growth. Then, with no effective “emission subsidy”, the economy is trapped in high population density.

The model differs from that of de Croix and Gosseries [1] as follows. First, they assume only one technology, but we two alternative technologies (or sectors): dirty and clean. Consequently, emissions are proportional to total output in their model, but depends on the relative proportion of dirty output in our model. Second, they ignore physical capital and assume that spending on education increments human capital, while we assume that total savings accumulate aggregate capital (*i.e.* human and physical

capital taken together). Third, an increase in population density decreases fertility in [1], but decreases welfare and increases mortality through emissions in our model. These differences lead different policy recommendations as follows. De la Croix and Gosseries [1] are very pessimistic about the efficiency of emission caps and suggest population capping schemes instead. In contrast, we show that emission caps or taxes decrease mortality, fertility and total population efficiently in the *traditional case* where the dirty sector is more capital intensive than the clean sector. However, we warn about the *prospective case* where overpopulation or a change of technology nullifies the efficiency of emissions-curtaining policy.

[1] D. De la Croix and A. Gosseries. The Natalist Bias of Pollution Control. *Journal of Environmental Economics and Management*, 63: 271–287, 2012.

[2] G.S. Becker 1981. *A Treatise on the Family*. Harvard University Press, Cambridge (Mass.), 1981.

### Buildup of backstop technologies characterised by sluggishness and learning: an optimal control approach

Magda Mirescu (1, 2),

(1) Chair of Industry, Energy and Environment, University of Vienna, Vienna, Austria (2) ORCOS, Vienna University of Technology, Vienna, Austria

Climate change is without doubt the most important challenge of the 21<sup>st</sup> century. One way to prevent it from happening is by shifting from pollution-intensive to climate-friendly or so-called *backstop* technologies. This paper investigates the optimal expansion of backstop technologies in two different settings: abundance and scarcity of non-renewable or *fossil* resources.

Fossil-fueled technologies are assumed to be already available and to require exhaustible resources, which are characterised by extraction and scarcity costs, but also damage to the environment. Backstop technologies, on the other hand, are assumed to require high investment costs to be built, which imply a lethargic increase in their installed capacity. These investment costs are however to some extent diminished by also considering the by now well established learning-by-doing effect associated with backstop technologies. Furthermore, a concave-convex system costs function makes too high a buildup too expensive to be optimal. Utility is assumed to be generated from both types of technologies.

From a modeling perspective, this paper contains a deterministic, non-linear, autonomous optimal control model with two states and two controls. The main result is that the learning effect is the main driver of interesting phenomena such as instability, multiplicity of equilibria and thresholds, and the system costs function the second.

[1] D. Grass, J.P. Caulkins, G. Feichtinger, G. Tragler, D. Behrens. *Optimal Control of Nonlinear Processes*. Springer, Heidelberg, 2008.

[2] E. Moser, D. Grass, G. Tragler. A Non-Autonomous Optimal Control Model of Renewable Energy Production under the Aspect of Fluctuating Supply and Learning by Doing. *OR Spectrum*, 38:545–575, 2016.

[3] M. Mirescu. Optimal Electricity Generation Portfolios in the Presence of Fuel Price and Availability Risks. *15<sup>th</sup> IAEE European Conference Proceedings on "Heading Towards Sustainable Systems Evolution or Revolution?"*, 2017.

[4] F. Wirl and C. Withagen. Complexities Due to Sluggish Expansion of Backstop Technologies. *Journal of Economics*, 72(2):153–174, 2000.

## 71. Real options 3

10:00 – 11:15

Chair: P.M. Kort

FH HS 4

### Dynamic capital structure choice and investment timing

Engelbert J. Dockner (1), Richard F. Hartl (2), Peter M. Kort (3,4),

(1) Deceased (2) Department of Business Administration, University of Vienna, Vienna, Austria

(3) Department of Econometrics and Operations Research & CentER, Tilburg University, Tilburg, The Netherlands (4) Department of Economics, University of Antwerp, Antwerp, Belgium

The paper considers the problem of an investor that has the option to acquire a firm. Initially this firm is run as to maximize shareholder value, where the shareholders are risk averse. To do so it has to decide each time on investment and dividend levels. The firm's capital stock can be financed by equity and debt, where less solvable firms pay a higher interest rate on debt. Revenue is stochastic.

We find that the firm is run such that capital stock and dividends develop in a fixed proportion to the equity. In particular, it turns out that more dividends are paid if the economic environment is more uncertain. We also derive an explicit expression for the threshold value of the equity above which it is optimal for the investor to acquire the firm. This threshold increases in the level of uncertainty reflecting the value of waiting that uncertainty generates.

### On cooperative bargaining under uncertainty over investment in CO<sub>2</sub> emission reduction technology along an industrial chain

Tine Compernelle (1), Jacco J.J. Thijssen (2),

(1) Department of Economics, University of Antwerp, Antwerp, Belgium (2) The York Management School, University of York, York, United Kingdom

An increasing concern for climate change puts pressure on industrial firms to implement practices for carbon emission reductions. Recently, it has been recognized that carbon emission reductions can be realized through cooperation among firms in industrial chains.

Central to the adoption of industrial symbiosis is the so-called “win-win condition”. It has been assumed in the literature that industrial symbiosis will emerge spontaneously, as an independent choice of both parties involved, under the condition that all parties achieve an economic benefit sufficient to cover the risk of the investment, i.e. the NPV of cooperation should exceed the sum of individual firm NPVs.

In reality, however, firms have an *option* to invest and this requires an adaptation of the “win-win condition” to include a comparison between the NPV of cooperation with the sum of the firms' individual option values. We put the option to cooperate in a dynamic context and combine real options theory with notions of cooperative bargaining theory. We show that when a firm's flexibility to invest on its own, is taken into account, the “win-win condition” as used in the literature may be misleading. In particular, we show that it is possible for simultaneous investment to be Pareto optimal, while firms can not be expected to agree to cooperate. This happens because the value of their outside option exceeds the benefits from cooperation.

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## The effects of possible policy withdrawal on investment timing and investment size

Roel L.G. Nagy (1), Peter M. Kort (2,3), Verena Hagspiel (1),

(1) Norwegian University of Science and Technology, Trondheim, Norway (2) Tilburg University, Tilburg, The Netherlands (3) University of Antwerp, Antwerp, Belgium

This paper analyzes the effect of policy uncertainty on investment timing and investment size, and the interaction between both. The policy uncertainty involves an one-time possible withdrawal of a tax credit policy. If the policy maker cannot enact it in the future, we find that increasing the probability of withdrawal of a tax credit policy increases the incentive to invest now and decreases the optimal investment size. Huisman and Kort (2015) [2] show that investing later means that the investor invests at a larger capacity, which is confirmed in this paper. It is found that a firm that invests at the timing threshold value invests at larger scale when the policy is not in effect than when it is in effect. This results from the fact that subsidy speeds up investment and earlier investment is done at a lower capacity.

Unlike the price premium in Chronopoulos, Hagspiel and Fleten (2016) [1], these conclusions do not hold only for low withdrawal probabilities, but for all withdrawal probability values, as the tax credit policy is only relevant at the time of investment. Therefore, increasing the withdrawal probability to a large value speeds up investment more.

When the investor is a social planner who aims to maximize social welfare, it is found that the social planner has the same timing as the profit-maximizing monopolist, but invests at twice the investment size. The monopolist seems to keep the price up by producing less.

[1] M. Chronopoulos, V. Hagspiel, S.-E. Fleten. Stepwise green investment under policy uncertainty. *International Association for Energy Economics*, 37 (4): 87-108, 2016.

[2] K.J. Huisman, P.M. Kort. Strategic capacity investment under uncertainty. *RAND Journal of Economics*, 46 (2): 376-408, 2015.

## 72. Infinite dimensional stochastic modeling in economics and finance 2

11:30 – 12:45

*Chair:* E. Bandini, F. Gozzi, G. Fabbri

FH HS 7

### Stochastic filtering and optimal control of pure jump Markov processes with noise-free partial observation

Alessandro Calvia (1),

(1) Department of Statistics and Quantitative Methods, University of Milano-Bicocca, Milan, Italy

In this talk I am going to address an optimal control problem with partial observation, mainly characterized by observations not corrupted by noise. These models have received a sporadic treatment in the literature, despite interesting potential applications, also in economics and finance.

Let  $X$  and  $Y$  be a given pair of stochastic processes, defined on a complete probability space  $(\Omega, \mathcal{F}, \mathbb{P})$ , with values in two complete and separable metric spaces (possibly infinite dimensional)  $I$  and  $O$  respectively. The unobserved (or signal) process  $X$  is a time-homogeneous pure jump Markov process, whose rate transition measure is known. The observed process  $Y$  is defined as  $Y_t = h(X_t)$ ,  $t \geq 0$ , where  $h: I \rightarrow O$

is a known surjective and measurable function. The aim of the optimal control problem is to minimize a discounted cost functional on infinite time horizon by controlling the rate transition measure of the unobserved process via the information provided by the observed process.

To solve an optimal control problem with partial observation, a two-step procedure is required. The first one is related to the *filtering problem*. I will provide an explicit SDE for the *filtering process*  $(\pi_t)_{t \geq 0}$ , that is a stochastic process taking values in the set of Borel probability measures on the set  $I$ , satisfying

$$\pi_t(\varphi) = \mathbb{E}[\varphi(X_t) \mid \mathcal{Y}_t] \quad \mathbb{P}\text{-a.s.}$$

for all  $t \geq 0$  and all  $\varphi: I \rightarrow \mathbb{R}$  bounded and measurable functions; here  $(\mathcal{Y}_t)_{t \geq 0}$  denotes the natural filtration of  $Y$ , i.e.  $\mathcal{Y}_t = \sigma(Y_s: 0 \leq s \leq t)$ , for all  $t \geq 0$ . The filtering process is also characterized as a *Piecewise Deterministic Markov Process*.

The second step is the solution of the optimal control problem. Thanks to the filtering process, we can introduce an associated *separated problem*, that is a discrete-time optimal control problem for the filtering process with complete observation. I will show the equivalence between the original and the separated control problems and prove a characterization of the value function of the latter problem as the unique fixed point of a suitably defined contraction mapping.

### Verification theorems for stochastic optimal control problems in Hilbert spaces by means of a generalized Dynkin formula

Salvatore Federico (1), Fausto Gozzi (2),

(1) Dipartimento di Economia Politica e Statistica, Università di Siena, Siena, Italy (2) Dipartimento di Economia e Finanza, LUISS University, Rome, Italy

Verification theorems are key results to successfully employ the dynamic programming approach to optimal control problems. In this paper we introduce a new method to prove verification theorems for infinite dimensional stochastic optimal control problems. The method applies in the case of additively controlled Ornstein-Uhlenbeck processes, when the associated Hamilton-Jacobi-Bellman (HJB) equation admits a *mild solution* (in the sense of [1]). The main methodological novelty of our result relies on the fact that it is not needed to prove, as in previous literature (see e.g. [2]), that the mild solution is a *strong solution*, i.e. a suitable limit of classical solutions of the HJB equation. To achieve our goal we prove a new type of Dynkin formula, which is the key tool for the proof of our main result. Some applications to economic problems are described.

- [1] S. Federico and F. Gozzi. Mild solution of semilinear elliptic equations in Hilbert spaces. *Journal of Differential Equations*, 62(5): 3343-3389, 2017.
- [2] F. Gozzi. Regularity of solutions of a second order Hamilton-Jacobi equation and application to a control problem. *Comm. Partial Differential Equations*, 20(5-6):775-826, 1995.

## Optimal control of infinite-dimensional Piecewise Deterministic Markov Processes

Michèle Thiullen (1), Elena Bandini (2),

(1) LPSM, Sorbonne Université - Campus Pierre et Marie Curie (UPMC), Paris, France (2) Università degli Studi di Milano-Bicocca, Milano, Italy

We consider optimal control of Piecewise Deterministic Markov Processes taking values in a Hilbert space when the control acts on the jump dynamics and on the flow. We show that the value function can be represented by constrained backward stochastic differential equations. We were motivated by previous work by E. Bandini (cf. [1]), in finite dimension, who relied on the control randomization method. We will see that the randomization method can be used in this infinite dimensional framework where the key argument is to prove a dynamic programming principle associated to the randomized control problem. The paper [2] by V. Renault, M. Thiullen and E. Trélat was another motivation for this work.

- [1] E. Bandini. Optimal control of Piecewise Deterministic Markov Processes: a BSDE representation of the value function. To appear in *ESAIM: Control, Optimization and Calculus of Variations*, <http://dx.doi.org/10.1051/cocv/2017009>, 2017.
- [2] V. Renault, M. Thiullen, E. Trélat. Optimal control of infinite-dimensional piecewise deterministic Markov processes and application to the control of neuronal dynamics via Optogenetics. *Netw. Heterog. Media*, 12(3):417–459, 2017.

## 73. Shape optimization 2

11:30 – 12:45

*Chair:* R. Kovacevic

FH 8 Nöbauer HS

### Topology optimization of contact problems with the level set method

François Jouve (1), Grégoire Allaire (2), Aymeric Maury (3),

(1) Laboratoire J.L.Lions (UMR CNRS 7598), University Paris Diderot, Paris, France (2) CMAP (UMR CNRS 7641), École Polytechnique, Palaiseau, France (3) GIREF, Dépt. de mathématiques et de statistique, Université Laval, Québec, Canada

The level set method has proven that it can become a trustworthy alternative to the SIMP method implemented in most of the commercial softwares of topology optimization. The precise definition of an interface between material and void in the level set representation of the shapes allows an efficient treatment of constraints depending on the geometry, like the maximum and/or minimum thickness constraints or different geometric conditions imposed by the casting process. In this conference we focus on contact problems, with or without friction, and show that the level set approach can also handle such nonlinear problems.

- [1] G.Allaire, F.Jouve, A.M.Toader. Structural optimization using sensitivity analysis and a level-set method. *J. Comp. Phys.*, 194(1):363–393, 2004.
- [2] A.Maury, G.Allaire, F.Jouve. Shape optimisation with the level set method for contact problems in linearised elasticity. *SMAI J. of Comp. Math.*, 3:249–292, 2017.



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### A Galerkin-type approach to shape optimisation in the space of convex sets

Bastian Harrach (1), Janosch Rieger (2),

(1) Institut für Mathematik, Goethe-Universität Frankfurt, Frankfurt am Main, Germany (2) School of Mathematical Sciences, Monash University, Melbourne, Australia

In this talk, I will discuss spaces of polytopes with fixed outer normals and their use in theoretical and practical shape optimization. These spaces possess a natural system of coordinates, and all admissible coordinates can be characterized by a linear inequality, which is handy both from an analytical as well as from a computational perspective.

These polytope spaces approximate the space of all nonempty convex and compact subsets in Hausdorff distance uniformly on every bounded set, so they behave like classical Galerkin approximations to function spaces. I will show that for simple shape optimization problems, the set of global minimizers of auxiliary problems posed in the polytope spaces converges to the set of global minimizers of the original problem.

### Topological sensitivities via a Lagrangian method for semilinear problems

Kevin Sturm (1),

(1) Vienna University of Technology, Vienna, Austria

The topological derivative is an indispensable tool to solve shape optimization problems numerically. Its idea is to find a first order asymptotic expansion of a cost function of interest with respect to singularly perturbed domain. While there are many results concerning linear problem, nonlinear problems pose a special difficulty due to the absence of a fundamental solution. In this talk I will discuss a Lagrangian approach to the computation of topological derivatives for a class of semilinear problems. Our approach provides a fairly simple framework without the need of remainder estimates which typically employed.

## 74. Variational analysis and optimal control problems 5

11:30 – 12:45

*Chair:* P. Wolenski, H. Zidani

FH HS 3

### Polynomial feedback laws for infinite-dimensional bilinear optimal control problems

Laurent Pfeiffer (1), Tobias Breiten (1), Karl Kunisch (1, 2),

(1) Institute of Mathematics and Scientific Computing, University of Graz, Austria (2) RICAM, Linz, Austria

We consider in this talk the following bilinear optimal control problem:

$$\mathcal{V}(y_0) = \min_{u \in L^2(0, \infty)} \int_0^\infty \|Cy(t)\|^2 + \frac{\alpha}{2} u(t)^2 dt,$$

subject to:  $\dot{y}(t) = Ay(t) + (Ny(t) + B)u(t), \quad y(0) = y_0.$

A Taylor expansion of the value function  $\mathcal{V}$  can be computed in the neighborhood of the origin by repeated differentiation of the associated Hamilton-Jacobi-Bellman equation [2]. The obtained approximation provides a polynomial feedback law, that we analyse theoretically [4] and numerically [3] with a control

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problem of the Fokker-Planck equation, a parabolic differential equation modelling the evolution in time of the distribution of a set of physical particles [1].

- [1] T. Breiten, K. Kunisch, and L. Pfeiffer. Control strategies for the Fokker-Planck equation. *ESAIM: Control, Optimisation and Calculus of Variations*, 2017. To appear.
- [2] T. Breiten, K. Kunisch, and L. Pfeiffer. Taylor Expansions of the Value Function Associated with a Bilinear Optimal Control Problem. SFB-Report, June 2017.
- [3] T. Breiten, K. Kunisch, and L. Pfeiffer. Numerical study of polynomial feedback laws for a bilinear control problem. SFB-Report, September 2017.
- [4] T. Breiten, K. Kunisch, and L. Pfeiffer. Infinite-Horizon Bilinear Optimal Control Problems: Sensitivity Analysis and Polynomial Feedback Laws. SFB-Report, February 2018.

### A higher order Maximum Principle for optimal unbounded control problems

Franco Rampazzo (1), Maria S. Aronna (2), Monica Motta (1),

(1) Department of Mathematics “T.Levi-Civita”, University of Padova, Padova, Italy (2) EMAP/FGV, Rio de Janeiro, Brazil

We consider control systems of the form:

$$\dot{x}(t) = f(x(t), u(t), v(t)) + \sum_{\alpha=1}^m g_{\alpha}(x(t), u(t))\dot{u}_{\alpha}(t), \quad t \in [0, T], \quad (1)$$

where  $x : [0, T] \rightarrow \mathbb{R}^n$  is the *state trajectory*,  $u : [0, T] \rightarrow \mathbb{R}^m$  is an *impulsive control*, and  $v(\cdot)$  is an *ordinary control* taking values in a bounded set. The control  $u$  is allowed to be a (discontinuous) bounded variation function, which gives the system an impulsive character. As is well known, due to nonlinearity a measure-theoretical approach fails to provide a robust notion of solution. Instead, we refer here to the concept of “graph completion solution”, which was introduced in [1] (and eventually generalized in [2] to the case of unbounded variation) via an embedding of the dynamics (1) in a space-time control systems and reparameterization.

Correspondingly, we will consider an optimal control problem with final state constraints and express some necessary conditions in the form of a higher order maximum principle involving iterated Lie brackets of the vector fields  $f, g_1, \dots, g_m$ .

- [1] A. Bressan, F. Rampazzo. On differential systems with vector-valued impulsive controls *Boll. Un. Mat. Ital. B* (7), 2 , 641–656, 1988.
- [2] M. S. Aronna. L-1 limit solutions for control systems. *Journal of Differential Equations* 258(3), 954–979 (2015)

### Sensitivity analysis for solution mappings of variational inequalities

Gerd Wachsmuth (1), Constant Christof (2),

(1) Brandenburgische Technische Universität Cottbus-Senftenberg, Institute of Mathematics, Chair of Optimal Control, Cottbus, Germany (2) Technische Universität Dortmund, Faculty of Mathematics, LS X, Dortmund, Germany

We consider the differential sensitivity analysis of variational inequalities in Banach spaces whose solution operators satisfy a generalized Lipschitz condition. We prove a sufficient criterion for the directional differentiability of the solution map that turns out to be also necessary for elliptic variational inequalities in Hilbert spaces (even in the presence of asymmetric bilinear forms, nonlinear operators and nonconvex functionals).

In contrast to classical results, our method of proof does not rely on Attouch's theorem on the characterization of Mosco convergence but is fully elementary. Moreover, our technique allows us to also study those cases where the variational inequality at hand is not uniquely solvable and where directional differentiability can only be obtained w.r.t. the weak or the weak- $\star$  topology of the underlying space.

## 75. Ageing and inequality

11:30 – 12:45

*Chair:* A. Prskawetz, M. Sanchez

FH HS 2

### Limited self-control and longevity

Holger Strulik (1),

(1) University of Göttingen, Göttingen, Germany

This paper proposes a new framework to discuss self-control problems in the context of life-cycle health and longevity. Individual decisions are conceptualized as the partial control of impulsive desires of a short-run self (the limbic system) by a rationally forward-looking long-run self (the prefrontal cortex). The short-run self strives for immediate gratification through consumption of health-neutral and unhealthy goods. The long-run self reflects the long-term consequences of unhealthy behavior on health outcomes and longevity and invests time and money to improve current and future health. The model is calibrated with data from the U.S. and used to provide an assessment of the impact of imperfect self-control on unhealthy consumption, physical exercise, lifetime health, and the age at death.

### Endogenous retirement behavior of heterogeneous households under pension reforms

Axel Börsch-Supan (1,2), Klaus Härtl (1,3), Duarte N. Leite (1,5), Alexander Ludwig (1,4),

(1) Munich Center for the Economics of Aging at the Max-Planck-Institute for Social Law and Social Policy, Germany (2) NBER, National Bureau of Economic Research, MA, USA (3) TUM, Technical University of Munich, Germany (4) SAFE, Goethe University Frankfurt, Germany (5) CEF.UP, Center for Economics and Finance at the University of Porto, Portugal

We propose a unified framework to measure the effects of different reforms of the pension system on retirement ages and macroeconomic indicators in the face of demographic change. A rich overlapping generations (OLG) model is built and endogenous retirement decisions are explicitly modeled within a public pension system. Heterogeneity with respect to consumption preferences, wage profiles, and survival rates is embedded in the model. By connecting confluent strands of literature on micro-incentives for retirement, life-cycle behavior and OLG models with population aging, we examine the macroeconomic impact of previously proposed reforms of the pension system under different macroeconomic regimes. Besides the expected direct effects of these reforms on the behavior of households, we observe that feedback effects do occur. Results suggest that individual retirement decisions are strongly influenced by numerous incentives produced by the pension system and macroeconomic variables, such as the statutory eligibility

age, adjustment rates, the presence of a replacement rate, and interest rates. Those decisions, in turn, have several impacts on the macro-economy which can create feedback cycles working through equilibrium effects on interest rates and wages. Taken together, these reform scenarios have strong implications for the sustainability of pension systems. It is shown that these results survive under different macroeconomic regimes. Because of the rich nature of our unified model framework, we are able to rank the reform proposals according to several individual and macroeconomic measures, thereby providing important support for policy recommendations on pension systems.

### The impact of reducing the pension generosity on inequality and schooling

Miguel Sánchez-Romero (1,2), [Alexia Prskawetz](#) (1,2),

(1) ECON, Vienna University of Technology, Vienna, Austria (2) Wittgenstein Centre of Demography and Global Human Capital (VID/ÖAW,WIC,WU), Austria

In this paper we investigate the impact of a reduction in the pension replacement rate on inequality and on the schooling choice. We develop an overlapping generations model in which individuals differ by their life expectancy and in the cost of attending schooling. Individuals optimally choose their consumption path and their educational attainment. Within our framework we show the conditions under which a reduction in the replacement rate may increase the number of skilled workers and reduce inequality.

## 76. Real options 4

11:30 – 12:45

*Chair:* P.M. Kort

FH HS 4

### Value-enhancing pre-investments under uncertainty

[Tord Olsen](#) (1), [Verena Hagspiel](#) (1),

(1) Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Trondheim, Norway

Real options models of investment mostly concern the firm's stochastic environment as exogenously given and subject to constant parameters. We consider a firm that can sequentially invest to alter the growth rate of a project's revenues through a value-enhancing pre-investment activity, both when the change is fixed, and when the magnitude of the change can be optimally chosen by the firm, before entering the market. We find that this incentivises the firm to invest sequentially, first in revenue-enhancing activities and then to enter the market at some later time. This is in contrast to the two-stage investment problem of Dixit & Pindyck [1], wherein it is never optimal for the firm to invest sequentially. There is both an option value of waiting that delays investment in value-enhancing activities, as well as an accelerating effect from the change in growth rate, which increases the value of the project. Thus, the resulting effect of uncertainty is not straightforward, as increasing uncertainty can both delay or expedite the investment in revenue-enhancing activities, dependent on the cost parameters and the magnitude of the change in the growth rate. When the firm can optimally choose the amount of the value-enhancing activity, we find that the firm invests more in these activities when uncertainty is higher. When the marginal cost of the activity increases, the firm undertakes less revenue-enhancement, but the overall amount spent increases.

[1] A. Dixit and R. S. Pindyck. *Investment under uncertainty*. Princeton university press, Princeton, 1994

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### Growth options and dynamic exposure to multiple risk factors

Jacco J.J. Thijssen (1), Jan-Henrik Steg (2),

(1) The York Management School, University of York, UK (2) Institute of Mathematical Economics, Bielefeld University, Germany

We present a theory of time-varying firm betas where firms compete over investment in a growth option. We model a duopoly where firms have assets in place that are exposed to a risk factor. Both firms have a growth option that exposes them to another risk factor. We construct a subgame perfect equilibrium in Markovian mixed strategies and show that both preemption and attrition can occur along typical equilibrium paths. This equilibrium is used to show that firms endogenously manipulate value in a way that affects firms' exposure to risk factors (firm betas). Our theory predicts that, while firms compete for first investment in the growth option, there will be periods of time where exposure to one of the risk factors is completely competed away.

### Photovoltaic Smart Grids in the prosumers investment decisions: a real option model

Francesco Menoncin (1), Michele Moretto (2), Sergio Vergalli (1), Dimitrios Zormpas (2),

(1) University of Brescia, Brescia, Italy (2) University of Padua, Padua, Italy

The last decades have been characterized by the development of the renewable energy sources. The search for a sustainable development of production has in fact led to the search for an alternative energy to the conventional one. In this context there has been an increase in the number of distributed generation power plants both in Italy and in many EU countries. The new alternative sources have the considerable advantage of having a lower environmental impact but are often characterized by a discontinuous production. This has involved some problems related to the management of the electricity grid (for example inefficiency, congestion rents, power outages, etc.) which can often be solved by the implementation of a "smarter" electricity grid. Smart grids have the significant advantage of increasing the flexibility of production and consumption. Smart grids give producers and consumers the opportunity to be active in the market and to strategically decide their optimal production / consumption scheme. Our paper provides a theoretical framework for modeling the decision of two agents to invest in two photovoltaic plants, assuming they are integrated into an intelligent network. To capture the value of managerial flexibility, a real option approach is implemented. Each agent can at the same time produce, consume and exchange both with the public grid and with the other agent (for this reason they are called "prosumers"). The purpose of the paper is to verify if the energy exchange between agents is convenient. Secondly, we will try to calculate the optimal size of the plant in order to maximize the benefit of each agent. Finally, the model will be calibrated and tested using energy market data.

### 77. Information provision and signalling games

14:00 – 15:40

*Chair:* C. Langbort, J. Marecek, R. Shorten

FH HS 7

### On strategic information provision in traffic network games

Cédric Langbort (1), Olivier Massicot (1), , Yijie Cheng (1), , Lichun Li (1),

(1) Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, USA

*Does providing traffic information to drivers reduce congestion?* This has been a central question ever since the introduction of advanced traffic information systems (ATIS) in transportation infrastructures. It is becoming even more pressing today as GPS and route recommendation systems have become widespread, offering the further possibility of tailoring information to users. A definite answer has, however, remained elusive. On the one hand, one might reason naively that additional information provides decision-makers ‘advance warning’, which might help them avoid (expected-to-be-) congested routes. On the other hand, if drivers have similar goals and behaviors, and are provided the same (public) information, they may all make the same choice, thus merely shifting congestion from one route to another...

In this talk, we introduce and study two mechanisms for information provision in a transportation context, whose properties in terms of social welfare can be rigorously analyzed. The first mechanism considers drivers as learners and treats congestion reduction as a control problem, whose input is the information provided to them. The second mechanism focuses on shaping Wardrop equilibria in a networked games via the tools of Bayesian Persuasion theory.

### Persuasion and coordination with decoder’s state information

Maël Le Treust (1), Tristan Tomala (2),

(1) ETIS UMR 8051, Université Paris Seine, Université Cergy-Pontoise, ENSEA, CNRS (2) HEC Paris, GREGHEC UMR, Paris, France

In articles [1-2], we investigate the problem of Bayesian persuasion [3] by considering the sender communicates to the receiver through a noisy channel. The channel noise reduces the sender’s utility. The case of quadratic distortion measures and Gaussian source and channel was solved in [4]. We characterize the optimal solution in terms of a splitting under an information constraint. We further extend this result by considering the decoder partially observes the state [5]. This setting relates to the problem of lossy source coding with decoder’s state information, solved by Wyner-Ziv [6]. The partial knowledge of the state at the decoder has a very interesting impact on the solution. Depending on the problem it may increase or decrease the sender’s utility. We characterize the optimal solution in term of the concavification of an auxiliary utility function.

- [1] M. Le Treust and T. Tomala. Persuasion with limited communication capacity. *draft*, <https://arxiv.org/abs/1711.04474>, Nov. 2017.
- [2] M. Le Treust and T. Tomala. Information design for strategic coordination of autonomous devices with non-aligned utilities. *in Proc. of IEEE Allerton Conference*, Oct. 2016.
- [3] E. Kamenica and M. Gentzkow. Bayesian persuasion. *American Economic Review*, vol. 101, pp. 2590 – 2615, 2011.
- [4] E. Akyol and C. Langbort and T. Başar. Information-theoretic approach to strategic communication as a hierarchical game. *Proceedings of the IEEE*, vol. 105(2), pp. 205–218, 2017.
- [5] M. Le Treust and T. Tomala. Strategic coordination with state information at the decoder. *in Proc. of International Zurich Seminar*, Feb. 2018.
- [6] A. D. Wyner and J. Ziv. The rate-distortion function for source coding with side information at the decoder. *IEEE Transactions on Information Theory*, vol. 22, pp. 1–11, Jan. 1976.

**Closed-loop analyses of information provision**

Jakub Marecek (1), Jonathan Epperlein (1), Robert N. Shorten (1,2), Jia Yuan Yu (3),

(1) IBM Research – Ireland, Dublin, Ireland (2) University College Dublin, Dublin, Ireland (3) Concordia University, Montreal, Canada

We study the problem of providing information about the state of shared resources to their users, assuming that the state of the system is a result of the actions of the users and that the information about the state, in turn, drive the actions of the users. In [1,2,3] Marecek et al. proposed a discrete-time model, where each user uses one out of multiple resources at each time instant. The per-use cost of a resource depends on the number of concurrent users. A central authority has up-to-date knowledge of the number of users across all resources and provide a scalar or an interval per each resource to all users at each time instant. In [1], randomisation was used to derive the scalar or interval signal. The resulting distribution of agents across resources converges in distribution. In [2], the interval to broadcast per resource is obtained by taking the minima and maxima of costs observed within a time window of length  $r$ , rather than by randomisation, and this signal is public. Still, the resulting distribution of agents across resources also converges in distribution, under plausible assumptions about the evolution of the population over time. In [3], the signal is again public, but the evolution of a heterogeneous population of users is governed by a Markov chain. Even there, we are able to show that the distribution of users across the resources converges in distribution, for suitable means of providing the information, under certain assumptions. This talk presents the model, the results, and the proof techniques, which may have wider applicability, as well as a number of open problems.

- [1] J. Marecek, R. Shorten, J. Y. Yu. Signaling and Obfuscation for Congestion Control *International Journal of Control*, 88(10): 2086-2096, 2015.
- [2] J. Marecek, R. Shorten, J. Y. Yu. r-Extreme Signalling for Congestion Control *International Journal of Control*, 89(1): 1972-1984, 2016.
- [3] J. Epperlein and J. Marecek. Resource allocation with population dynamics. *55th Annual Allerton Conference on Communication, Control, and Computing*. IEEE: Piscataway, 2017.

**On PI control and smart cities**

André R. Fioravanti (1), Jakub Marecek (2), Robert N. Shorten (3), Matheus Souza (1), Fabian R. Wirth (4),

(1) University of Campinas, Campinas, Brazil (2) IBM Research – Ireland, Dublin, Ireland (3) University College Dublin, Dublin, Ireland (4) University of Passau, Passau, Germany

We discuss results presented at the 56th IEEE Conference on Decision and Control, 2017. Specifically, we discuss the applicability of classical control theory to problems in smart grids and smart cities. We use tools from iterated function systems to identify controllers with desirable properties. In particular, controllers are identified that can be used to design not only stable closed-loop systems, but also to regulate large-scale populations of agents in a predictable manner. We also illustrate by means of an example and associated theory that many classical controllers are not be suitable for deployment in these applications.

- [1] Fioravanti, A., Maracek, J., Shorten, R., Souza, M., Wirth, F., *On Classical Control and Smart Cities*, In Proceedings of 56th IEEE Conference on Decision and Control, 2017.

78. Numerical analysis for PDE constrained optimization 5

14:00 – 15:40

*Chair:* A. Rösch, J. Pfefferer

FH 8 Nöbauer HS

Discretization schemes and error estimates for second-order partial differential equations in non-variational form

Jan Blechschmidt (1), Roland Herzog (1), Max Winkler (1),

(1) Technische Universität Chemnitz, Faculty of Mathematics, Germany

In this talk, we consider second-order problems in non-variational (non-divergence) form with possibly non-differentiable diffusion coefficients. These arise for instance as generators of stochastic diffusion processes. Applications include the solution of Hamilton-Jacobi-Bellman equations as well as Isaacs equations. While the classical finite difference approach is applicable for their solution, handling complicated geometries and unstructured meshes comes at an effort. These difficulties can be overcome by finite element and finite volume schemes. We discuss various discretization schemes and present error estimates as well as numerical results.

Optimal control of a non-smooth evolution equation with viscous regularization

Tobias Geiger (1),

(1) Julius-Maximilians-Universität Würzburg, Würzburg, Germany

We study the optimal control of an evolution equation with non-smooth dissipation, which is close to a rate independent equation. The solution mapping of this system is non-smooth and hence the analysis is quite challenging. Our aim is to find an optimality system and we present two approaches to get such a system. The first one is to regularize the dissipation via approximation by a smooth function. The second one is a time discretization of the state equation. In both cases we get optimality systems for an approximation of the optimal control problem. By passing to the limit we obtain optimality conditions for the original non-smooth problem. Finally, we compare the systems that were derived by the different approaches and show some numerical examples.

Second-order sufficient conditions for optimal control of non-smooth, semilinear equations

Livia Betz (1),

(1) Faculty of Mathematics, University of Duisburg-Essen, Essen, Germany

This talk is concerned with an optimal control problem governed by a semilinear, non-smooth operator differential equation. The nonlinearity is assumed to be only Lipschitz-continuous on bounded sets and directionally differentiable. By employing its limited differentiability properties, Bouligand differentiability of the control-to-state map is shown. This enables us to establish second-order sufficient optimality conditions. The gap between necessary and sufficient conditions turns out to be minimal.



Friday, July 6<sup>th</sup>

## Numerical identification of motor units using an optimal control approach

Anton Schiela (1), Tobias Sproll (1), Madeleine Lowery (2),

(1) Universität Bayreuth, Bayreuth, Germany

(2) University College Dublin, Dublin, Ireland

A numerical approach to locate motor units in human muscles by high density surface EMG measurements is presented. For this purpose a mathematical model has been derived which can be evaluated by finite element computations. On that basis an optimal control problem is specified that can be solved by a function space oriented optimization method. Numerical results are reported for a test problem.

## 79. Variational analysis in optimization (In honor of A.L.Dontchev) 3

14:00 – 15:40

*Chair:* R. Cibulka, F. Aragon

FH HS 3

### Ioffe's regularity criterion in Fréchet spaces

Radek Cibulka (1), Marián Fabian (2),

(1) Department of Mathematics and NTIS, Faculty of Applied Sciences, University of West Bohemia, Pilsen, Czech Republic (2) Mathematical Institute of the Czech Academy of Sciences, Prague, Czech Republic

We present Ioffe's criterion for local surjectivity of mappings between graded Fréchet spaces in the spirit of the well known criterion in Banach spaces [1]. As an application we get "hard inverse mapping theorem" in the flavor of Nash-Moser. The technology of proofs was strongly influenced by a recent paper [2] by I. Ekeland. Main tools used are Ekeland's variational principle, an elementary chain rule for the derivative of a compound mapping, and some easy observations from the basic (first semester) calculus. Contrary to the original proof, we completely avoid using deeper results from Lebesgue integration theory such as Fatou's lemma and Lebesgue's dominated convergence theorem.

[1] R. Cibulka, M. Fabian and A.D. Ioffe. On primal regularity estimates for single-valued mappings. *J. Fixed Point Theory Appl.*, 17(1):187–208, 2015.

[2] I. Ekeland. An inverse function theorem in Fréchet spaces. *Ann. Inst. H. Poincaré Anal. Non Linéaire*, 28(1):91–105, 2011.

Friday, July 6<sup>th</sup>

### Lipschitz stability in discretized optimal control

Asen L. Dontchev (1), Ilya V. Kolmanovsky (2), Mikhail I. Krastanov (3), Marco M. Nicotra (2), Vladimir M. Veliov (4),

(1) Mathematical Reviews and the University of Michigan, USA (2) Dept. of Aerospace Engineering, The University of Michigan, USA (3) Dept. of Probability, Operations research and Statistics Faculty of mathematics and informatics Sofia University, Bulgaria (4) ORCOS, Vienna University of Technology, Vienna, Austria

We consider a control constrained nonlinear optimal control problem with a parameter representing perturbations. Our main assumptions involve smoothness of the functions involved, an integral coercivity condition and a condition that the reference optimal control is an isolated solution of the variational inequality appearing in the maximum principle. We also consider a corresponding discrete-time optimal problem obtained from the continuous-time one by applying the Euler scheme. Based on an enhanced version of Robinson's implicit function theorem, we show that there exists a natural number  $N_0$ , which depends only on the coercivity constant and the Lipschitz constants of the functions involved in the description of the problem and their derivatives around the reference solution, such that if the number  $N$  of discretization steps is greater than  $N_0$ , then the solution mapping of the discrete-time problem has a Lipschitz continuous single-valued localization with respect to the parameter whose Lipschitz constant and the sizes of the neighborhoods do not depend on  $N$ . As an application, we show that for all sufficiently large  $N$  the number of iterations needed for the Newton/SQP method, applied to the discretized problem, to achieve a given accuracy is independent of both  $N$  and small changes of the parameter.

### Separable reduction of local metric regularity

Marián Fabian (1),

(1) Mathematical Institute, Czech Academy of Sciences, Praha, Czech Republic

Let  $X, Y$  be metric spaces,  $X$  complete. We prove that the property of a set-valued mapping  $F : X \rightarrow 2^Y$ , with closed graph, to be locally metrically regular (and consequently, the properties of  $F$  to be linearly open or pseudo-Lipschitz) is separably reducible via a rich family of separable subspaces of  $X \times Y$ . In fact, we prove that, moreover, this extends to computation of the functor  $X \times Y \ni (x, y) \mapsto \text{reg } F(x|y)$ , that associates with  $F$  the rate of local metric regularity at  $(x, y)$ , is separably reducible via a rich family consisting of some separable "rectangles"  $L \times M$  in  $X \times Y$ . The functor  $X \times Y \ni (x, y) \mapsto \text{subreg } F(x|y)$  of subregularity is also separably reducible. The lecture will follow a forthcoming joint paper [1].

[1] M. Fabian, A.D. Ioffe, and J. Revalski. Separable reductions of local metric regularity. *to appear*

### Differential inclusions, regularity of set-valued maps and the Euler method

Elza M. Farkhi (1, 2),

(1) School of Math. Sciences, Tel-Aviv University, Tel Aviv, Israel (2) Institute of Mathematics and Informatics, Bulgarian academy of Sciences, Sofia, Bulgaria

The talk surveys old and new results on approximation of differential inclusions and regularity of set-valued functions. We focus our attention on regularity of set-valued maps, mainly extending the Lipschitz

continuity, from one side, and stability properties of the solutions of differential inclusions and their relation to the Euler discretization scheme, from another. We discuss stability properties that may hold for non-Lipschitz (and even discontinuous) multifunctions determining the differential or difference inclusions, as Filippov-type theorems, exponential formulae, relaxation-type and existence theorems, and approximation estimates.

## 80. Contributed session: economic dynamics 3

14:00 – 15:40

Chair: B. Zou

FH HS 2

### Do Mincerian wage equations inform how schooling influences productivity?

Christian Groth (1), [Jakub Growiec](#) (2, 3),

(1) University of Copenhagen, Denmark (2) SGH Warsaw School of Economics, Poland (3) Narodowy Bank Polski

We study the links between the Mincerian wage equation (the cross-sectional relationship between wages and years of schooling) and the human capital production function (the causal effect of schooling on labor productivity). Based on a stylized Mincerian general equilibrium model with imperfect substitutability across skill types, *ex ante* identical workers, and a complete continuous-time treatment of demographics with finite lifetimes, we demonstrate that the mechanism of compensating wage differentials renders the Mincerian wage equation uninformative for the human capital production function. Proper identification of the human capital production function should take into account the equilibrium allocation of individuals across skill types.

### Path dependence and distributive cycles in a BoPC growth model

[S. Sordi](#) (1), [Marwil J. Dávila-Fernández](#) (1),

(1) Department of Economics and Statistics, University of Siena, Siena, Italy

In a recent contribution ([Davila-Fernandez and Sordi, 2017](#)), we have generalized Goodwin's (1967) model with the purpose of studying the interaction between distributive cycles and international trade in economies in which growth is balance-of-payments constrained (BoPC). Taking this contribution with its 4-dimensional (4D) dynamic system as the starting point, this paper demonstrates that it is possible to reproduce its main results in a 3D set up that considerably simplifies the analysis without compromising the existence of persistent and bounded dynamics. Empirical evidence giving support to the specification adopted for the investment function is provided. We then proceed to investigate the possibility of further bifurcations in a route to more complex behavior. Our most important result lies in providing a simpler base-line model for studying distributive dynamics in open economies that is nevertheless perfectly compatible with complex dynamics and, therefore, with path dependence.

[1] M.J. Dávila-Fernández and S. Sordi. Distributive cycles and endogenous technical change in a BoPC growth model. Working Paper n. 760. Department of Economics and Statistics (submitted to *Economic Modelling*), University of Siena, 2017.

[2] R.M. Goodwin. A growth cycle. In C. Feinstein, ed., *Socialism, Capitalism and Economic Growth*. Cambridge University Press, Cambridge, 1967.

- [3] A.P. Thirlwall. The balance of payments constraint as an explanation of international growth rate differences. *Banca Nazionale del Lavoro Quarterly Review*, 32(128):45-53, 1979.

#### Growth maximizing government size and social capital

Fabio Privileggi (1), Gaetano Carmeci (2), Luciano Mauro (3),

(1) Dept. of Economics and Statistics “Cognetti de Martiis”, Università di Torino, Torino, Italy (2) Dept. of Economics, Business, Mathematics and Statistics “Bruno de Finetti”, Università degli studi di Trieste, Trieste, Italy (3) Dept. of Political and Social Sciences, Università degli studi di Trieste, Trieste, Italy

Our paper intersects two topics in growth theory: the growth maximizing government size and the role of social capital in development. We modify a simple OLG framework by introducing two key features: endogenous growth and a role for public officials in monitoring the public expenditures for intermediate goods and services supplied to private firms. Public officials have the opportunity to steal a fraction of public resources under their own control, subject to a probability of being caught and pay a fine. Hence, not all tax revenues raised by the Government reach private firms, as a fraction of them is being diverted by public officials, thus hampering growth. Under certain conditions on parameters, our main result establishes that, if the probability of detection or the fine charged on public officials who are caught stealing, or both, increase, then an increase of the tax rate is required in order to maintain an optimal growth rate, provided that also the number of public officials is increased as well. As both the probability of detection and the fine positively depend on the Social Capital level, we conclude that maximum growth rates are compatible with Big Government size, measured both in terms of expenditures and public officials, only when associated with high levels of Social Capital.

#### Higher welfare in the decentralized economy with a pollution externality under non-constant discounting

María Pilar Martínez-García (1), Francisco Cabo (2), Guiomar Martín-Herrán (2),

(1) Universidad de Murcia, Murcia, Spain (2) IMUVa, Universidad de Valladolid, Valladolid, Spain

We analyze an endogenous growth model with a pollution externality in the consumers' utility. Assuming non-constant discounting, time-consistent consumers anticipate the behavior of their future selves. For these preferences, the future is relatively more highly valued than under exponential discounting (assuming a same overall impatience). This opens up the possibility for a greater welfare in the market economy setting, which is characterized by a greater growth, since the pollution externality is not internalized. We prove that, for a small pollution externality, this possibility exists under any non-constant discount function. As the harm from pollution increases, this possibility becomes less likely. This result is not sustained in the case of constant discounting. For a specific discount function we analyze the range for the pollution externality compatible with a greater welfare under the market economy. This range depends on the intertemporal elasticity of substitution, the total factor productivity, and the parameter which describes the decay of the instantaneous discount rate with the time distance from the present.

## 81. Dynamic games in economics 2

14:00 – 15:40

Chair: S. Wrzaczek

FH HS 4

## On the influence of exogenous factors on the game theoretic process of resource exploitation

Ekaterina V. Gromova (1), J. Daniel López-Barrientos (2), Ekaterina S. Miroshnichenko (3),

(1) St. Petersburg State University, St. Petersburg, Russia (2) Facultad de Ciencias Actuariales, Universidad Anáhuac México, México (3) Bwin Interactive Entertainment AG, Vienna, Austria

In this work, we analyze an  $n$ -person differential competitive game with random time horizon  $T$  to model the situation of the extraction of a non-renewable resource. We proceed by means of standard dynamic programming arguments to obtain Nash equilibria in the form of feedback controllers and closed formulas for the value functions. We assume that the hazard rate of the so-called random horizon is a  $u$ -shaped function and we compare our results for two cases of general interest in the Risk Theory, namely, the Weibull and Chen distributions, i.e.

$$\lambda(t) = \lambda\delta t^{\delta-1}, \quad (1)$$

and

$$\lambda(t) = \lambda\delta t^{\delta-1} \hat{A} \hat{u} e^{t^\delta}, \quad (2)$$

respectively, where  $\lambda \geq 0$  and  $\delta \geq 0$  are fixed parameters.

Our goal is to show the impact of a priori knowledge on the random variables describing real-life systems of resource extraction.

- [1] E. K. Boukas, A. Haurie and P. Michel, "An Optimal Control Problem with a Random Stopping Time," *Journal of optimization theory and applications*, vol. 64, no. 3, pp. 471–480, 1990.
- [2] Chen, Z. *A new two-parameter lifetime distribution with bathtub shape or increasing failure rate function*. *Statistics & Probability Letters* 49, pp. 155-161, 2000.
- [3] Dockner, E.J., Jorgensen, S., N. van Long, Sorger, G. *Differential Games in Economics and Management Science*. Cambridge University Press, 2000.
- [4] E. Gromova and Anna Tur, On the form of integral payoff in differential games with random duration, 2017. DOI: 10.1109/ICAT.2017.8171597.
- [5] J. Marin-Solano and E. V. Shevkopyas, "Non-constant discounting and differential games with random time horizon", *Automatica*, vol. 47, no. 12, pp. 2626–2638, 2011.
- [6] L. A. Petrosjan and N. V. Murzov, "Game-theoretic problems of mechanics", *Litovsk. Mat. Sb.* 6, pp. 423–433, 1966 (in Russian).
- [7] Weibull, W. (1951) *A statistical distribution function of wide applicability*, *J. Appl. Mech. Trans. ASME O.* 18 (3): 293-297.
- [8] M. E. Yaari, "Uncertain Lifetime, Life Insurance, and the Theory of the Consumer", *The Review of Economic Studies*, vol. 32, no. 2, pp. 137–150, 1965.

## How optimal control may avoid chaotic dynamics: market inefficiency in asymmetric multi-modal differential games

Anton A. Bondarev (1),

(1) Department of Business and Economics, University of Basel, Basel, Switzerland

In this paper I study the potential consequences of the combined multi-modality and asymmetry for dynamic games. It turns out that once the asymmetry in payoffs or investment strategies across varying leaders in the game is sufficiently high, the game at hand may exhibit the so-called non-deterministic chaotic behavior, leading to the fully unpredictable behavior. Still if one considers the optimal program

for the social planner, this dynamics can be sometime avoided because of aggregation and the resulting lower dimensionality of the cooperative outcome. Moreover it is demonstrated, that for a certain simple class of games the cooperative solution is topologically equivalent with respect to the increase in the number of players, whereas the decentralized solution is not.

I explore what structures are necessary to be included into the model to observe this non-deterministic chaos and other types of complex behavior on the example of the R&D game with spillovers and imitation. It turns out that while mathematically this type of dynamics appears to be generic for at least 3-dimensional systems, economic structure has to be very specific. In this case the fully centralized regulation appears to be necessary whereas in simpler cases it still can be limited to conventional subsidies.

### Microfoundation of oligopolistic models and potential games

Luca Lambertini (1,2), [Arsen Palestini](#) (3),

(1) Department of Economics, University of Bologna, Bologna, Italy (2) ENCORE, University of Amsterdam, Amsterdam, The Netherlands (3) Sapienza University of Rome, Rome, Italy

The relationship between the derivation of an aggregate demand for a market and the structure of the resulting static oligopolistic game is investigated. In particular, we study the connection between the properties of the representative consumer's utility function and the existence of (i) a *potential function* in the ensuing oligopoly game, as in Monderer and Shapley [1], and (ii) a *best-response potential function*, as in Voorneveld [2]. In particular, we establish a necessary condition for the existence of either the potential or the best-response potential function and illustrate a number of different applications based on the most commonly used utility functions.

[1] Monderer, D., Shapley, L. S. (1996). Potential games, *Games and Economic Behavior*, 14(1), 124-143.

[2] Voorneveld, M. (2000). Best-response potential games, *Economics Letters*, 66(3), 289-295.

### Linear quadratic game of exploitation of common renewable resources with inherent constraints

Rajani Singh (1), [Agnieszka Wiszniewska-Matyszek](#) (1),

(1) Institute of Applied Mathematics and Mechanics, University of Warsaw, Warsaw, Poland

In this paper, we analyse a linear quadratic multistage game of extraction of a common renewable resource—fishery—by many players with inherent state dependent constraints for exploitation (a player cannot extract more than available) and infinite time horizon.

The game is defined such that increasing number of players does not mean introduction of additional users of the resource, but decomposition of the decision making structure of the same mass of users (into regions, countries, firms).

We analyse the social optimum and symmetric Nash equilibrium for feedback information structure. The social optima can be calculated for arbitrary number of players, while the Nash equilibrium can be computed only for the continuum of players case, for which we obtain piecewise linear equilibrium with value function contrary to intuitions from standard linear quadratic games: nonsmooth and non-monotone, piecewise quadratic with infinitely many intervals [1]. For finitely many players, a negative result can be proven, that the equilibrium cannot be of assumed regularity [1]. Further research suggests possibility

of only discontinuous Nash equilibria—a finite horizon truncation of this game has only discontinuous symmetric Nash equilibria ([2]).

In our games, the social optimum is sustainable, while the Nash equilibrium leads to depletion of the fishery in finite time for realistic levels of initial biomass of fish. Therefore, we also study introduction of a tax in order to enforce socially optimal behaviour of the players.

Besides, this model constitutes a counterexample to simplifications of techniques often used in computation of Nash equilibrium and/or optimal control—during the process of computation of the social optimum, we have discovered that the resulting dynamic optimization problem constitutes a counterexample to correctness of skipping or relaxation of checking terminal condition—a simplification often used in applications.

- [1] R. Singh, A. Wiszniewska-Matyskiel. *Linear quadratic game of exploitation of common renewable resources with inherent constraints*, Topological Methods in Nonlinear Analysis, DOI: 10.12775/TMNA.2017.057, 2018.
- [2] R. Singh, A. Wiszniewska-Matyskiel. *Discontinuous Nash Equilibria in a Finite Horizon Linear-Quadratic Dynamic Game with Linear Constraints*, submitted to IEEE Transactions on Automatic Control, 2018.

## 82. Sub-optimal solutions in games and control 2

16:00 – 17:40

Chair: Y. Averboukh, D. Gromov

FH HS 7

Impulsive continuity equations and quasi-solutions of ensemble control problems involving elastic collision

Nikolay V. Pogodaev (1), Maxim V. Staritsyn (1),

(1) Matrosov Institute for System Dynamics and Control Theory, SB RAS, Irkutsk, Russia

The talk comes across the control continuity equation

$$\mu_0 = \vartheta; \quad \partial_t \mu_t + \nabla \cdot (\mu_t f_t) = 0, \quad t \in \mathcal{T} \doteq [0, T], \quad (1)$$

driven by input-affine vector fields  $t \mapsto f_t(x) \doteq f(x, u(t))$ ,  $x \in \mathbb{R}^n$ ,  $f(x, u) = g(x) + H(x)u$ , where  $g, H : \mathbb{R}^n \mapsto \mathbb{R}^n, \mathbb{R}^{n \times m}$  are sufficiently regular functions, and  $\vartheta$  is a fixed probability measure on  $\mathbb{R}^n$ . We assume no geometric constraints on control  $u \in L_\infty(\mathcal{T}, \mathbb{R}^m)$ , instead,

$$\|u\|_{L_1(\mathcal{T}, \mathbb{R}^m)} = M \quad (2)$$

with given  $M > 0$ . As one observes, the arcs  $t \mapsto \mu_t$  may somehow tend to discontinuous measure-valued functions, which implies that the tube  $\mathbb{X}$  of solutions to (1), (2) is not compact in the natural topology, and related optimal control problems are typically ill-posed. In the talk, we present the notion of generalized (discontinuous) solution to (1), (2), which brings a compactification of  $\mathbb{X}$ , and elaborate its representation through a measure differential equation. We discuss a connection of system (1), (2) with problems of ensemble control under elastic collision: as a typical case, we suggest a model of a cart carrying a probability distribution (e.g. a hillock of sand or a piece of pudding) as it hits on the wall. Finally, we raise some connected optimization issues, and present a numeric implementation of approximate (sub-optimal) solutions for certain relevant examples.

Friday, July 6<sup>th</sup>

## Quasi-solutions of complementarity systems with measures and related mixed-constrained optimal impulsive control problems

Maxim V. Staritsyn (1),

(1) Matrosov Institute for System Dynamics and Control Theory, SB RAS, Irkutsk, Russia

The talk addresses a nonlinear measure differential equation subject to an abstract relation between one-sided limits of its states:

$$(CS) \quad \begin{cases} dx(t) = f(x(t)) dt + G(x(t)) \mu(dt), & t \in \mathcal{T} \doteq [0, T], \\ |\mu|(\mathcal{T}) \leq M, \\ (x(\tau^-), x(\tau)) \in \mathcal{Z} \quad |\mu|\text{-a.e. on } \mathcal{T}, \end{cases}$$

with given  $T, M > 0$ , vector- and matrix functions  $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$  and  $G : \mathbb{R}^n \rightarrow \mathbb{R}^{n \times m}$  of sufficient regularity, and a closed set  $\mathcal{Z} \subseteq \mathbb{R}^n \times \mathbb{R}^n$ ;  $\mu$  is an  $\mathbb{R}^n$ -valued Borel measure with the total variation  $|\mu|$ , and  $x(t^-)$  stands for the left one-sided limit of a function  $x : \mathcal{T} \rightarrow \mathbb{R}^n$  at a point  $t$  (states are supposed to be right continuous). Depending on the context,  $\mu$  plays the part of either the impulsive control or a slack variable (e.g., a complementary force of the media in contact dynamics).

Simple examples show that ordinary control processes, produced by absolutely continuous measures  $\mu_{ac}$ , are not quasi-solutions of (CS) in the natural, naive sense. We propose an alternative notion of  $\varepsilon$ -solution involving a pair of ‘‘comparison’’ processes being perturbations of the reference one in the weak\* topology of  $BV$ . We invent that the limit of the tube of quasi-solutions as  $\varepsilon \rightarrow 0$  is a relaxation of (CS), which can be constructively described by a specific time-space transform. Finally, we state an optimal control problem for the relaxed complementarity system and prove the existence of a minimizer.

## Near-optimal strategies in Lion and Man game

Olga O. Yufereva (1),

(1) Krasovskii Institute of Mathematics and Mechanics, Yekaterinburg, Russia

Lion and Man game is a two-person pursuit-evasion game with the restriction on the players’ speeds: they have the same top speed. We also suppose that both players know their current positions. We consider this game in compact metric spaces (extending notion of ‘speed’ restriction if it is needed) and non-anticipative strategies leading to capture with a positive, fixed in advance radius.

The report will be about pursuer’s winning strategies in ‘similar’ spaces. In particular, we will consider how can the pursuer win in a space  $Y$  that is an approximation of a space  $X$  if he has a winning strategy in the space  $X$ . It means that some errors in awareness of players’ positions and some errors in control are permissible. To compare metric compact spaces we use Gromov–Hausdorff distance. Moreover, this approach allows us to relate conditions of successful pursuit in different similar spaces. E.g., we can deal both with a sequence of finite graphs, which are much easier to use, and with the space, which is the limit of this sequence.

This study was supported by the Russian Science Foundation (project no. 17-11-01093).



**On differential games with random time horizon and a hybrid probability distribution**

Ekaterina V. Gromova (1,2), Anastasiya Malakhova (1), Dmitry Gromov (1,2),

(1) St. Petersburg State University, Saint Petersburg, Russia (2) Krasovskii Institute of Mathematics and Mechanics, Yekaterinburg, Russia

When considering cooperative differential games it is natural to assume that the duration of the game is not fixed *a priori*, but represented by a random variable with given probability distribution function (p.d.f.) [1]. However, in most cases the respective p.d.f. either cannot be described analytically or is too complicated to be dealt with. One possible approach consists in substituting the initial p.d.f. with an approximating one. This leads to a hybrid differential game formulation as discussed in [2,3]. In this contribution we consider several particular classes of hybrid games arising in the described context with particular emphasis on determining Nash equilibrium solutions.

- [1] Petrosyan L.A., Shevkopyas E.V. Cooperative differential games with random duration. *Vestnik of St. Petersburg State University*, Series 10, 4:18-23, 2000.
- [2] Gromov D., Gromova E.V. Differential Games with Random Duration: A Hybrid Systems Formulation. *Contributions to Game Theory and Management*, 7:104-119, 2014.
- [3] Gromov, D. Gromova, E. On a Class of Hybrid Differential Games. *Dynamic Games and Applications*. 7(2):266-288, 2017.

**83. Contributed session: dynamic games 2**

**16:00 – 17:40**

*Chair: M. Gusev*

**FH 8 Nöbauer HS**

**Game theory with information: Witsenhausen intrinsic model**

Michel De Lara (1), Daniel Kadnikov (1), Jean-Philippe Chancelier (1),

(1) CERMICS, École des Ponts ParisTech, France

In a context of competition, information – who knows what and before whom – plays a crucial role. Here, we concentrate on three models where the concept of information is present: Kuhn’s extensive tree model (K-model), Alos-Ferrer, Ritzberger infinite tree model (AFR-model) and Witsenhausen model (W-model).

In the extensive form model, Kuhn uses the language of graph theory to define four main ingredients of the game: players, game tree, information sets and strategies. The infinite tree AFR-model, as implied by its name, generalizes K-model with its finite tree to any tree, bet it infinite (repeated games), transfinite (long cheap talk) and even continuous (stochastic and differential games). To handle infinite trees, Alos-Ferrer and Ritzberger use the language of set theory (posets), elaborating the most general framework to describe tree structures in games existing up to now.

The model proposed by Witsenhausen has the following main ingredients: a set of agents taking their decisions from a measurable decision space; Nature taking values in a measurable sample space; configuration space which is the product of the decision spaces by the sample space; information fields that are sigma-fields on the configuration space; strategies that are mappings from configurations to decisions which are measurable w.r.t. information fields. W-model deals with information in all generality. For

example, it allows to look at a problem without a priori knowing the order in which decisions were made by agents. In the subclass made of causal systems, there is at least one ordering in which agents take their decisions consistently with the given information sigma-fields.

We study whether AFR and W-models have the same potential to model games. First, we embed the subclass of causal W-models into the AFR-formalism by building an AFR-tree and translating definitions of information and strategies from W-formalism to AFR-formalism. Second, we sketch the move in the opposite direction.

- [1] H. S. Witsenhausen. The Intrinsic Model for Discrete Stochastic Control: Some Open Problems. In *Control Theory, Numerical Methods and Computer Systems Modelling*, A. Bensoussan and J. L. Lions editors, Springer, vol. 107, 322–335, 1975.
- [2] C. Alos Ferrer, K. Ritzberger. *The Theory of Extensive Form Games*. Springer, Heidelberg, 2016.

### Zero-sum linear-quadratic differential game: gradient techniques

Oleg Kelis (1), Aviv Gibali (2),

(1) Technion, Israel Institute of Technology, Haifa, Israel (2) Ort Braude College of Engineering, Karmiel, Israel

In this study we focus in a zero-sum linear-quadratic differential game. One of the main features of such a game is that the weight matrix of the minimizer’s control cost in the cost functional is singular. Due to this singularity, the game cannot be solved either by applying the Isaacs MinMax principle e.g. [1], or the Bellman-Isaacs equation approach e.g. [2]. In e.g. [3] such a game was analyzed with so-called regularization approach in the case where the weighting matrix of the minimizer’s control cost equals zero. In an earlier result e.g. [4], O. Kelis, studied and analyzed a game in which the weight matrix of the minimizer’s control cost has more general singular form than in e.g. [3] also using the regularization approach. In the present work we introduce a slightly more general case of the weight matrix of the minimizer’s control cost than in e.g. [4]. This means that only a part of coordinates of the minimizer’s control is singular, while the rest of coordinates are regular. As application we introduce a pursuit-evasion differential game and we propose two gradient methods, the Arrow-Hurwicz-Uzawa and the Korpelevich methods, for solving this game. We present numerical illustrations demonstrating the iterative procedures performances.

- [1] R. Isaacs. *Differential games*. John Wiley and Sons, New York, 1967.
- [2] N.N. Krasovskii, A. I. Subbotin. *Game-theoretical control problems*. Springer, New York, Verlag, 1988.
- [3] J. Shinar, V.Y. Glizer, V. Turetsky. Solution of a singular zero-sum linear-quadratic differential game by regularization. *International Game Theory Review*, 16(2):1440007-1–1440007-32, 2014.
- [4] V.Y. Glizer and O. Kelis. Solution of a zero-sum linear-quadratic differential game with singular control cost of minimizer. *Journal of Control and Decision*, 2(3):155–184, 2015.

Friday, July 6<sup>th</sup>

## Group pursuit

Meir Pachter (1),

(1) Air Force Institute of Technology, Wright-Patterson A.F.B., USA

We consider pursuit-evasion differential games in the Euclidean plane where an evader is engaged by multiple pursuers and point capture is required. All the players have simple motion a la Isaacs but at least one of the pursuers is faster than the evader. We first revisit Isaacs' "Two Cutters and a Fugitive Ship" pursuit-evasion differential game in the Euclidean plane where two pursuers, say cutters, chase a fugitive ship. All move with simple motion, the speeds of the cutters each being greater than that of the fugitive ship, the evader. Coincidence with either one, or both pursuers, is capture, and time of capture is the payoff/cost. It is shown that group/swarm pursuit is fundamentally shaped by two critical pursuers and sometimes by just one critical pursuer, and this irrespective of the size N of the pursuit pack. Thus, the pursuit devolves into pure pursuit by one of the players or into a pincer movement maneuver by two players who engage the evader, a menage a trois. The critical pursuers are identified, state feedback optimal strategies are synthesized and the Value of the game is derived.

## 84. Variational analysis in optimization (In honor of A.L.Dontchev) 4 16:00 – 17:40

*Chair:* R. Cibulka, F. Aragon

FH HS 3

### Variational analysis and optimal control

Alexander Ioffe (1),

(1) Technion, Israel Institute of Technology, Haifa, Israel

The purpose of the talk is to briefly discuss a program of research aimed at development of a new approach to (in principle all chapters of) optimal control theory based on ideas coming from the theory of metric regularity. One of the main elements of this approach is associated with the study of unconstrained minimization problems for functions of the form

$$\int_0^T L(t, x(t), \dot{x}(t), u(t))dt + \max_{t \in [0, T]} g(t, x(t)) + \ell(x(0), x(T))$$

with  $L$ ,  $g$  and  $\ell$  generally non-differentiable but satisfying certain Lipschitz properties as functions of  $x$ ,  $\dot{x}$ ,  $u$ . By now the part of the theory related to the first order conditions (maximum principle) is basically completed but extensions of the second order theory and Hamilton-Jacobi theory to such functionals are still to be developed.

### On a Bolza problem

Mikhail I. Krastanov (1, 2), Nadezhda K. Ribarska (1, 2),

(1) Faculty of Mathematics and Informatics, Sofia University, Sofia, Bulgaria (2) Institute of Mathematics and Informatics, Bulgarian Academy of Sciences, Sofia, Bulgaria

The classical problem of the calculus of variations is studied under the assumption that the integrand is a continuous function. A non-smooth variant of the classical du Bois-Raymond lemma is presented. Under suitable additional assumptions, a non-smooth version of the classical Euler equation is proved.

- [1] M. Bivas, M. Krastanov, N. Ribarska, On tangential transversality, preprint, 2018.
- [2] M. Bivas, M. Krastanov, N. Ribarska, On strong tangential transversality, preprint, 2018.
- [3] M. Krastanov and N. Ribarska, A functional analytic approach to a Bolza problem, to appear.

### Nearness condition for set-valued mappings

Michel A. Théra (1,2), Annamaria Barbagallo (3), Emil Ernst (4),

(1) University of Limoges, France (2) Federation University, Australia (3) University of Naples “Federico II”, Naples, Italy (4) Institut de Mathématiques de Marseille, I2M UMR 7373, University of Marseille, France

The theory of nearness between operators acting on Banach spaces has been presented and developed by S. Campanato at the end of the eighties (see e.g. [1]) in order to study existence and regularity results for some differential elliptic equations. The aim of the talk is to introduce a concept of nearness between set-valued mappings, extending the well-known definition by S. Campanato. In particular, given two set-valued mappings  $A, B : X \rightrightarrows Y$ , we consider a compatible set-valued mapping, namely a set-valued mapping  $T : X \rightrightarrows Y$  such that

1. for every  $x \in X$  and every  $y \in B(x)$

$$T(y) \cap A(x) \neq \emptyset,$$

2. for every  $x \in X$

$$\bigcup_{y \in B(x)} T(y) \supset A(x).$$

We say that  $A$  is *near*  $B$  if there exist a compatible set-valued mapping  $T : Y \rightrightarrows Y$  and two positive constants  $\alpha$  and  $k$  with  $0 < k < 1$  such that for every  $s_A$  selection of  $A$  and every  $s_B$  selection of  $B$  satisfying:

$$s_A(x) \in T(s_B(x)), \quad \forall x \in X,$$

$s_A$  is near in Campanato sense  $s_B$  with constants  $\alpha$  and  $k$ . After that we investigate which properties of set-valued mappings are preserved by nearness. Moreover, we discuss some examples and deduce that the surjectivity and the bijectivity properties are preserved with some additional conditions on the set-valued mappings. Such remarks leave some open questions which will give new research ideas.

- [1] S. Campanato, *On the condition of nearness between operators*, Ann. Mat. Pura Appl. (4), vol. 167, pp. 243–256, (1994).

### Existence and purification of variational problems

Toru Maruyama (1),

(1) Dep. Economics, Keio University, Tokyo, Japan

A triple of simple variational problems are compared. We prove the existence of solutions for each of the problems. And then, some relationships between the optimized values of the problems are examined. The problem is reformulated in terms of Young measures, the topological and geometric properties of which play effective roles.

### 85. Contributed session: economic dynamics 4

16:00 – 17:40

*Chair:* J. Haunschmied

FH HS 2

### Corporate cheating under nonlinear reputation dynamics

Markus Eigruber (1),

(1) University of Vienna, Faculty of Business, Economics and Statistics, Chair of Industry, Energy and Environment, Vienna, Austria

Reputation is a critical measure of trust for agents as well as a valuable asset for corporations. Generally, firms recognize this fact and focus on taking actions that increase their respective image, which is well researched in the literature on advertising for goodwill. However, some real world cases point to the fact that firms are sometimes also willing to trade off their reputation for increased profits through deceptive behavior. In this paper, we want to model these decisions by exploring the situation of a monopoly facing this tradeoff over an infinite horizon. We model the social effects of cheating via a well known nonlinear dynamic of ecological economics, the shallow lake equation. By the means of a phase diagram as well as bifurcation analysis we find that the enfolding dynamics are similar to the problems of optimal resource extraction with a tipping point, i.e. the existence of multiple steady states and the possibility for a Skiba point.

### Innovation investment with financial constraint

Herbert Dawid (1), Xingang Wen (1),

(1) Department of Business Administration and Economics, Bielefeld University, Bielefeld, Germany

This paper presents a dynamic model of a firm which can invest in technology to produce a new product (a partial substitute for the current old product) with uncertain demand. The product innovation success enables the firm to be active in both markets. A financial constraint is introduced such that a firm with negative liquidity has to exit the market with a certain probability if it cannot service its debt. Liquidity evolves over time based on the profit on the established market net of dividends, as well as the costly R&D investment and interest payments. A numerical method is used to calculate the firm's value functions in different modes (pre- and post-innovation) and states (positive and negative liquidity), taking into consideration the mode and state transitions. Moreover, the paper analyzes the firm's optimal investment and the influence of financial constraint on the firm's dynamics.

Friday, July 6<sup>th</sup>

### On dynamics in a Keynesian model of monetary and fiscal stabilization policy mix with twin debt accumulation

Rudolf Zimka (1), Toichiro Asada (2), Michal Demetrian (3),

(1) Faculty of Economics, Matej Bel University in Banská Bystrica, Slovakia (2) Faculty of Economic, Chuo University, Tokyo, Japan (3) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia

In this contribution, a six-dimensional model of flexible prices with the monetary and fiscal policy mix, describing the development of the firms' private debt, the output, the expected rate of inflation, the rate of interest, government expenditure, and government bonds is analyzed. The stress put on the "twin debt accumulation" means that in the model both private debt accumulation and the public debt (government bond) accumulation are explicitly introduced. Questions concerning the existence of limit cycles around its normal equilibrium point are rigorously investigated. The bifurcation equation of the model is derived. In the structure of the model an important role plays so called the "credibility" parameter  $\xi$ ,  $0 < \xi < 1$ , that measures the "degree of credibility" of the central banks inflation targeting in the eyes of the public. It is shown that a decrease in the value of the credibility parameter  $\xi$  causes both an enlargement of a business cycle and an increase in the speed at which solutions approach this business cycle. This means that smaller values of the "credibility" parameter  $\xi$  have a destabilizing effect, its larger values have a stabilizing effect. Numerical examples illustrate the gained results..

### 86. Regime change modeling in economics and finance

16:00 – 17:40

*Chair:* W. Semmler, M. Gross

FH HS 4

### Inflation-deflation expectations and economic stability in a Kaleckian system

Toichiro Asada (1), Hiroki Murakami (1),

(1) Faculty of Economics, Chuo University, Hachioji, Tokyo, Japan

In this paper, we analyze the impact of inflation-deflation expectations and the effect of the monetary authority's inflation-targeting policy in a Kaleckian system, on the basis of macro-foundation approaches. For this purpose, we build a dynamical system composed of four variables (the rate of utilization, the wage share, the nominal rate of interest and the expected rate of inflation) and examine the properties, especially stability, of this dynamical system. We then find that the existence of (adaptive) inflation-deflation expectations always destabilizes our Kaleckian system (irrespective of the revision speed of expectations) while that the monetary authority's intensive inflation-targeting policy can make the system stable but the effect of this policy depends heavily upon the public credibility of it. We also perform numerical simulations to check that our analysis is valid.

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### Macroprudential analysis with the Eurace@BiECB model

Marco Gross (1), Björn Hilberg (1), Sander van der Hoog (2), Dirk Kohlweyer (2),

(1) European Central Bank, Frankfurt, Germany (2) Bielefeld University, Bielefeld, Germany

We develop an Agent-Based Model (ABM) for the euro area that can be used to conduct macroprudential policy analyses, specifically to assess the effects of capital- and borrower-based macroprudential instruments in one integrated micro-founded model framework. We calibrate the ABM with data for the euro area, its member states, its households, and banks; involving a large-scale household survey-based micro dataset, bank balance sheet data and macroeconomic statistics to mirror the real world cross-section dimensions of the euro area's household, firm, bank and central bank universe in the model. The novel features of the ABM we develop pertain in particular to the banking system structure, the mortgage loan market and the housing market dynamics.

### Financial frictions and housing collateral constraints in a macro model with heuristics

Corrado Macchiarelli (1), Paul De Grauwe (1),

(1) Brunel University London, London, UK (2) London School of Economics, London, UK

The role of household debt in the real activity has attracted considerable attention recently mostly in the light of the observed increases in property prices and the increase of household indebtedness prior to the 2008 bust in many countries. The relevant literature on housing points to a number of the mechanism being likely to trigger or amplify real estate cycles (including bubbles). We focus on the interaction between banks and real estate developments, in particular assessing the implications of changing property prices on consumption decisions. We build on a previously described framework to introduce a real estate sector, accounting in itself for an explicit balance sheet dimension for consumers. The model thus results in an economy where - on the demand side - a collateral constraint limits households ability to borrow against the value of real estate, and - on the supply side - loan supply is constrained by bank capital. This allows studying the interactions of these two limits by drawing a stark distinction between the supply and demand for credit. While lending constraints are not a new feature of this framework, we take a step further and analyse the implications of lending constraints in a bounded rationality framework, proposing an extension of the model in De Grauwe and Macchiarelli (2015). Together with considering bounded rationality rules, the model features an endogenous mechanism for describing the probability distribution of housing bubbles.

### Portfolio sector bias in the energy sector

Ibrahim Tahri (1),

(1) Potsdam Institute for Climate Impact Research, Potsdam, Germany

A potential motive behind investors' preference for holding fossil fuel assets over renewable energy (RE) assets might stem from an asymmetry of information vis-à-vis RE potential payoffs or/and simply an underestimation of the risks of future fossil fuel returns, which also suggests that there might exist a portfolio bias toward fossil fuel sectors. Not well diversified portfolios can expose investors to unnecessary

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idiosyncratic risks. An established and intuitive potential justification for such puzzle is information asymmetry among investors. Such concentration in portfolios can be explained through a combined learning-investment model. A key characteristic in this type of models is the role of endogenous information choice, where thanks to some general equilibrium forces there are increasing returns to information, which in turn leads to full specialization in learning. As the holdings of the asset increase, the marginal benefit of an additional unit of information on that asset is greater. In this paper, we attempt to provide a theoretical support to describe the potential presence of sector equity bias in the portfolio choice in the energy sector. For this purpose, we rely on a new strand of literature which combines information theory to portfolio choice theory in order to explain the portfolio home equity bias.



Poster Session, Thursday, July 5<sup>th</sup>

87. Poster session

13:15 – 14:00

Freihaus, 2<sup>nd</sup> Floor

Dynamic games in closed-loop supply chains: government's perspective and firms' perspective in e-scrap industry

I-Hsuan Hong (1), Wen-Chih Chen (2),

(1) Institute of Industrial Engineering, National Taiwan University, Taipei, Taiwan (2) Department of Industrial Engineering and Management, National Chiao Tung University, Hsinchu, Taiwan

We discuss main ideas of dynamic games and are using them in closed-loop supply chains applications: advanced recycling fee (ARF) and subsidy fee determination in a government's perspective and recycling option in a firm's perspective. In a government's perspective, we present a Stackelberg-type model to determine ARFs and socially optimal subsidy fees in decentralized reverse supply chains where each entity independently acts according to its own interests. In a firm's perspective, we propose a retailer collection model whereby the retailer collects end-of-life products and the manufacturer cooperates with a third-party firm to handle used products, and a non-retailer collection model whereby a third-party firm is subcontracted by the manufacturer for collection work.

Pricing renewable identification numbers (RINs) under uncertainty

Hamed Ghoddusi (1), Mohamad Afkhami (1),

(1) School of Business, Stevens Institute of Technology, Hoboken, USA

We offer a novel modeling framework to determine the price dynamics of renewable identification numbers (RINs), a *floor-and-trade* market-based mechanism for enforcing renewable energy standards. Our inter-temporal modeling approach is different than the usual practice which prices RINs in a static way. Using a continuous-time stochastic control formulation, we explicitly model the option value embedded in the RINs prices as an American spread option, given the institutional constraints of the US market. We derive a closed-form solution of the RINs prices when underlying commodity prices are geometric Brownian motion. We also characterize the solution for setups with mean-reverting and jump specifications for the underlying prices, which need to be solved numerically. We propose a tight numerical approximation using duality methods. Among other results, we show that the price of RINs has a U-shape relationship with the volatility of ethanol and gasoline prices and a *negative* relationship with the correlation between the two price processes. We also show that once one of the underlying prices experiences high volatility, RIN prices converge to a fixed level irrespective of the other underlying dynamic's volatility. The analytic framework can be used to model the dynamics of certificate prices in other markets with similar mechanisms (especially environmental service markets).

**On the frequency of adjustment in impulse control problems**

Hamed Ghoddusi (1), Julia Eisenberg (2),

(1) School of Business, Stevens Institute of Technology, USA (2) Department of Mathematical Science, University of Liverpool, Liverpool, UK

Consider a typical impulse control problem (e.g. a menu-cost model) with fixed adjustment costs and a (s-S)-type optimal adjustment policy. How would an increase in the uncertainty of the environment (e.g. the volatility of the underlying process) affect the frequency of lumpy adjustments? For example, in the case of menu-costs [1] suggests that if the volatility of inflation process increases, the frequency of adjusting prices in a menu-cost model increases too. We provide a general model for the expected frequency of hitting the lower and upper boundaries and show that the previous result is driven by a very particular choice of the drift and volatility for the underlying Brownian motion. If the inflation process is modeled as a Brownian motion with an arbitrary drift (especially one corresponding to a GBM with a zero drift), the result will change: the steady-state frequency of upward adjustment will increase but the frequency of downward adjustments will indeed go down. The intuition is based on results offered by [2]: when the volatility of a bounded (from below) Markov process increases, the likelihood of hitting an upper bound first increase and then decrease.

[1] H Per Svejstrup. Frequent price changes under menu costs. *Journal of Economic Dynamics and Control*, 23(7):1065-1076, 1999.

[2] H Ghoddusi and A Fahim. Volatility can be detrimental to option values!. *Economics Letters*, 149:5–9, 2016.

**On the optimal labor income share**

Jakub Growiec (1, 2), Peter McAdam (3), Jakub Mućk (1, 2),

(1) SGH Warsaw School of Economics, Poland (2) Narodowy Bank Polski, Poland (3) European Central Bank, Frankfurt am Main, Germany

Labor's share of income has attracted interest in recent years reflecting its apparent decline. These falls, witnessed across many countries, are usually deemed undesirable. Any such assertion, however, begs the question of what is the socially optimal labor share. We address this question using a micro-founded endogenous growth model calibrated on US data. We find that in our central calibration the socially optimal labor share is 17% (11 pp) above the decentralized equilibrium, calibrated to match the average observed in history. We also study the dependence of both long-run growth equilibria on model parameters and relate our results to Piketty's "Laws of Capitalism". Finally, we demonstrate that cyclical movements in factor income shares are socially optimal and that the decentralized equilibrium typically does not generate excess volatility.

### The digital era, viewed from a perspective of millennia of economic growth

Jakub Growiec (1),

(1) SGH Warsaw School of Economics & Narodowy Bank Polski

I propose a synthetic theory of economic growth and technological progress over the entire human history. Based on this theory as well as on the analogies with three previous eras (the hunter-gatherer era, the agricultural era and the industrial era) and the technological revolutions which initiated them, I draw conclusions for the contemporary digital era. I argue that each opening of a new era adds a new, previously inactive dimension of economic development, and redefines the key inputs and output of the production process. Economic growth accelerates across the consecutive eras, but there are also big shifts in factor shares and inequality. The two key inputs to the digital-era production process are hardware and software. Human skilled labor is complementary to hardware and substitutable with software, which increasingly includes sophisticated artificial intelligence (AI) technologies. I also argue that economists have not yet designed sufficient measurement tools, economic policies and institutions appropriate for the digital-era economy.

### Mean field game of controls: variational structure and finite version

J. Frédéric Bonnans (1), Saeed Hadikhanloo (1), Laurent Pfeiffer (2),

(1) CMAP, Ecole Polytechnique, CNRS, Université Paris Saclay, and Inria, France (2) Institute of Mathematics and Scientific Computing, University of Graz, Graz, Austria

Mean field games (MFGs) are a class of models that describe the Nash equilibria in the dynamic games when the number of players tends to infinity. These class of models were introduced by seminal works of Lasry and Lions in [1]. In the original form of MFGs, there are infinite number of infinitesimal players; each of them solves an optimal control problem that includes the distribution of the states of other players as an input. Instead, in the models of Mean Field Games of Controls (MFGC), we deal with a problems that the dependency is also through the distribution of controls. These type of models naturally appears in the economical applications of the theory: suppose there is a market with huge number of traders, each of them is optimizing its buying/selling strategy as a function of price. The price at equilibrium, is endogenous and it is not determined by the distribution of states (or stock levels), but rather with the distribution of controls (or purchasing/selling rates) that captures the net demand.

[1] J.-M. Lasry and P.-L. Lions. Mean Field games. *Japanese journal of mathematics*, 2(1):229–260, 2007.

### Switching barriers in advertising competition

Dominika Machowska (1),

(1) Department of Econometrics, Faculty of Economics and Sociology, University of Łódź, Poland

The paper focuses on the consequences of the presence of switching barriers in the competitive market on which companies use offensive and defensive advertising as tools to enhance and protect their market share. We extend the Lanchester model by incorporating several significant factors from the economic point of view. First, the switching barriers are incorporated, for the first time, into this type of the model

describing competitive behaviour. Next, the assumption about a growing market allows us to analyse the competition via offensive advertising for a potential market. Third, it is assumed, in contrast to previous studies, that the market share in the absence of advertising efforts declines. Thus, the decay rate is incorporated into the new model. Finally, the companies' profit depends on the discount rate and on the positive salvage value. The paper studies a differential game played over a finite horizon and provides closed-form expressions for the feedback Nash equilibrium. Additionally, the sensitivity of these equilibria is analysed. The results show how the combination of competition and switching barriers has a relevant influence on the policies of the companies under the assumption that the market share declines without advertising.

#### **The effects of technological shocks in an optimal goodwill model with a random product life cycle**

Mariuz Górajski (1), Dominika Machowska (1),

(1) Department of Econometrics, Faculty of Economics and Sociology, University of Lodz, Lodz, Poland

We consider the optimal goodwill control problem in a segmented market where the length of the product life cycle is affected by unpredictable technological turbulence. In order to maximize profit over a random time horizon, a company controls the marketing efforts directed to each market segment. Assuming an exponential distribution for the product life cycle, we modify the optimal goodwill model into the infinite time horizon control problem. Based on the semigroup approach, we prove the existence and uniqueness of the optimal solution. We formulate optimality conditions for the problem and we prove the existence of a stationary long-run equilibrium. Next, we construct a numerical algorithm to find the optimal solution. Finally, we examine several scenarios of optimal marketing strategies.

#### **On the mathematical analysis of the model of antibiotic resistant bacteria and the immune cells**

Imene Meriem Mostefaoui (1,2), Ali Moussaoui (2),

(1) Ecole Supérieure en Génie Electrique et Energétique d'Oran, Algeria (2) Laboratoire D'Analyse Non Linéaire et Mathématiques Appliquées, Université de Tlemcen, Algeria

Currently, WHO (World Health Organization) report confirms that the antibiotic-resistant infections are the greatest threat to health. Despite the new therapeutic strategies, the bacteria develop mechanisms to defend themselves against antibiotics. In this topic, we propose a mathematical model describing the dynamics of resistant bacteria, non-resistant bacteria and immune cells exposed to an antibiotic. The global stability of equilibria is performed by using a Lyapunov functions.

#### **A note on the “unique” business cycle in the Keynesian theory**

Hiroki Murakami (1),

(1) Faculty of Economics, Chuo University, Hachioji, Tokyo, Japan

In this paper, we explore the existence and “uniqueness” of a limit cycle in a Keynesian model of business cycles. In a model with the simplest (linear) Keynesian consumption function and the logistic investment function based upon the profit principle, we establish the existence of a periodic orbit (irrespective of the

speed of quantity adjustment) and verify, with the help of the theory on generalized Liénard systems, the uniqueness of it for the case in which the speed of quantity adjustment is large enough.

**Necessary optimality conditions for constrained optimal control problems under a constant rank condition**

Jamielli Tomaz Pereira (1), Roberto Andreani (1), Valeriano Antunes de Oliveira (2), Geraldo Nunes Silva (2),

(1) IMECC, UNICAMP, Campinas, Brasil (2) IBILCE, UNESP, Sao José do Rio Preto, Brasil

**On a large population game theoretic model of associative mating**

David Mark Ramsey (1),

(1) Faculty of Computer Science and Management, Wroclaw University of Science and Technology, Wroclaw, Poland

A model of partnership formation is considered. There are two classes of player (male and female) of equal size. There is a continuum of players and two types of both sexes. These two types can be interpreted, e.g. as two subspecies. Each searcher prefers to pair with an individual of the same type. Players search from time zero until they find a mutually acceptable prospective partner or the mating season ends. When a pair is formed, both individuals leave the pool of searchers. Hence, the proportion of players still searching and the distribution of types changes over time. Prospective partners are found at a rate non-decreasing in the proportion of players still searching. A searcher's payoff is the value of the partner obtained discounted according to the search time. Nash equilibria are derived which satisfy the following optimality criterion: a prospective partner is accepted if and only if the payoff from such a partnership (given that it formed) is greater or equal to the expected payoff obtained from future search.

**Historical dynamics and country size in geopolitical model**

Kirill Rivkin (1),

(1) Seagate Technologies, US

**Economic migration and capital flows: designing policies for global inequality reduction**

Matthias Wildemeersch (1), Elena Rovenskaya (1), Alexia Prskawetz (2), Jesus Crespo Cuaresma (3),

(1) IIASA, Laxenburg, Austria (2) Vienna University of Technology, Vienna, Austria (3) Vienna University of Economics and Business, Vienna, Austria

Inequality is widely considered to hinder economic growth and can potentially trigger social unrest. Historical records show that inequality varies largely over time and across countries, and ongoing trends are a source of growing concern. In this research, we aim to enhance the understanding of the driving forces of inequality, and propose market policies able to reduce international inequality. We do this by developing a network model that consolidates the intertwined effects of migration and foreign direct investment on

the consumption distribution. Based on the theoretical framework, we aim to design regulatory responses that maintain high levels of economic welfare while reducing inequality.

**Approximations for mixed optimal stopping and control problems with nonlinear expectations and jumps**

Roxamna Dumitrescu (1), Christoph Reisinger (2), Yufei Zhang (2),

(1) King's College, London, UK (2) University of Oxford, Oxford, UK

We propose a class of numerical schemes for mixed optimal stopping and control of processes with infinite activity jumps and where the objective is evaluated by a nonlinear expectation. Exploiting an approximation by switching systems, piecewise constant policy timestepping reduces the problem to non-local semi-linear equations with different control parameters, uncoupled over individual time steps, which we solve by fully implicit monotone approximations to the controlled diffusion and the nonlocal term, and specifically the Lax-Friedrichs scheme for the nonlinearity in the gradient. We establish a comparison principle for the switching system and demonstrate the convergence of the schemes, which subsequently gives a constructive proof for the existence of a solution to the switching system. Numerical experiments are presented for a recursive utility maximization problem to demonstrate the effectiveness of the new schemes.

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