International Institute for
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A guide to the methodology and potential applications of economic agent-based models (ABMs)

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Economic agent-based modeling methodology

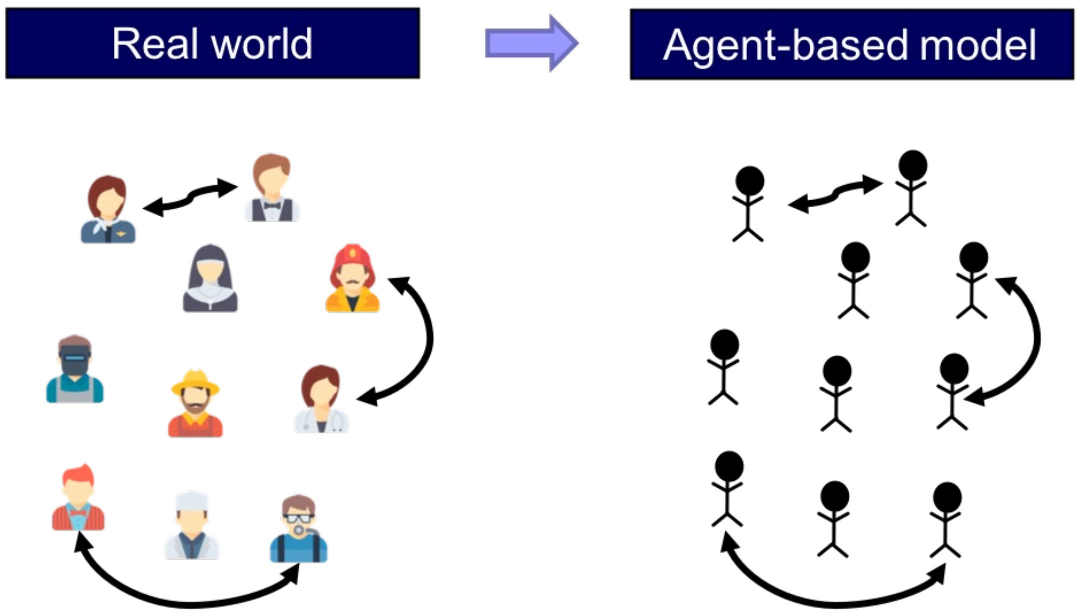
Agent-based modeling of economic systems

Agent-based models (ABMs) are **computer simulation models** with the following features:

- They model **individual agents** and their individual **decisions** (decentralized decision-making)
- Can include thousands or even **millions** of agents
- Can capture **bounded rationality** (often in the form of some heuristics)
- Depict **emergent patterns** from micro-processes that aggregate to a macro level: the economy as a **complex system** subject to **fundamental uncertainty**

ABM is a (relatively) **new** way to model complex systems

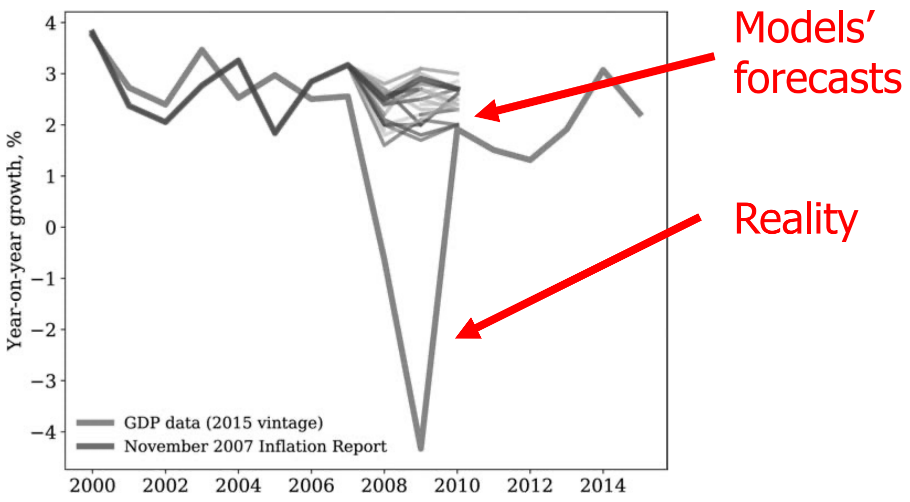
ABMs have potential to be "**more realistic**" models of socioeconomic systems



Why ABM for economic systems?

- It seems that standard economic models perform rather well for “normal” times and not so well in “abnormal” times
- Many models currently used by central banks and large international institutions had “difficulty explaining both the depth and the slow recovery of the Great Recession.” (Lindé, Smets & Wouters, 2016)
- More generally, “… ABMs are a promising complement to the current crop of macroeconomic models, especially when making sense of the types of extreme macroeconomic movements the world has witnessed for the past decade.” (Haldane & Turrell, 2017)

GDP of the UK



Source: (Haldane & Turrell, 2017)

- introducing **heterogeneous agents**
- relaxing **rational expectations**

Comparison of different types of economic models

Agent-based models explain the evolution of an economy by **simulating** the **micro-level behaviour** of **individual agents** to give a **macro-level** picture:

DSGE	TANK, HANK	ABM	ABM (next gen)
Representative agents	Heterogeneous agents	Heterogeneous agents	Heterogeneous agents
Log-linearized and solved numerically	Log-linearized and solved numerically	Solved numerically at the agent level	Solved numerically at the agent level
Rational or model-consistent expectations	Bounded rationality through myopia or limited foresight	Bounded rationality in expectations	Bounded rationality in expectations
Agents optimize given expectations	Agents optimize given expectations	Agents use simple heuristics	Agents use simple heuristics **calibrated to micro & macro data**
Match the historical evolution of variables	Match the historical evolution of variables	reproduce stylized facts and generate endogenous business cycles	reproduce stylized facts and **match historical evolution of variables**

"In principle it might even be possible to create an agent-based economic model capable of making useful forecasts of the real economy, although this is ambitious ... like climate modelling, [it's] a huge undertaking." (Farmer & Foley, 2009)

Comparison of different types of economic models

Figure 8. Macroeconomic ABMs may be thought of as lying within a wider modelling space, here shown as having two axes. Internal consistency is best represented by strongly microfounded behaviour, while external consistency is demonstrated by agreement with the data. On the other axis is the degree of agent heterogeneity which the model can include, with representative agents on one end and heterogeneity along many dimensions at the other. The within variation of each model type is likely to be larger than the variation between them, but the figure illustrates their approximate location within the wider modelling space.

Source: (Haldane & Turrell, 2017).

ABM for economic forecasting

- Statistical models using (mostly linear) time series analysis offer good forecasting performance
    - large-scale macroeconometric models that use large amounts of data are possible…
    - …but are weak in providing an explanation and interpretation of economic events
- DSGE and other models derived from economic theory
    - provide explanation and interpretation of economic events…
    - …by depicting the micro-founded behaviour of agents
    - but for methodological reasons are restricted to smaller models with fewer variables than statistical models
- ABMs
    - combine advantages from large-scale statistical models and models derived from economic theory
    - can be large-scale and derived from economic theory at the same time
    - can compete with other models in out-of-sample prediction performance

ABM forecast performance
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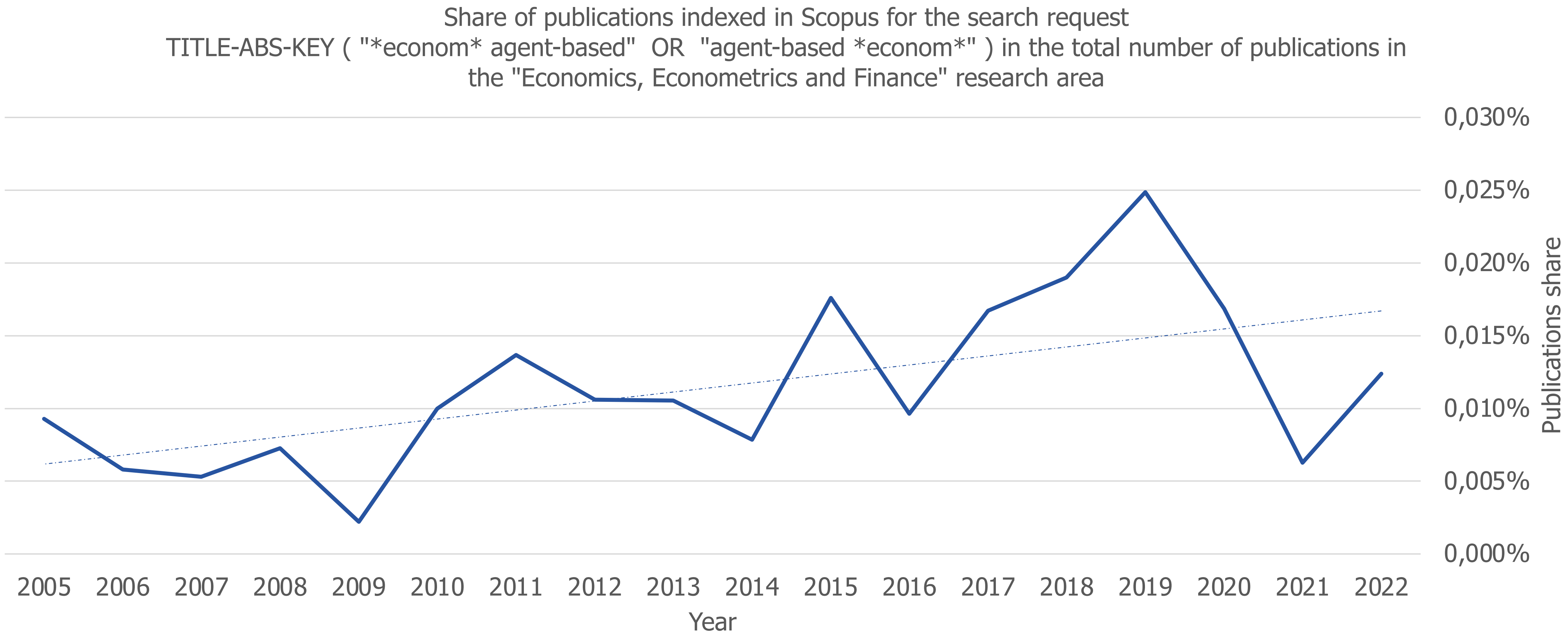
Proliferation of ABMs in the economic literature



IIASA macroeconomic ABM

Overview of the ABM

Agents:

- Non-financial corporations (firm sector), limited companies and self-employed
- Financial corporations (banking sector), one representative bank
- Individual persons (household sector)
    - Employed (active on labor market)
    - Unemployed (involuntarily idle)
    - Investor (own firms)
    - Inactive households (not active on labor market, receive social benefits)
- General government (consists of central, state and local governments)
- Central Bank

Overview of the ABM

Mechanisms:

- Firms in 64 sectors (NACE) produce goods and services by using labor, capital and intermediate inputs from other firms
- *Bounded rationality*: Firms and consumers form expectations about future developments using adaptive learning and simple heuristics depending on the expected growth rate and inflation
- Consumption networks and supply chains are formed through *search-and-matching* processes:
  - Firms are randomly *"visited"* by consumers
  - The likelihood that firms are visited by consumers correlates negatively with the price and positively with firm size
  - Inventories and involuntary savings result from the search and matching process
- The labor market is also modeled with a search-and-matching process
- Demand for funding of firms is based on expectations of the expected future cash flow
- Banks grant loans based on financial conditions of firms and with respect to minimum capital requirements
- The central bank follows a Taylor rule
- The general government acts a consumer (government consumption) and as a "redistributive entity"

Agents & mechanisms in more detail

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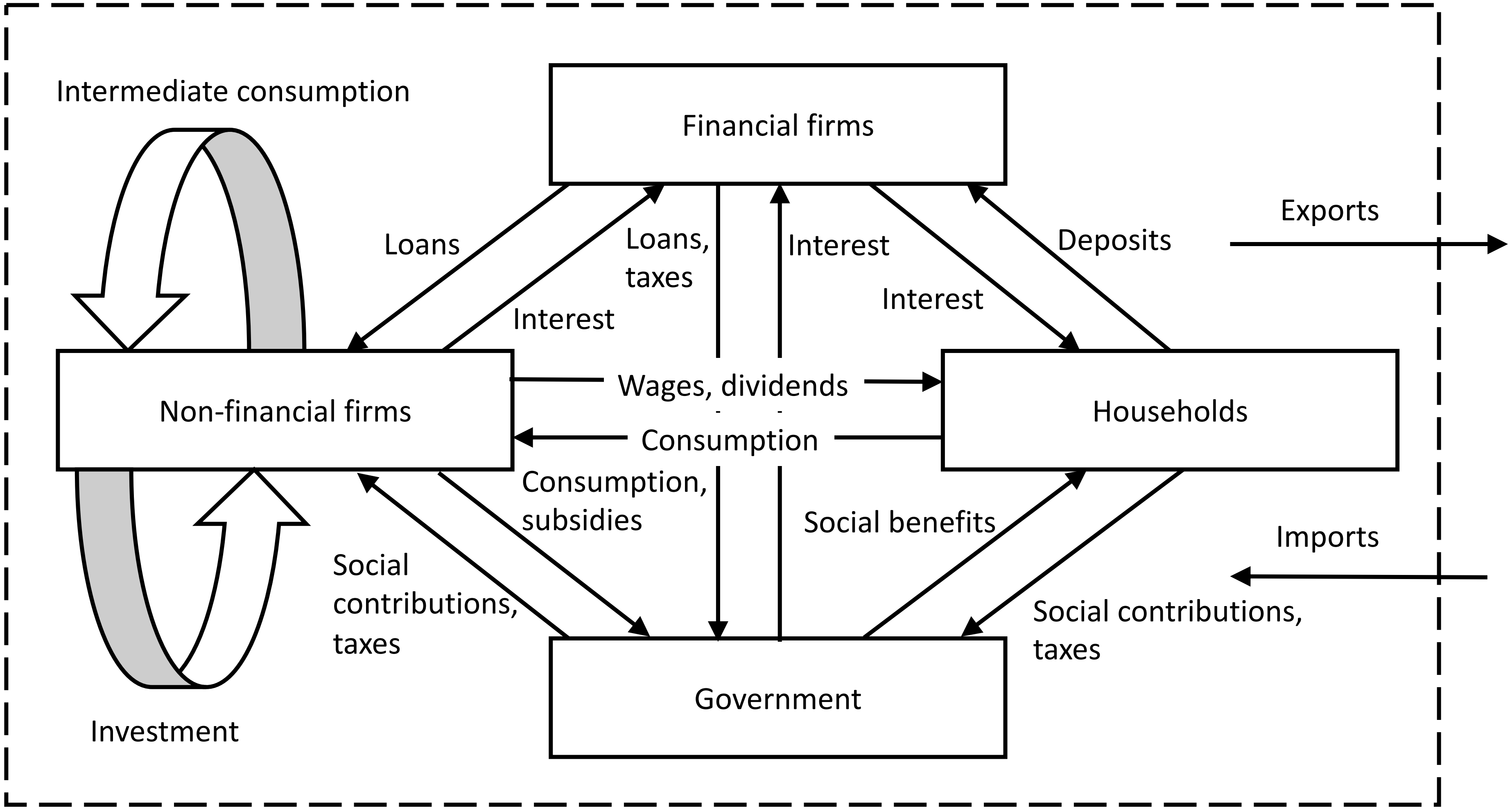
Overview of the ABM



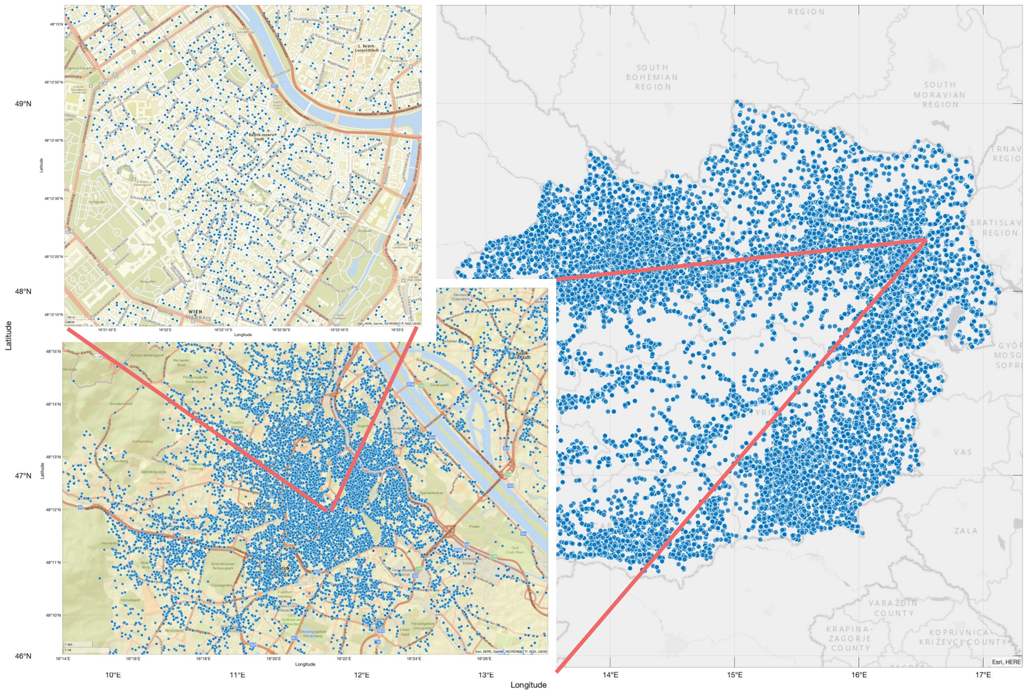
Major economic agents and their interactions

Key modeling choices and mechanisms of the ABM

- Includes **all sectors** (financial, non-financial, households, a general government) populated with a large number of **heterogenous agents** calibrated to census and survey (LFS) data
- Includes a **complete GDP identity** with *all transactions* in products, non-financial assets, and distributive transactions calibrated to national accounting data
- Rational expectations are relaxed with **adaptive learning** (Hommes & Zhu, 2014)
- Includes a **multi-sector production network** calibrated to input-output tables
- Has **decentralized markets**, which allows for **trade frictions**
- Incorporates **financial frictions** with a **financial accelerator** and **debt-financed investment** (Bernanke, Gertler, & Gilchrist 1996)
- Allows **non-linear responses**, which may be underestimated by linearized DSGE models (Lindé, 2018), and for the possibility of **endogenous economic crises without exogenous shocks**
- The ABM is **validated** based on the comparison of its **forecast performance** (out-of-sample prediction) with that of econometric and DSGE models

Calibration of the ABM for Austria

Data type	Data purpose
Census and business demography	Populate the model with realistic numbers of agents-individuals and agents-firms
Input-output *industry × industry* tables (IOTs); all economic activities as classified by the European System of Accounts: 64 industries (NACE-level 2)	Describe the sale and purchase relationships between producers and consumers within an economy, i.e., flows of final and intermediate goods and services defined according to industry outputs tables
Government statistics and sector accounts	Calibrate tax rates, social insurance rates, etc.
National accounts (GDP and main components) and money market interest rates	Estimate exogenous processes and the Taylor rule to determine the policy rate
Statutory guidelines, financial regulation, and banking practices	Determine capital requirements, inflation targets, unemployment benefit replacement rate, etc.



611278 firms

Calibration in more detail
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ABM implementation

Two implementations of the IIASA Macroeconomic ABM exist:

- The “reference” implementation is written in MATLAB. In the spirit of Dynare, the model is implemented almost as it is described in the manuscript. This implementation is available on https://github.com/iiasa/abm and on zenodo.
- A Distributed Memory Parallel (DMP-HPC) implementation was developed in Gill et al. (2021).

DMP implementation in more detail
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ABM for informing economic policies on migration (ABM2Policy project)

Economic effects of migration

- In Europe, large migratory shocks have led to a heated political debate on their management
- Uncertainty about the **migratory impact on the economy and society** has, in many instances, polarized the debate
- There is a need for tools to inform stakeholders and policymakers of the most likely economic and social consequences of migration

- Investigation of the **economic consequences** of an extreme **migration scenario** for **Austria**
- **Enhance** the **policy realism** of the IIASA macroeconomic ABM
- Consider **social heterogeneity** to allow studying **distributional impacts**
- Make use of **detailed microdata** from Statistic Austria

- GDP
- Government debt
- Unemployment rate…
- Wages…
- Social benefits…

…by economic sector and socioeconomic status

ABM2Policy project website
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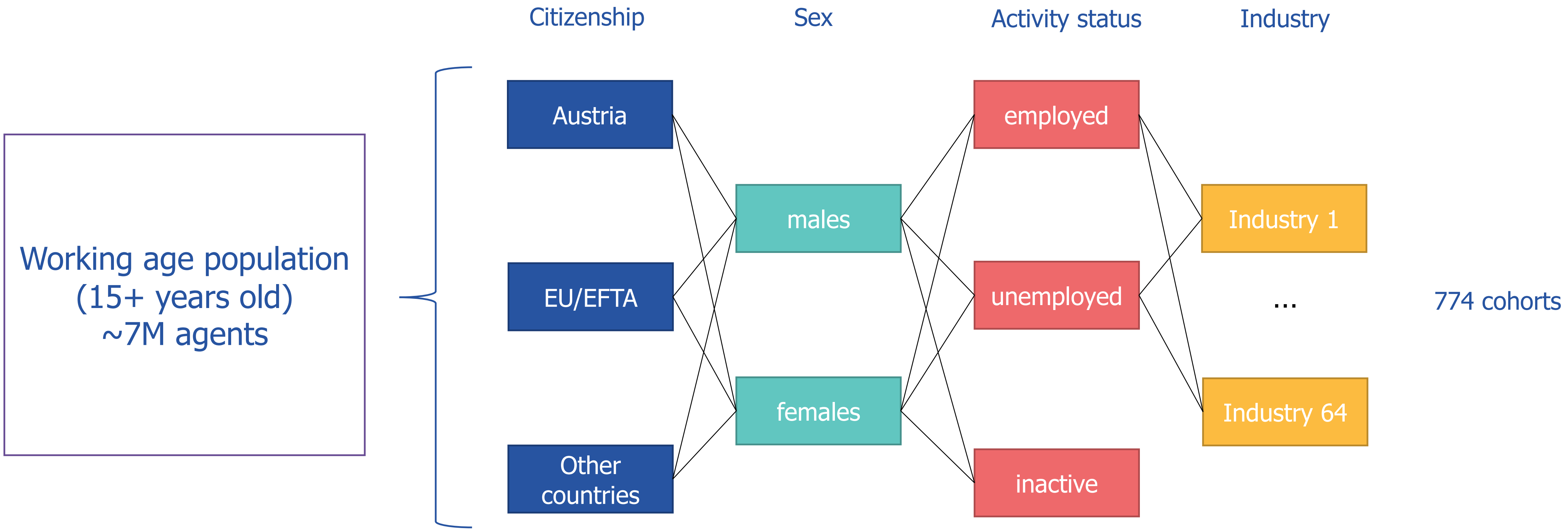
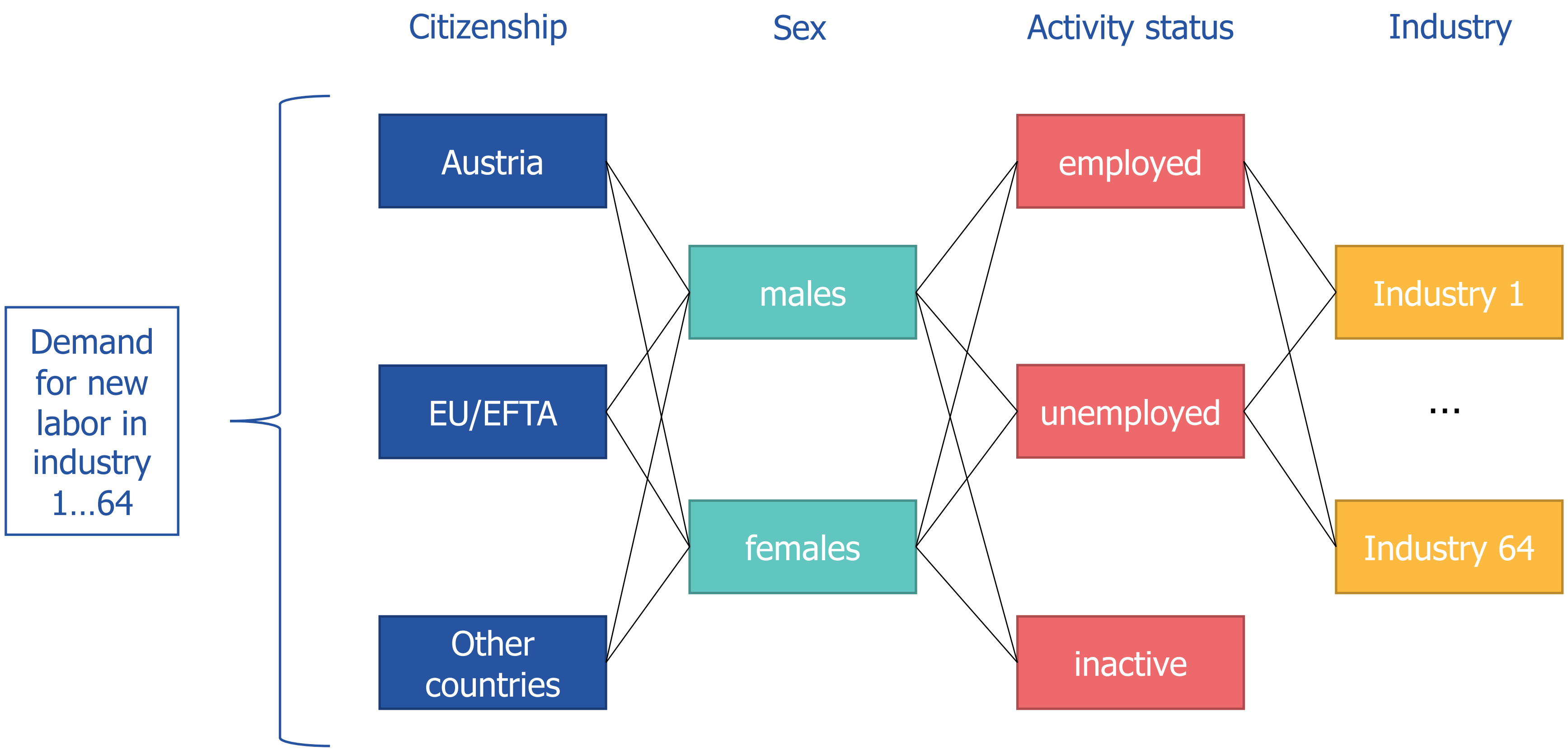
Calibration of the population module of the ABM



Data source: Statistics Austria

Calibration of labour market transitions

Labor market transitions to employment are guided by transition probabilities which are estimated from absolute values: flows of individuals between the activity states (employed, unemployed, inactive) divided by stocks of individuals in each activity state.



Data source: Statistics Austria, Register-based Labour Market Career (ERV) data

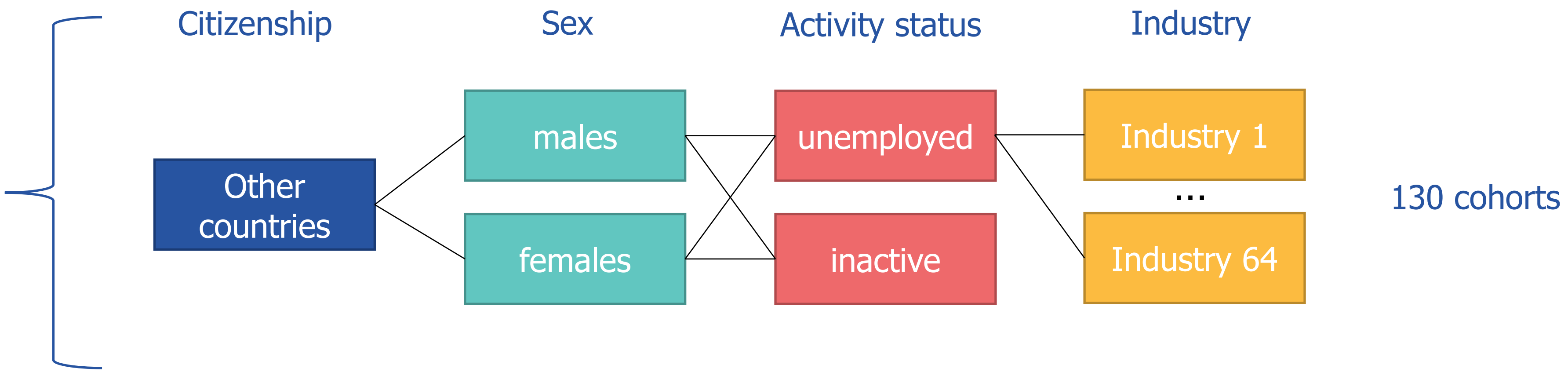
Data on the employment history of each person in Austria from 2009 onwards (~4.1 mln. employees; ~20 mln. employment relationships)

Calibration of the migration scenario

Migration scenario: 250,000 additional agents-migrants of working age (15-64 years old) are dynamically added to the ABM every quarter for six quarters.

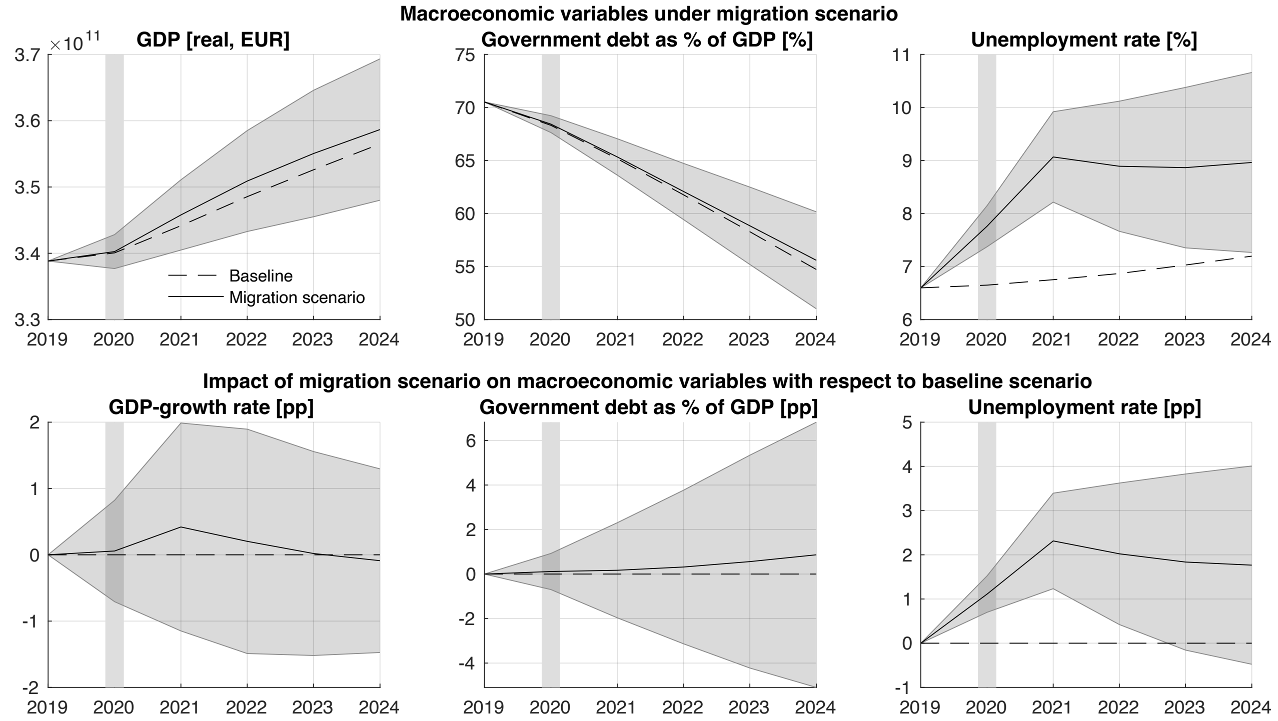
The numbers of agents-migrants with certain attributes (citizenship, sex, activity status and industry) are calibrated to resemble the composition of the 2015 refugee crisis in Austria.

Migration influx
(15-64 years old)
Quarter 1: ~22k agents
Quarter 2: ~39k agents
Quarter 3: ~63k agents
Quarter 4: ~70k agents
Quarter 5: ~31k agents
Quarter 6: ~24k agents



Data sources: JRC migration scenarios, Statistics Austria, UNHCR, Online-Arbeitsmarktinformationssystem

Macroeconomic impacts and labour market dynamics under the migration scenario



Nationality	Gender	Variable	0	1	2	3	4	5
NATIVES	MEN	u.r. (%)	5.20%	5.33%	5.59%	5.83%	6.10%	6.35%
		Δ u.r. (p.p)	+0.00%	+0.03%	+0.10%	+0.25%	+0.46%	+0.71%
		# U (units)	85350	87833	92680	97509	102824	107966
		Δ # U (units)	+0	+493	+1527	+3743	+7156	+11140
	WOMEN	u.r. (%)	5.21%	5.39%	5.73%	6.06%	6.37%	6.64%
		Δ u.r. (p.p)	+0.00%	+0.01%	+0.03%	+0.13%	+0.31%	+0.54%
		# U (units)	80615	83663	89854	95893	101781	107241
		Δ # U (units)	+0	+76	+300	+1588	+4266	+7671
EU	MEN	u.r. (%)	7.07%	6.80%	6.28%	5.92%	5.78%	5.77%
		Δ u.r. (p.p)	+0.00%	+0.09%	+0.30%	+0.52%	+0.74%	+0.96%
		# U (units)	14483	14219	13731	13504	13647	14028
		Δ # U (units)	+0	+129	+437	+785	+1238	+1721
	WOMEN	u.r. (%)	8.91%	8.91%	8.89%	8.87%	8.92%	9.01%
		Δ u.r. (p.p)	+0.00%	+0.04%	+0.14%	+0.34%	+0.59%	+0.87%
		# U (units)	18211	18404	18845	19343	19996	20739
		Δ # U (units)	+0	+49	+148	+399	+815	+1321
Other Countries	MEN	u.r. (%)	11.80%	11.51%	10.86%	10.23%	9.73%	9.36%
		Δ u.r. (p.p)	+0.00%	+0.09%	+0.34%	+0.67%	+1.02%	+1.36%
		# U (units)	28023	27450	26161	24912	23975	23309
		Δ # U (units)	+0	+198	+727	+1447	+2242	+3023
	WOMEN	u.r. (%)	14.34%	14.41%	14.53%	14.65%	14.80%	14.96%
		Δ u.r. (p.p)	+0.00%	+0.03%	+0.10%	+0.24%	+0.45%	+0.73%
		# U (units)	30149	30378	30865	31383	32003	32657
		Δ # U (units)	+0	+54	+144	+343	+726	+1244
Refugees	MEN	u.r. (%)	28.86%	25.29%	18.76%	13.81%	10.57%	8.42%
		Δ u.r. (p.p)	+0.00%	+35.66%	+45.87%	+38.82%	+31.86%	+26.04%
		# U (units)	11319	10162	7955	6199	5003	4183
		Δ # U (units)	+0	+41755	+91063	+78827	+66050	+55540
	WOMEN	u.r. (%)	32.47%	21.00%	9.14%	4.61%	2.89%	2.18%
		Δ u.r. (p.p)	+0.00%	+33.20%	+33.17%	+19.66%	+11.62%	+7.19%
		# U (units)	1795	1298	700	430	318	275
		Δ # U (units)	+0	+7290	+12977	+8401	+5493	+3823

u.r.: Unemployment rate in the baseline scenario; Δ u.r.: Difference in the unemployment rate (in p.p.) between the migration scenario and the baseline scenario; #U: Absolute number of unemployed persons in the baseline scenario; Δ#U: Difference in the absolute number of unemployed persons between the migration scenario and the baseline scenario

Sectoral labour market dynamics under the migration scenario

Industry	Variable	0	1	2	3	4	5
A	u.r. (%)	8.19%	8.08%	8.26%	8.67%	9.21%	9.71%
	Δ u.r. (p.p)	+0.00%	+2.38%	+5.07%	+4.73%	+4.53%	+4.55%
	# U (units)	1791	1770	1831	1955	2112	2265
	Δ # U (units)	+0	+583	+1311	+1252	+1229	+1256
B	u.r. (%)	2.75%	2.76%	2.73%	2.83%	3.01%	3.12%
	Δ u.r. (p.p)	+0.00%	+0.02%	+0.10%	+0.18%	+0.29%	+0.43%
	# U (units)	167	172	179	191	206	216
	Δ # U (units)	+0	+2	+7	+13	+20	+31
C	u.r. (%)	3.40%	3.53%	3.71%	3.94%	4.24%	4.51%
	Δ u.r. (p.p)	+0.00%	+0.36%	+0.78%	+0.75%	+0.80%	+0.89%
	# U (units)	21669	22715	24448	26522	29033	31414
	Δ # U (units)	+0	+2442	+5431	+5421	+5917	+6663
D	u.r. (%)	1.40%	1.12%	0.81%	0.72%	0.70%	0.69%
	Δ u.r. (p.p)	+0.00%	+0.05%	+0.06%	+0.03%	+0.10%	+0.20%
	# U (units)	73	59	42	38	37	37
	Δ # U (units)	+0	+2	+3	+2	+6	+11
E	u.r. (%)	4.05%	4.20%	4.94%	5.86%	6.83%	7.79%
	Δ u.r. (p.p)	+0.00%	+0.61%	+1.13%	+0.80%	+0.83%	+1.08%
	# U (units)	637	663	790	958	1142	1331
	Δ # U (units)	+0	+101	+196	+146	+158	+210
F	u.r. (%)	5.17%	5.11%	4.98%	4.92%	4.97%	5.07%
	Δ u.r. (p.p)	+0.00%	+0.57%	+1.01%	+0.65%	+0.49%	+0.52%
	# U (units)	14768	14626	14371	14372	14676	15134
	Δ # U (units)	+0	+1738	+3176	+2127	+1658	+1789
G	u.r. (%)	6.54%	6.59%	6.71%	6.86%	7.05%	7.26%
	Δ u.r. (p.p)	+0.00%	+0.61%	+1.08%	+0.82%	+0.74%	+0.78%
	# U (units)	41306	41795	43050	44528	46361	48307
	Δ # U (units)	+0	+4198	+7853	+6272	+5808	+6125
H	u.r. (%)	6.07%	5.97%	5.71%	5.52%	5.50%	5.51%
	Δ u.r. (p.p)	+0.00%	+0.81%	+1.63%	+1.40%	+1.28%	+1.32%
	# U (units)	11780	11625	11230	11008	11119	11262
	Δ # U (units)	+0	+1695	+3505	+3060	+2850	+2944
I	u.r. (%)	18.31%	17.92%	17.04%	16.05%	15.12%	14.25%
	Δ u.r. (p.p)	+0.00%	+4.27%	+8.82%	+8.03%	+7.18%	+6.49%
	# U (units)	46739	45712	43345	40775	38376	36155
	Δ # U (units)	+0	+14089	+30914	+27608	+24183	+21409
K	u.r. (%)	3.88%	3.95%	4.29%	4.71%	5.19%	5.66%
	Δ u.r. (p.p)	+0.00%	+0.13%	+0.20%	+0.13%	+0.29%	+0.55%
	# U (units)	4324	4422	4854	5429	6080	6741
	Δ # U (units)	+0	+156	+251	+194	+403	+736

Industry	Variable	0	1	2	3	4	5
J	u.r. (%)	2.63%	2.83%	3.18%	3.51%	3.87%	4.19%
	Δ u.r. (p.p)	+0.00%	-+0.01%	-+0.15%	-+0.24%	-+0.19%	-+0.03%
	# U (units)	3087	3348	3815	4285	4795	5264
	Δ # U (units)	+0	-+13	-+169	-+274	-+207	+0
L	u.r. (%)	5.96%	5.78%	5.43%	5.13%	4.93%	4.78%
	Δ u.r. (p.p)	+0.00%	+0.25%	+0.23%	+0.08%	+0.11%	+0.24%
	# U (units)	2915	2830	2670	2535	2450	2391
	Δ # U (units)	+0	+132	+144	+69	+87	+155
M	u.r. (%)	4.62%	4.54%	4.54%	4.66%	4.91%	5.20%
	Δ u.r. (p.p)	+0.00%	+0.24%	+0.41%	+0.34%	+0.46%	+0.70%
	# U (units)	9586	9436	9525	9901	10559	11339
	Δ # U (units)	+0	+531	+942	+807	+1104	+1688
N	u.r. (%)	19.02%	18.41%	17.09%	15.85%	14.86%	14.09%
	Δ u.r. (p.p)	+0.00%	+4.91%	+10.13%	+9.11%	+8.05%	+7.22%
	# U (units)	52442	50577	46711	43221	40538	38516
	Δ # U (units)	+0	+17621	+38362	+33602	+28993	+25517
O	u.r. (%)	2.42%	3.07%	4.41%	5.62%	6.67%	7.62%
	Δ u.r. (p.p)	+0.00%	+0.08%	+0.26%	+0.33%	+0.45%	+0.59%
	# U (units)	16096	20652	30195	39264	47477	55139
	Δ # U (units)	+0	+587	+1887	+2426	+3432	+4581
P	u.r. (%)	4.45%	4.56%	4.73%	4.82%	4.83%	4.81%
	Δ u.r. (p.p)	+0.00%	+0.35%	+0.72%	+0.73%	+0.82%	+0.95%
	# U (units)	7781	8013	8399	8626	8718	8748
	Δ # U (units)	+0	+646	+1374	+1413	+1588	+1842
Q	u.r. (%)	8.05%	8.15%	8.32%	8.46%	8.57%	8.64%
	Δ u.r. (p.p)	+0.00%	+1.28%	+2.78%	+2.63%	+2.46%	+2.39%
	# U (units)	23866	24274	25051	25699	26283	26748
	Δ # U (units)	+0	+4250	+9562	+9149	+8675	+8460
R	u.r. (%)	9.72%	9.20%	8.13%	7.14%	6.34%	5.72%
	Δ u.r. (p.p)	+0.00%	+0.55%	+1.00%	+0.90%	+0.93%	+1.04%
	# U (units)	3877	3661	3224	2824	2511	2268
	Δ # U (units)	+0	+248	+463	+417	+425	+465
S	u.r. (%)	7.01%	7.00%	6.96%	6.88%	6.84%	6.83%
	Δ u.r. (p.p)	+0.00%	+0.94%	+1.84%	+1.56%	+1.40%	+1.34%
	# U (units)	7041	7056	7063	7044	7073	7123
	Δ # U (units)	+0	+1038	+2110	+1827	+1657	+1601
TOTAL	u.r. (%)	6.60%	6.65%	6.75%	6.86%	7.02%	7.19%
	Δ u.r. (p.p)	+0.00%	+1.12%	+2.31%	+2.02%	+1.83%	+1.76%
	# U (units)	269945	273406	280793	289173	299546	310399
	Δ # U (units)	+0	+50046	+107322	+95533	+87986	+85482

	Industry
A	Agriculture, Forestry and Fishing
B	Mining and Quarrying
C	Manufacturing
D	Electricity, Gas, Steam and Air Conditioning Supply
E	Water Supply; Sewerage, Waste Management and Remediation Activities
F	Construction
G	Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles
H	Transportation and Storage
I	Accommodation and Food Service Activities
J	Information and Communication
K	Financial and Insurance Activities
L	Real Estate Activities
M	Professional, Scientific and Technical Activities
N	Administrative and Support Service Activities
O	Public Administration and Defence; Compulsory Social Security
P	Education
Q	Human Health and Social Work Activities
R	Arts, Entertainment and Recreation
S	Other Service Activities
T	Activities of Households as Employers; Undifferentiated Goods and Services Producing Activities of Households for Own Use
U	Activities of Extraterritorial Organisations and Bodies

Further applications of the IIASA Macroeconomic ABM

Click to view

Some insights and good practices

- To ABM or not to ABM?
- Simple or complicated ABMs?
- Dealing with uncertainty in ABM

To ABM or not to ABM?

- Building an ABM is often fun (like building a LEGO model), but demands **computational resources** and **data**
- **Rigor** and **comprehensive analysis** of an ABM can be increasingly complex
- ABMs are especially useful when the agents have **heterogeneous decision-making processes** and/or **interact in non-random ways** (social and trade networks, spatially explicit systems, etc.)
- Sometimes other modeling paradigms (systems dynamics, analytical models, regressions, etc.) can be more suitable, i.e., have a higher explanatory power/complexity ratio
  - There is a small set of agents => systems dynamics
  - There is a very large set of agents who interact randomly => microsimulation

Source: Rattanachai Singtrangarn | Dreamstime.com

Simple or complicated ABMs?

- **Abstract** (”toy”) models vs. **large-scale** simulators
- From modeling a **specific emergent phenomenon** to modeling the **entire economic system**
- Avoiding the **YAAWN syndrome** (Yet Another Agent-Based Model ... Whatever ... Nevermind) (O’Sullivan et al., 2016)
- “**Simple** or **complicated** agent-based models? A complicated issue” (Sun et al., 2016)

Dealing with uncertainty in ABM

- **Monte-Carlo** simulations (MCS)
  - A broad class of computational algorithms that rely on **repeated random sampling** to obtain numerical results
  - Typically, each random realization is generated by first randomly sampling the parameters (usually, several/many random parameters in combination) from their assumed distributions, and then computing a model simulation with the model defined by these randomly chosen constant parameters (Young, Parkinson, & Lees, 1996)
  - In case of stochastic disturbance inputs, the inputs must also be randomly generated for each realization but as time series spanning the simulation time interval (Young, Parkinson, & Lees, 1996)

Summary

- **ABMs offer a complementary tool to current suite of models for central banks and other institutions**
  - Rich firm and household heterogeneity
  - Nonlinear effects
  - Competitive out-of-sample forecasting performance
- **Strength in realistic expectation formation and behavior modelling**
  - Bounded rationality and learning
- **Great potential for policy analysis & scenario building**
  - Understanding inflation dynamics
  - Analyzing and forecasting economic crises
- ABM require **computational power** and **micro-level data** which typically come from differnet sources and are often inconsistent. Calibration of ABMs is a huge challenge.

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Appendices

IIASA Macroeconomic ABM agents & mechanisms in detail

- [Non-financial corporations (firm sector)]
- [Individual persons (household sector)]
- [General government]
- [Financial corporations (banking sector)]

Non-financial corporations (firm sector)

Non-financial and Financial Corporations (Firms): Economic activities

Output (P.1) → part of which results in realized sales:

+ P_i Q_i where P_i is the price charged, and Q_i are realized sales of firm i

- Intermediate consumption (P.2)

- Capital consumption (P.51C)

- Wages and salaries (D.11)

- Employers' social contributions (D.611)

- Taxes on products (D.21)

- Other taxes on production (D.29)

+ Subsidies on products (D.31)

+ Other subsidies on production (D.39)

= Operating surplus (B.2A3N)

- Interest (D.41)

- Taxes on income (D.51)

- dividend payments (D.42)

Firms: Expectations

Agents' expectations are modelled by a parsimonious form of **adaptive learning** where agents act as econometricians and learn the optimal (consistent with the sample mean and first-order autocorrelation) parameters of simple AR rules following Hommes and Zhu (2014).

Expectations on GDP growth and inflation are formed using AR(1):

$$\gamma^e(t) = \alpha^\gamma(t-1)\gamma(t-1) + \beta^\gamma(t-1) + \epsilon^\gamma(t)$$

$$\pi^e(t) = \alpha^\pi(t-1)\pi(t-1) + \beta^\pi(t-1) + \epsilon^\pi(t)$$

where $\alpha^\gamma(t-1)$, $\alpha^\pi(t-1)$, $\beta^\gamma(t-1)$, $\beta^\pi(t-1)$, are coefficients re-estimated every period and $\epsilon^\gamma(t)$, and $\epsilon^\pi(t)$ are random shocks.

Firms: Supply Choice & Pricing

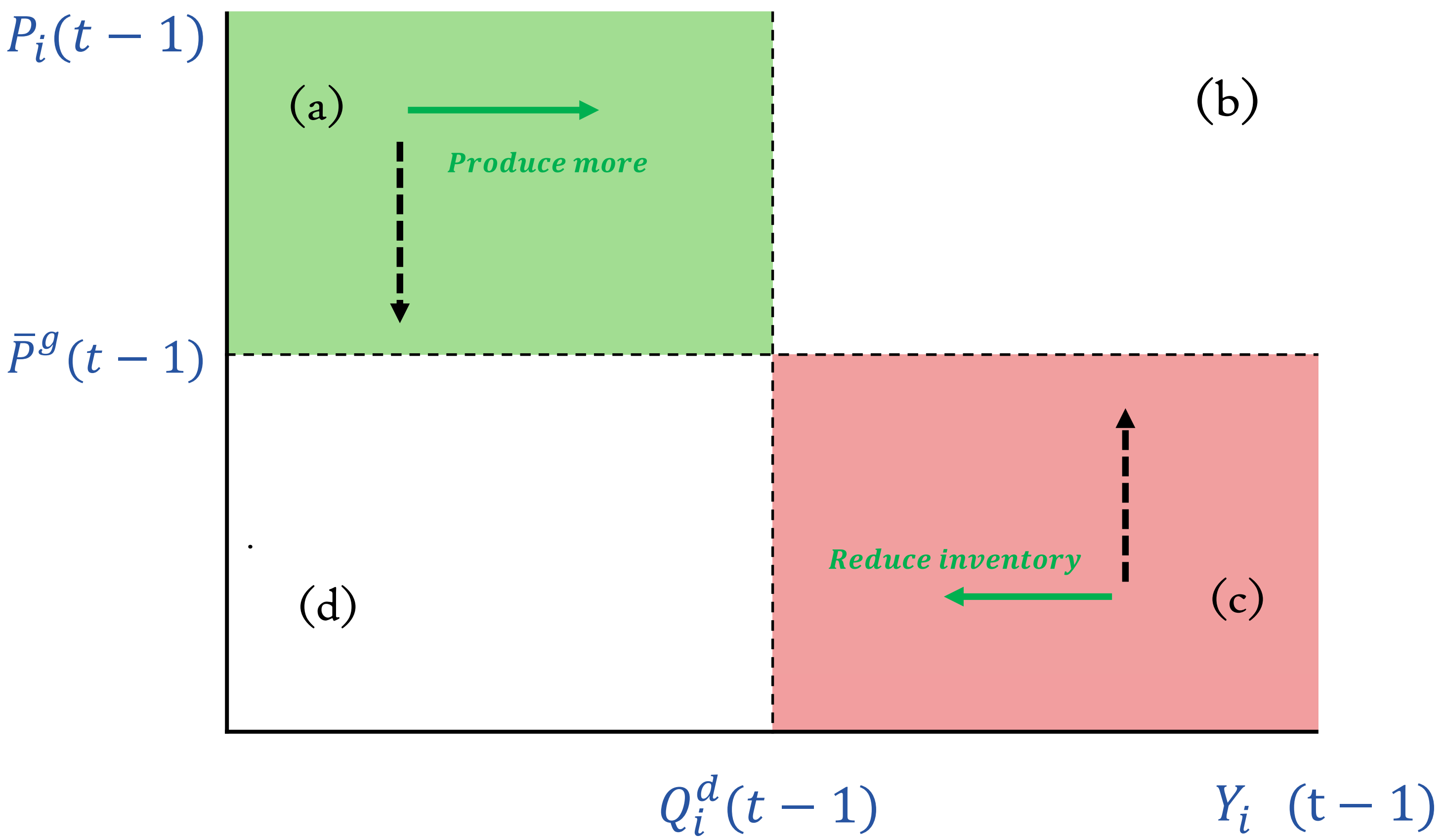
Supply choice: Firms change supply based on expectations of economic growth $\gamma^e(t)$ and perceived local market conditions using two indicators: the level of excess supply, which is the difference between the previous period's supply $Y_i\ (t-1)$ and demand $Q_i^d(t-1)$, and the deviation of the firm's own price $P_i(t-1)$ from the average price of firms' producing the same good, $\bar{P}^g(t-1)$:

$$Q_i^S(t) = Y_i\ (t-1)\,(1+\gamma^e(t))\,(1+\gamma_i^d(t))$$

Price-setting includes **three components** of inflation (*built-in inflation, demand-pull inflation, and cost-push inflation*):

$$P_i(t) = P_i(t-1) \cdot \underbrace{(1+\pi_i^c(t))}_{cost-push\ inflation} \cdot \underbrace{(1+\pi_i^d(t))}_{demand-pull\ inflation} \cdot \underbrace{(1+\pi^e\,(t))}_{built-in\ inflation}$$

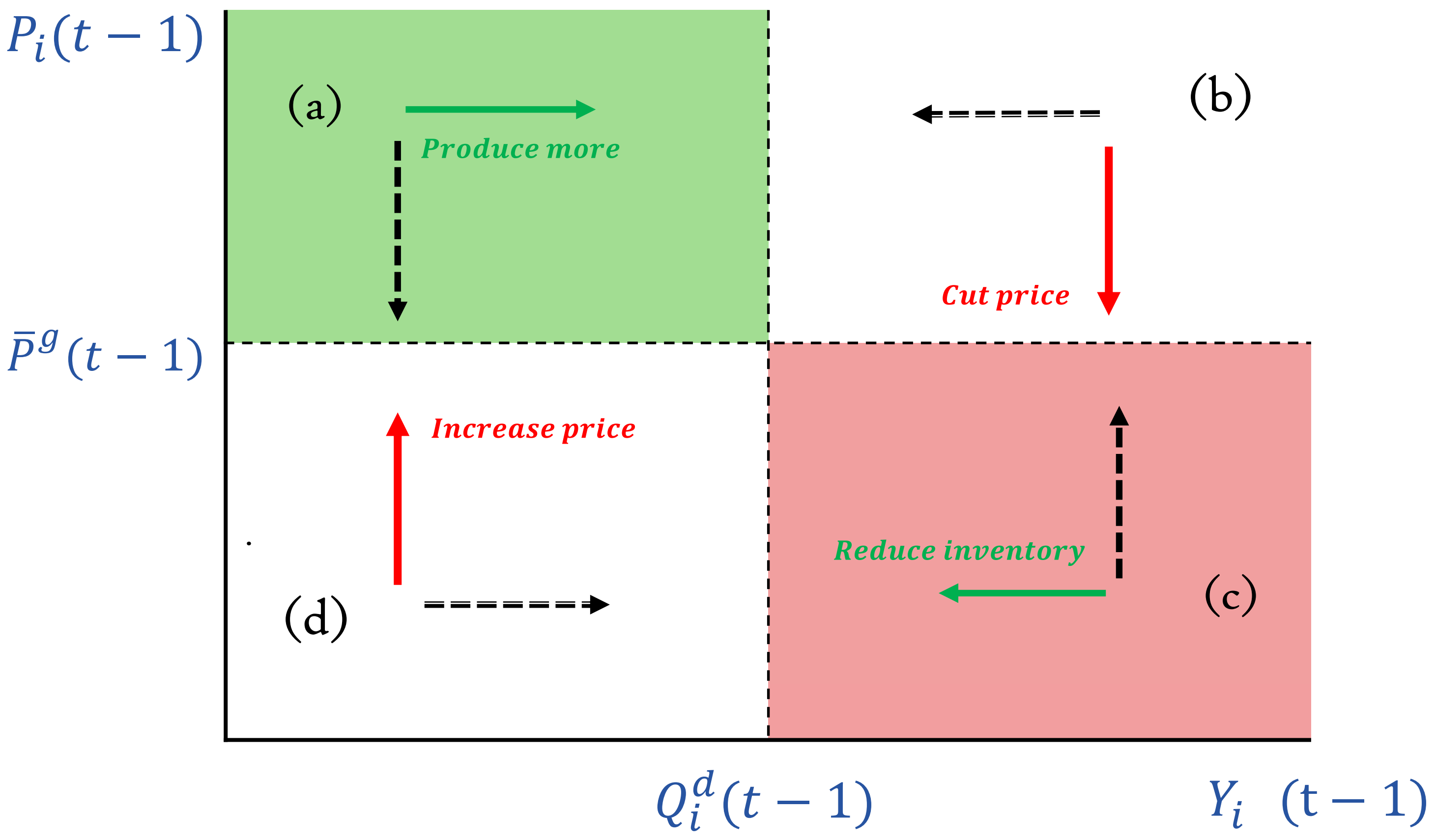
Firms: Supply Choice & Pricing



$$\gamma_i^d(t) = \begin{cases} positive, & if \text{ optimistic about demand despite higher price than average} \\ negative, & if \text{ positive inventory and price is already competitive} \end{cases}$$

Delli Gatti et al. (2011)

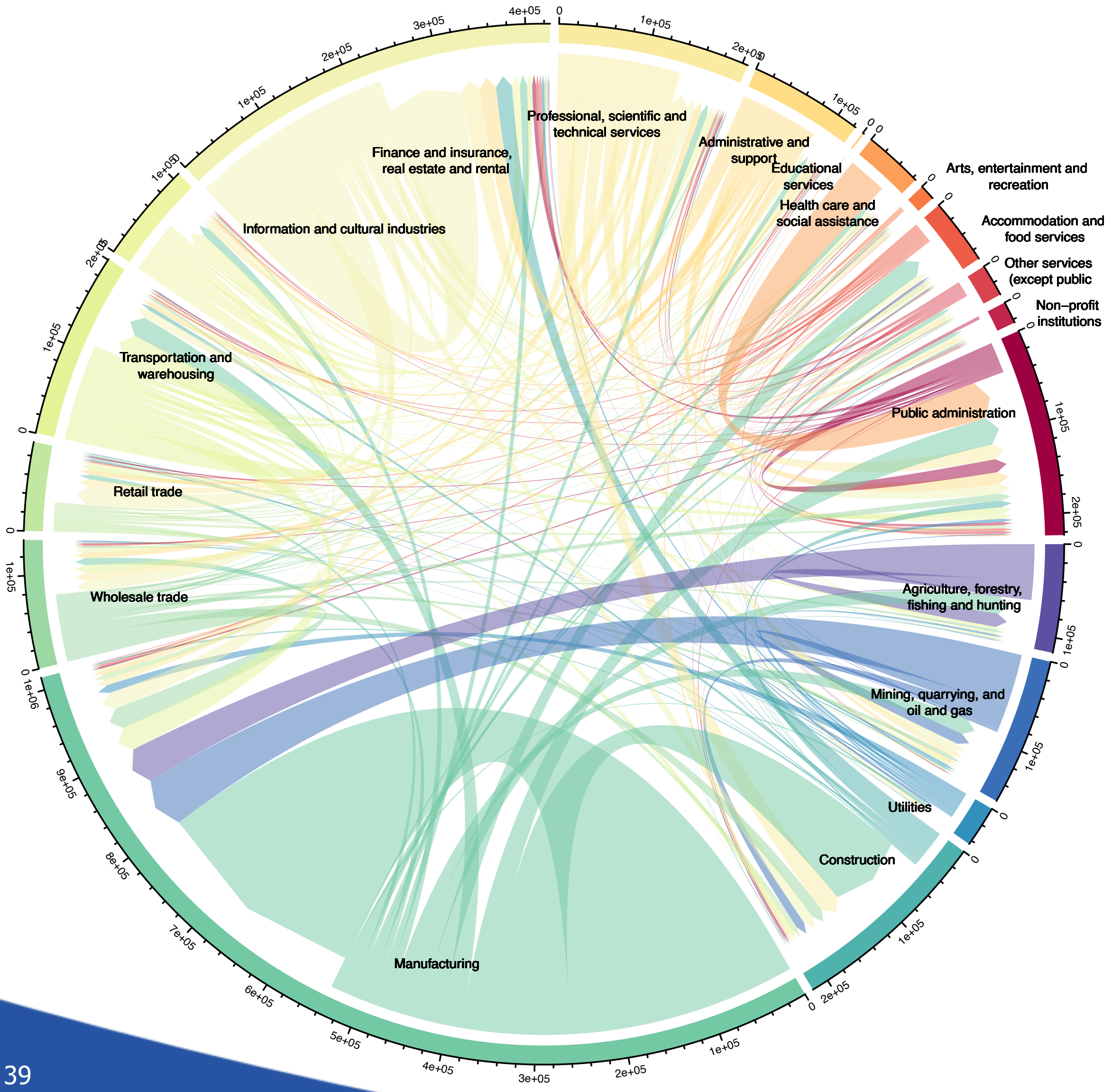
Firms: Supply Choice & Pricing



$$\pi_i^d(t) = \begin{cases} positive, & if \text{ optimistic about demand and price is competitive} \\ negative, & if \text{ positive inventory but charged higher price than average} \end{cases}$$

Delli Gatti et al. (2011)

Firms: Output



Firm *i* produces $Y_i(t)$ with **Leontief technology** using labour $N_i(t)$, intermediate inputs $M_i(t)$ and capital stock $K_i(t-1)$:

$$Y_i(t) = \ min(Q_i^s(t), \alpha_i N_i(t), \beta_i M_i(t), \kappa_i K_i(t-1))$$

α_i, β_i and κ_i: productivity coefficients, a_{sg} technologically determined input coefficients

$$\pi_i^c(t) = \underbrace{\frac{(1+\ \tau^{SIF})\bar{w}_i}{\bar{\alpha}_i}\left(\frac{\bar{P}^{HH}(t-1)}{P_i(t-1)} - 1\right)}_{Wage} + \underbrace{\frac{1}{\beta_i}\left(\frac{\sum_g \boldsymbol{\alpha_{sg}}\bar{P}^g(t-1)}{P_i(t-1)} - 1\right)}_{Production\ Inputs} + \underbrace{\frac{\delta_i}{\kappa_i}\left(\frac{\bar{P}^{CF}(t-1)}{P_i(t-1)} - 1\right)}_{Financing\ Cost}$$

Firms: Demand & Sales

Demand: each firm i experiences demand $Q_i^d(t)$ from consumers. The level of demand will be determined by consumers only after the firm has set its price and carried out production $Y_i(t)$ and is subject to the search and matching mechanism specifying the visiting consumers of firm i :

$$Q_i^d(t)\begin{cases} < S_i\ (t-1)+Y_i(t)\ if\ demand\ from\ consumers\ is\ smaller\ than\ supply \\ = S_i\ (t-1)+Y_i(t)\ if\ demand\ from\ consumers\ exactly\ matches\ supply \\ > S_i\ (t-1)+Y_i(t)\ if\ demand\ from\ consumers\ is\ larger\ than\ supply \end{cases}$$

where $S_i\ (t-1)$ is the inventory of finished goods.

Sales $Q_i\ (t)$ are then the realized demand dependent on the supply available from firm i after the production process has taken place:

$$Q_i\ (t) = \ min\left(S_i\ (t-1)+Y_i(t), Q_i^d(t)\right)$$

Firms: external funding & investment

If internal financial resources $D_i\ (t-1)$ of a firm are not enough to finance its expected expenditures $\Delta D_i^e(t)$, the firm will ask for a bank loan to cover its financing gap,

$$\Delta L_i^d(t) = \Delta D_i^e(t) - D_i\ (t-1)$$

The availability of credit depends on the financial condition of the firm and will be limited by the expected market value of the collateral and the total outstanding debt,

$$\Delta L_i\ (t) \leq \zeta^{LTV}(1+\pi^e\ (t))\bar{P}^{CF}(t-1)K_i^e(t) - (1-\theta)L_i\ (t-1)$$

If firm i has a funding gap, i.e. the difference between requested and granted external funding $(\Delta L_i^d(t) - \Delta L_i\ \ (t))$, the firms' investment is reduced,

$$I_i^d(t) = \frac{\delta_i Q_i^s(t)}{\kappa_i} - \frac{\Delta L_i^d(t) - \Delta L_i\ (t)}{\left(1+\pi^e\ (t)\right)\bar{P}^{CF}(t-1)}$$

where δ_i is the firm's capital depreciation rate. Therefore, a fall in asset prices results in a deterioration of the ability of firms to borrow, which has a negative impact on their investment.

Individual persons (household sector)

Households: Economic activities

\+ Wages and salaries (D.11)
\+ Property Income (D.4)
\+ Mixed Income from Self-Employment (B2A3N)
\+ Social benefits other than social transfers in kind (D.62)
\+ Other current transfers net (D7, D8, D.9)
\- Final consumption expenditure (P.3)
\- Taxes on products (D.21)
\- Taxes on income (D.5)
\- Employees' social contributions (D.612, D.613, D.614)
\- Capital formation (dwellings) (P.51)

Households: Income

Income: each household forms expectations on its expected nominal disposable income $Y_h^e(t)$ (i.e. expected net income after taxes and including social or unemployment benefits):

$$Y_h^e(t) = \begin{cases} \left(w_h(t)\left[1 - \tau^{SIW} - \tau^{INC}(1 - \tau^{SIW})\right] + sb^{other}\right) \bar{P}^{HH}(t-1)(1+\pi^e(t)) & \text{if employed} \\ \left(w_h(t) + sb^{other}\right) \bar{P}^{HH}(t-1)(1+\pi^e(t)) & \text{if unemployed} \\ \left(sb^{inact} + sb^{other}\right) \bar{P}^{HH}(t-1)(1+\pi^e(t)) & \text{if not economically active} \\ \theta^{DIV}(1-\tau^{INC})(1-\tau^{FIRM})\max(0, \Pi_i^e(t)) + sb^{other}\bar{P}^{HH}(t-1)(1+\pi^e(t)) & \text{if an investor} \\ \theta^{DIV}(1-\tau^{INC})(1-\tau^{FIRM})\max(0, \Pi_k^e(t)) + sb^{other}\bar{P}^{HH}(t-1)(1+\pi^e(t)) & \text{if a bank investor} \end{cases}$$

Here,

$w_h(t)$ is wage income or unemployment benefits (which are a fixed fraction θ of the wage last earned before the unemployment) of household h,

$\bar{P}^{HH}(t-1)$ is last period's consumer price index,

$\Pi_i^e(t)$ are expected profits of firm i, $\Pi_k^e(t)$ are expected bank profits,

sb^{inact} are social benefits for inactive persons (mostly pension payments), sb^{other} social benefits distributed equally to all households

τ^{INC} is the income tax rate, τ^{SIW} is the rate of social insurance contributions to be paid by the employee, θ^{DIV} is the dividend payout ratio, and τ^{FIRM} the corporate tax rate.

Households: Consumption, Investment & Savings

Households spend a fraction of their expected income on **consumption**:

$$C_h^d(t) = \frac{\psi Y_h^e(t)}{1+\tau^{VAT}}$$

and on **investment**:

$$I_h^d(t) = \frac{\psi^H Y_h^e(t)}{1+\tau^{CF}}$$

where ψ, ψ^H are propensities to consume, invest out of expected income; τ^{VAT}, τ^{CF} are value added, investment tax rates. Total household consumption allocated to goods g according to fixed coefficients from IOTs, analogous to firm investment above.

Savings: difference between realized disposable income $Y_h\ (t)$, realized consumption expenditure $C_h\ (t)$, used to accumulate financial wealth:

$$D_h(t) = D_h(t-1) + \overbrace{Y_h(t) - [(1+\tau^{VAT})C_h(t) + (1+\tau^{CF})I_h(t)]}^{\text{Savings}}$$

General Government

General Government: Economic activities

The government mainly acts as a consumer (**government consumption**) and as a **"redistributive" entity** consumes on the goods market to provide a public good, collects taxes, and provides transfers:

+ Taxes on income (D.5, D.91)
+ Taxes on products and production (D.2)
+ Property Income (D.4)
+ Social contributions (D.61)
- Final consumption (P.3)
- Subsidies (D.3)
- Interest payments (D.41)
- Social benefits other than social transfers in kind (D.62)
- Other current expenditures (D.7, D.8, D.9)

General Government: Revenues

$$
\begin{aligned}
Y^G(t) = {} & \overbrace{(\tau^{SIF} + \tau^{SIW})\bar{P}^{HH}(t) \sum_{h \in H^E(t)} w_h(t)}^{\text{Social security contributions}} + \overbrace{\tau^{INC}(1 - \tau^{SIW})\bar{P}^{HH}(t) \sum_{h \in H^E(t)} w_h(t)}^{\text{Labour income taxes}} \\
& + \overbrace{\tau^{VAT} \sum_h C_h(t)}^{\text{Value added taxes}} \\
& + \overbrace{\tau^{INC}(1 - \tau^{FIRM})\theta^{DIV} \left(\sum_i \max(0, \Pi_i(t)) + \max(0, \Pi_k(t)) \right)}^{\text{Capital income taxes}} \\
& + \overbrace{\tau^{FIRM} \left(\sum_i \max(0, \Pi_i(t)) + \max(0, \Pi_k(t)) \right)}^{\text{Corporate income taxes}} + \underbrace{\tau^{CF} \sum_h I_h(t)}_{\text{Taxes on capital formation}} \\
& + \underbrace{\sum_{s, i \in I_s} \tau_i^Y P_i(t) Y_i(t)}_{\text{Net taxes/subsidies on products}} + \underbrace{\bar{P}^{CF}(t) \sum_i \tau_i^K K_i(t)}_{\text{Net taxes/subsidies on production}} + \underbrace{\tau^{EXPORT} \sum_l C_l(t)}_{\text{Export taxes}} .
\end{aligned}
$$

General Government: Deficit & Debt

The **government deficit** (or surplus) resulting from its redistributive activities is

$$\Pi^G(t) = \overbrace{Y^G(t)}^{\text{Government revenues}} - \overbrace{\sum_j C_j(t)}^{\text{Government consumption}} - \overbrace{r^G L^G(t)}^{\text{Interest payments}}$$
$$- \underbrace{\sum_{h \in H^{inact}} \bar{P}^{HH}(t) sb^{inact} + \sum_{h \in H^U(t)} \bar{P}^{HH}(t) w_h(t) + \sum_h \bar{P}^{HH}(t) sb^{other}}_{\text{Social benefits and transfers}}$$

The **government debt** is determined by the year-to-year deficits/surpluses of the government sector:

$$L^G(t) = L^G(t-1) + \Pi^G(t)$$

Financial corporations (banking sector)

Banking sector

The bank takes deposits from firms and households, and extends a total amount of loans $L^{tot}(t) = \Sigma_{i=1}^{I} L_i(t)$

The bank will grant a loan to firm i up to the point where the borrower's leverage (loan-to-value) ratio after the loan,

$$\frac{L_i(t)}{\bar{P}^{CF}(t-1)K_i \ \ (t)} \leq \zeta^{LTV}$$

is below ζ^{LTV}, which is a constant.

Furthermore, the bank is subject to minimum capital requirements, i.e. it can only extend total loans up to a maximum multiple of its equity base or net worth $E^B(t)$.

The interest rate $r(t)$ for bank credit to firms is determined by means of a fixed risk premium μ over the policy rate $\bar{r}(t)$ set by the central bank according to a Taylor rule:

$$r(t) = \bar{r}(t) + \mu$$

The Central Bank

The central bank **sets the policy rate** $\bar{r}(t)$ based on implicit inflation and growth targets, **provides liquidity** to the banking system (advances to the bank), and takes deposits from the bank in the form of reserves deposited at the central bank.

The policy rate is determined by an augmented Taylor rule, where the central bank agent learns the optimal parameters. Following Blattner and Margaritov (2010), we include forecasted quarter-over-quarter inflation and real GDP growth in the reaction function:

$$\bar{r}(t) = \rho(t-1)\bar{r}(t-1) + (1-\rho(t-1))(r^*(t-1) + \pi^* + \xi^\pi(t-1)(\pi^e(t) - \pi^*) + \xi^\gamma(t-1)\gamma^e(t))$$

where $\rho(t-1)$ is the interest rate smoothing parameter that reflects the gradual adjustment to the policy rate, $r^*(t-1)$ is the real equilibrium interest rate, π^* is the inflation target, $\xi^\pi(t-1)$ is the policy parameter on inflation deviations from the target, and $\xi^\gamma(t-1)$ is the weight on the forecasted real GDP growth rate.

Exports, Imports, Government Consumption

These economic aggregates are either assumed to be exogenously given from data (conditional forecasts) or to follow autoregressive (AR) processes due to the assumption of a small open economy setting.

Imports $Y^I(t)$, exports $C^E(t)$ and government consumption $C^G(\mathrm{t})$ (all real and in log levels) follow AR(1) processes:

$$Y^I(t) = \alpha^I Y^I(t-1) + \beta^I + \epsilon^I(t)$$

$$C^E(t) = \alpha^E C^E(t-1) + \beta^E + \epsilon^E(t)$$

$$C^G(\mathrm{t}) = \alpha^G C^G(t-1) + \beta^G + \epsilon^G(t)$$

Complete GDP identity

$$
\begin{aligned}
GDP(t) = {} & \underbrace{\sum_i \tau_i^{\mathrm{Y}} P_i(t) Y_i(t) + \sum_h \tau^{\mathrm{VAT}} C_h(t) + \sum_h \tau^{\mathrm{CF}} I_h(t) + \sum_j \tau^{\mathrm{G}} C_j(t) + \sum_l \tau^{\mathrm{EXPORT}} C_l(t)}_{\text{Taxes on products}} \\
& + \underbrace{\sum_i (1-\tau_i^{\mathrm{Y}}) P_i(t) Y_i(t)}_{\text{Total sales of goods and services}} - \underbrace{\sum_i \frac{1}{\beta_i} \bar{P}_i(t) Y_i(t)}_{\text{Intermediate inputs}} \quad \text{(Production approach)} \\
= {} & \underbrace{\sum_h (1+\tau^{\mathrm{VAT}}) C_h(t)}_{\text{Household consumption}} + \underbrace{\sum_j (1+\tau^{\mathrm{G}}) C_j(t)}_{\text{Government consumption}} + \underbrace{\sum_h (1+\tau^{\mathrm{CF}}) I_h(t) + \sum_i P_i^{\mathrm{CF}}(t) I_i(t)}_{\text{Gross fixed capital formation}} \\
& + \underbrace{\sum_i P_i(t)(Y_i(t) - Q_i(t)) + \bar{P}_i(t) \left(\Delta M_i(t) - \frac{1}{\beta_i} Y_i(t) \right)}_{\text{Changes in inventories}} \\
& + \underbrace{\sum_l (1+\tau^{\mathrm{EXPORT}}) C_l(t)}_{\text{Exports}} - \underbrace{\sum_m P_m(t) Q_m(t))}_{\text{Imports}} \quad \text{(Expenditure approach)} \\
= {} & \underbrace{\sum_i \tau_i^{\mathrm{Y}} P_i(t) Y_i(t) + \sum_h \tau^{\mathrm{VAT}} C_h(t) + \sum_h \tau^{\mathrm{CF}} I_h(t) + \sum_j \tau^{\mathrm{G}} C_j(t) + \sum_l \tau^{\mathrm{EXPORT}} C_l(t)}_{\text{Taxes on products}} \\
& + \underbrace{\sum_i P_i(t) Y_i(t) - (1+\tau^{\mathrm{SIF}}) \bar{P}^{\mathrm{HH}}(t) N_i(t) w_i(t) - \frac{1}{\beta_i} \bar{P}_i(t) Y_i(t) - \tau_i^{\mathrm{Y}} P_i(t) Y_i(t) - \tau_i^{\mathrm{K}} P_i(t) Y_i(t)}_{\text{Gross operating surplus and mixed income}} \\
& + \underbrace{\sum_i (1+\tau^{\mathrm{SIF}}) \bar{P}^{\mathrm{HH}}(t) N_i(t) w_i(t)}_{\text{Compensation of employees}} + \underbrace{\sum_i \tau_i^{\mathrm{K}} P_i(t) Y_i(t)}_{\text{Net taxes on production}} \quad \text{(Income approach)}
\end{aligned}
$$

IIASA Macroeconomic ABM calibration

Calibration

All parameters are calibrated to micro and macro data such that there is **no burn-in period** that has to be disregarded.

Data sources include national accounts, input-output tables, government statistics, demography data, and firm-level data.

Name	Code
Population by current activity status, NACE Rev. 2 activity and NUTS 2 region	cens_11an_r2
Business demography by legal form (from 2004 onwards, NACE Rev. 2)	bd_9ac_l_form_r2
Symmetric input-output table at basic prices (product by product)	naio_10_cp1700
Cross-classification of fixed assets by industry and by asset (stocks)	nama_10_nfa_st
Government revenue, expenditure and main aggregates	gov_10a_main
General government expenditure by function (COFOG)	gov_10a_exp
Quarterly non-financial accounts for general government	gov_10q_ggnfa
Quarterly government debt	gov_10q_ggdebt
Financial balance sheets	nasq_10_f_bs
Non-financial transactions (annually)	nasa_10_nf_tr
Non-financial transactions (quarterly)	nasq_10_nf_tr
GDP and main components (output, expenditure and income)	namq_10_gdp
Money market interest rates - quarterly data	irt_st_q

Eurostat data tables used

Parameters

Parameter	Description	Value	Source
G/S	Number of products/industries	62	census data, business demography data
H^{act}	Number of economically active persons	4729215	
H^{inact}	Number of economically inactive persons	4130385	
J	Number of government entities	152820	
L	Number of foreign consumers	305639	
I_s	Number of firms/investors in the s^{th} industry	see Online Appendix D	
$\bar{\alpha}_i$	Average productivity of labour of the i^{th} firm	parameters are firm/sector specific; see Online Appendix D	input-output tables
κ_i	Productivity of capital of the i^{th} firm		
β_i	Productivity of intermediate consumption of the i^{th} firm		
δ_i	Depreciation rate for capital of the i^{th} firm		
$\bar{w}_i$	Average wage rate of firm i		
a_{sg}	Technology coefficient of the g^{th} product in the s^{th} industry		
b_g^{CF}	Capital formation coefficient of the g^{th} product (firm investment)		
b_g^{CFH}	Household investment coefficient of the g^{th} product		
b_g^{HH}	Consumption coefficient of the g^{th} product of households		
c_g^{G}	Consumption of the g^{th} product of the government in mln. Euro		
c_g^{E}	Exports of the g^{th} product in mln. Euro		
c_g^{I}	Imports of the g^{th} product in mln. Euro		
τ_i^{Y}	Net tax rate on products of the i^{th} firm		
τ_i^{K}	Net tax rate on production of the i^{th} firm		
τ^{INC}	Income tax rate	0.2134	government statistics, sector accounts
τ^{FIRM}	Corporate tax rate	0.0762	
τ^{VAT}	Value-added tax rate	0.1529	
τ^{SIF}	Social insurance rate (employers' contributions)	0.2122	
τ^{SIW}	Social insurance rate (employees' contributions)	0.1711	
τ^{EXPORT}	Export tax rate	0.0029	
τ^{CF}	Tax rate on capital formation	0.0876	
τ^{G}	Tax rate on government consumption	0.0091	
r^{G}	Interest rate on government bonds	0.0091	
μ	Risk premium on policy rate	0.0293	
ψ	Fraction of income devoted to consumption	0.9394	
ψ^{H}	Fraction of income devoted to investment in housing	0.0736	
θ^{DIV}	Dividend payout ratio	0.7768	
θ^{UB}	Unemployment benefit replacement rate	0.3586	Basel III, ECB statutes, banking practices, literature
θ	Rate of instalment on debt	0.05	
ζ	Banks' capital ratio	0.03	
ζ^{LTV}	Loan-to-value (LTV) ratio	0.6	
ζ^{b}	Loan-to-capital ratio for new firms after bankruptcy	0.5	
π^*	Inflation target of the monetary authority	0.005	

Model parameters for the Austrian economy for 2010:Q4

Initial conditions

Initial condition	Description	Value	Source
$P_i(0)$	Initial price of the i^{th} firm	firm level	sector accounts
$Y_i(0)/Q_i^{\mathrm{d}}(0)$	Initial production/demand of the i^{th} firm (in mln. Euro)		
$K_i(0)$	Initial capital of the i^{th} firm (in mln. Euro)		
$M_i(0)$	Initial stocks of raw materials, consumables, supplies of the i^{th} firm (in mln. Euro)		
$S_i(0)$	Initial stocks of finished goods of the i^{th} firm (in mln. Euro)		
$N_i(0)$	Initial number of employees of the i^{th} firm		
$D_i(0)$	Initial liquidity (deposits) of the i^{th} firm (in mln. Euro)		
$L_i(0)$	Initial debt of the i^{th} firm (in mln. Euro)		
$\Pi_i(0)$	Initial profits of the i^{th} firm (in mln. Euro)		
$D_h(0)$	Initial personal assets (deposits) of the h^{th} household (in mln. Euro)	-	sector accounts, government statistics
$K_h(0)$	Initial household capital (in mln. Euro)	-	
$w_h(0)$	Initial wage of the h^{th} household (in mln. Euro)	-	
$sb^{\mathrm{inact}}(0)$	Initial pension/social benefits in mln. Euro	0.0022	
$sb^{\mathrm{other}}(0)$	Initial social benefits received by all households in mln. Euro	0.0007	
$L^{\mathrm{G}}(0)$	Initial government debt (in mln. Euro)	243871.1	
$\Pi_k(0)$	Initial banks' profits (in mln. Euro)	6516.2	
$E_k(0)$	Initial banks' equity (in mln. Euro)	97802.3	
$E^{\mathrm{CB}}(0)$	Initial central banks' equity (in mln. Euro)	115947.6	
$D^{\mathrm{RoW}}(0)$	Initial net creditor/debtor position of the national economy to RoW (in mln. Euro)	0	

Initial conditions for the Austrian economy for 2010:Q4

IIASA Macroeconomic ABM forecast performance

Out-of-sample forecast performance in comparison to VAR for Austria

	GDP	Inflation	Government consumption	Exports	Imports	GDP EA	Inflation EA	Euribor
VAR(1)	*RMSE-statistic for different forecast horizons*							
1q	0.45	0.33	0.66	1.53	1.66	0.41	0.17	0.05
2q	0.82	0.3	0.67	2.83	2.66	0.79	0.15	0.08
4q	1.78	0.28	1	6.18	5.67	1.85	0.16	0.18
8q	4.06	0.28	1.61	13.46	11.96	4.08	0.18	0.42
12q	5.83	0.25	2.1	18.93	16.08	5.36	0.19	0.57
ABM	*Percentage improvements (+) or losses (-) relative to VAR(1) model*							
1q	-13 (0.36)	9.8 (0.21)	-14.1 (0.31)	10 (0.45)	7.5 (0.54)	-1.1 (0.94)	11.5 (0.12)	25.6 (0.16)
2q	4.3 (0.82)	7 (0.02**)	-14.5 (0.06*)	28.8 (0.04**)	16.8 (0.24)	2.6 (0.90)	-4.7 (0.64)	17.7 (0.35)
4q	25.6 (0.40)	0.1 (0.99)	3.6 (0.71)	47.4 (0.06*)	35.6 (0.12)	19.8 (0.60)	-4.8 (0.59)	37.7 (0.00***)
8q	46 (0.39)	-0.4 (0.92)	15.9 (0.13)	60.5 (0.16)	50.3 (0.23)	32.1 (0.63)	5.3 (0.58)	62.5 (0.02**)
12q	49.2 (0.50)	-0.5 (0.90)	13.4 (0.49)	62.2 (0.26)	48.1 (0.37)	25 (0.79)	5.8 (0.14)	64.2 (0.01**)

RMSE-statistic for main aggregates from ABM simulations in comparison to a VAR(1) model for the forecast period from 2010:Q2-2019:Q4 for Austria.

Poledna, S., Miess, M. G., Hommes, C., & Rabitsch, K. (2023)

Comparison to DSGE models

As a comparison, we use the benchmark model of Smets and Wouters (2007) and the main DSGE model of the Bank of Canada ToTEM III.

ToTEM III is a large-scale, multi-sector, small-open-economy model with many shocks:

- Imperfectly competitive finished-goods sector for consumption, investment, government and non-commodity exports
- Small degree of nominal rigidity combined with firm-specific capital services
- Separate commodity-producing sector featuring perfect competition and flexible prices
- Commodities are used in the production of finished goods or are exported

Out-of-sample forecast performance in comparison to VAR and DSGE model for Canada

	GDP	Inflation	Consumption	Investment	Exports	Imports
VAR(1)	*RMSE-statistic for different forecast horizons*					
1q	0.48	0.73	0.33	1.54	2.17	1.8
2q	0.76	0.68	0.54	2.7	2.98	2.68
4q	1.24	0.65	1.01	5.19	3.53	4.55
8q	1.9	0.69	1.66	9.95	4.57	9.22
12q	2.24	0.71	1.98	15.14	4.65	13.83
ToTEM (III)	*Percentage gains (+) or losses (-) relative to VAR(1) model*					
1q	-27.2 (0.09)	14.4 (0.07)	-49.2 (0.00)	-18.8 (0.03)	14.9 (0.05)	24.2 (0.00)
2q	-56 (0.01)	7.3 (0.09)	-77.5 (0.00)	-28.7 (0.02)	20.4 (0.16)	27.6 (0.01)
4q	-73.4 (0.00)	1.9 (0.71)	-76.7 (0.02)	-16.8 (0.15)	6.8 (0.67)	30.1 (0.02)
8q	-58.5 (0.03)	8 (0.14)	-56.6 (0.18)	15.9 (0.50)	8.7 (0.78)	48 (0.00)
12q	-33.8 (0.29)	6.4 (0.23)	-39.2 (0.07)	41.5 (0.01)	24.7 (0.19)	64.9 (0.03)
CAN-ABM	*Percentage gains (+) or losses (-) relative to VAR(1) model*					
1q	0.6 (0.93)	10.1 (0.07)	-51.5 (0.01)	5.4 (0.49)	-0.7 (0.89)	13.5 (0.20)
2q	4 (0.46)	-0.6 (0.84)	-67.8 (0.02)	13.3 (0.02)	0.8 (0.90)	21.6 (0.07)
4q	17.2 (0.02)	-5.3 (0.27)	-25.3 (0.43)	23.6 (0.08)	-6.1 (0.36)	42.3 (0.02)
8q	20.6 (0.04)	-6.4 (0.19)	7.7 (0.85)	33.5 (0.09)	-15.5 (0.31)	65.9 (0.01)
12q	33.4 (0.00)	-2.4 (0.58)	31.8 (0.67)	43.3 (0.00)	-38.5 (0.17)	79.6 (0.05)

RMSE-statistic for main aggregates from ABM simulations in comparison to a VAR(1) and the main DSGE model of the Bank of Canada (ToTEM III) for the forecast period from 2010:Q2-2019:Q4 for Canada.

Hommes et al. (2022)

Out-of-sample forecast performance in comparison to VAR for the euro area

	GDP	Inflation	Euribor	Government consumption	Exports
VAR(1)	*RMSE-statistic for different forecast horizons*				
1q	0.74	0.21	0.09	0.31	2.1
2q	1.63	0.21	0.18	0.48	4.88
4q	3.59	0.23	0.39	0.88	10.73
8q	6.98	0.25	0.71	1.75	20.46
12q	7.72	0.22	0.7	2.61	22.47
ABM	*Percentage gains (+) or losses (-) relative to VAR(1) model*				
1q	3.1 (0.31)	8.5 (0.10)	1.4 (0.47)	-98.4 (0.90)	-3.4 (0.54)
2q	11 (0.11)	4.6 (0.29)	9.1 (0.27)	-64.2 (0.85)	18.5 (0.24)
4q	30.4 (0.12)	9.6 (0.18)	26.1 (0.12)	-9 (0.82)	36.4 (0.13)
8q	45.3 (0.13)	14.6 (0.15)	46.7 (0.09)	-17.3 (0.82)	52.4 (0.11)
12q	38.1 (0.14)	9.1 (0.12)	42.5 (0.03)	-19.8 (0.84)	52.8 (0.07)
ABM (with financial frictions)	*Percentage gains (+) or losses (-) relative to VAR(1) model*				
1q	8.1 (0.40)	3.1 (0.43)	-2.3 (0.53)	-18.8 (0.96)	-4.5 (0.56)
2q	21.2 (0.21)	11.6 (0.26)	10.8 (0.30)	-4.6 (0.73)	18.6 (0.24)
4q	35.1 (0.14)	3.1 (0.33)	32.3 (0.13)	-7 (0.86)	36.6 (0.13)
8q	53.9 (0.14)	18 (0.14)	53.1 (0.10)	-14.1 (0.84)	51.9 (0.11)
12q	52.5 (0.16)	4.9 (0.29)	57.6 (0.03)	-12.4 (0.92)	52.2 (0.07)

RMSE-statistic for main aggregates from ABM simulations in comparison to a VAR(1) for the forecast period from 2005:Q2-2019:Q4 for the euro area.

Hommes & Poledna (2023)

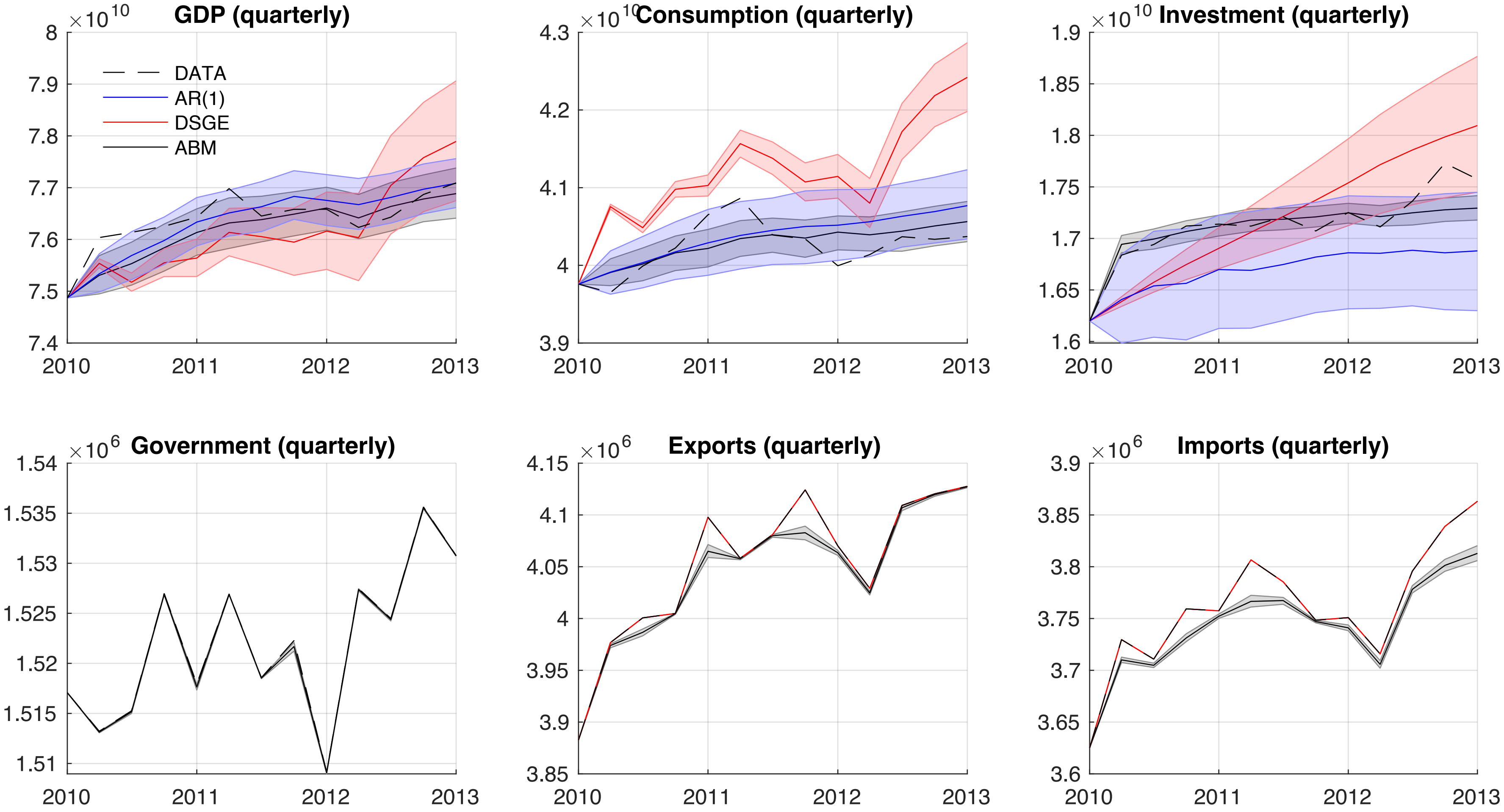
Out-of-sample forecast performance of sectoral gross value added (GVA) for Austria

	A	B, C, D and E	F	G, H and I	J	K	L	M and N	O, P and Q	R and S
VAR(1)	*RMSE-statistic for different forecast horizons*									
1q	5.25	1.2	1.49	0.8	1.66	3.29	0.41	1.17	0.46	0.62
2q	7.32	1.71	1.93	1.15	2.01	3.63	0.6	1.57	0.61	0.83
4q	9.9	2.24	3.35	1.83	2.96	5.03	0.9	2.28	0.88	1.19
8q	10.76	2.83	5.99	2.96	2.75	4.58	1.22	3.75	1.46	1.86
12q	13.67	3.31	8.06	3.79	3.63	4.45	1.72	5.04	1.94	2.63
ABM	*Percentage improvements (+) or losses (-) relative to VAR(1) model*									
1q	0.5 (0.95)	-2.3 (0.82)	23.9 (0.04**)	-6.8 (0.40)	4.9 (0.47)	14.8 (0.04**)	-39.1 (0.01***)	-15.7 (0.24)	-1.3 (0.87)	12.3 (0.32)
2q	2.6 (0.36)	7.3 (0.18)	8.8 (0.04**)	-7.4 (0.61)	2.5 (0.82)	0.6 (0.90)	-90.2 (0.00***)	-14.1 (0.33)	-15.1 (0.34)	10.4 (0.52)
4q	8.4 (0.08*)	5.8 (0.17)	8.5 (0.01***)	-3.6 (0.88)	-2.8 (0.74)	1.8 (0.45)	-150.8 (0.00***)	-24.3 (0.36)	-34.3 (0.36)	14.5 (0.47)
8q	8.1 (0.44)	7.6 (0.16)	7.8 (0.00***)	15.6 (0.66)	-48.2 (0.01***)	5.8 (0.35)	-250 (0.00***)	-24.2 (0.51)	-54.4 (0.41)	28.7 (0.35)
12q	9.1 (0.39)	6.8 (0.21)	10.2 (0.09*)	38.4 (0.56)	-64.6 (0.00***)	5.4 (0.62)	-271 (0.00***)	-31.3 (0.51)	-74.1 (0.43)	27.5 (0.46)

RMSE-statistic for sectoral gross value added (GVA) from ABM simulations in comparison to a VAR(1) models. GVA is shown for the sectors Agriculture, forestry and fishing (A); Industry (except construction) (B, C, D and E); Manufacturing (C); Construction (F); Wholesale and retail trade, transport, accommodation and food service activities (G, H and I); Information and communication (J); Financial and insurance activities (K); Real estate activities (L); Professional, scientific and technical activities, as well as administrative and support service activities (M and N); Public administration, defence, education, human health and social work activities (O, P and Q); Arts, entertainment, and recreation, as well as other service activities (R and S).

Poledna, S., Miess, M. G., Hommes, C., & Rabitsch, K. (2023)

Conditional forecast performance in comparison to DSGE



Comparison of ABM conditional forecasts (black), ARX(1) (blue), DSGE conditional forecasts (red), and observed Eurostat data for Austria (dashed line) for a forecast horizon of 12 quarters.

IIASA Macroeconomic ABM applications

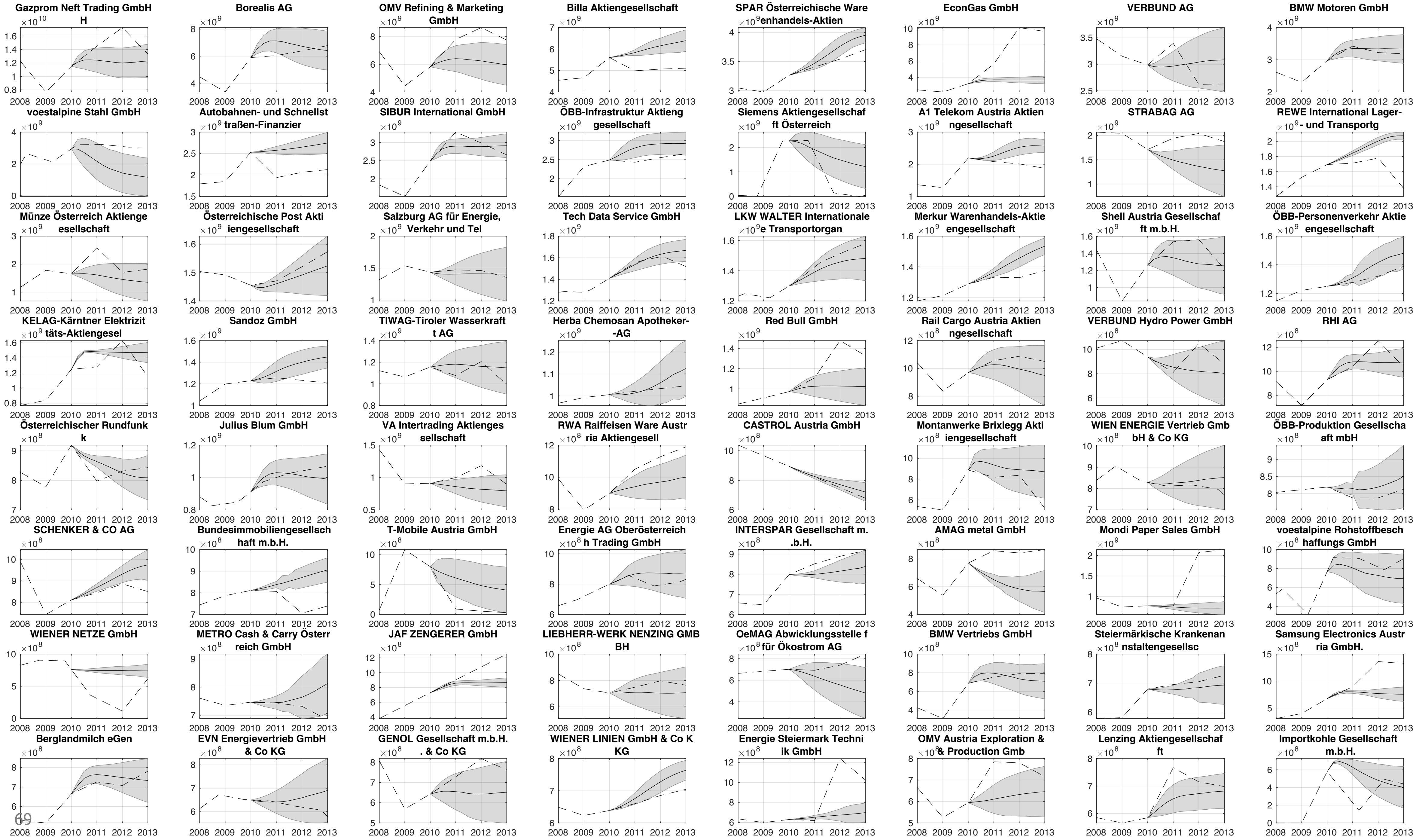
- Earnings forecasts for Austrian firms
- Flash projections in the COVID pandemic in Austria
- Post-pandemic inflation in Canada
- Financial crisis in the euro area
- Economic effects of natural disasters

Earnings forecasts for Austrian firms (work in progress)

Earnings forecasts for Austrian firms

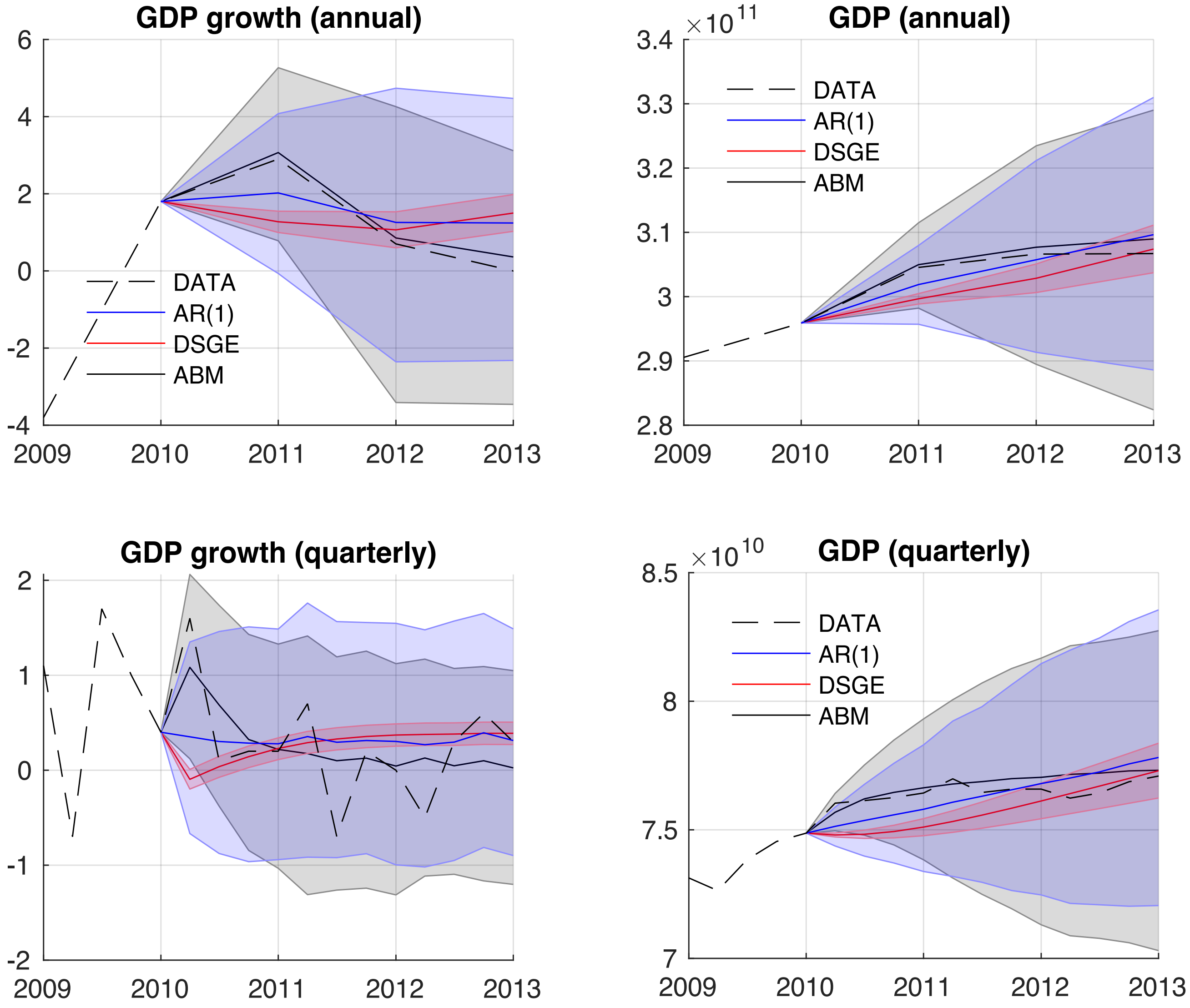
Based on the SABINA database from Bureau van Dijk

- Company financials, in a detailed format, with up to 10 years of history for 175.000 companies in Austria
- Directors, shareholders and subsidiaries
- Activity codes and trade descriptions
- Stock data for listed companies
- Detailed corporate structures and the corporate family Business and company-related news
- M&A deals and rumors



Gazprom Neft Trading GmbH
H
Borealis AG
OMV Refining & Marketing
GmbH
Billa Aktiengesellschaft
SPAR Österreichische Ware
enhandels-Aktien
EconGas GmbH
VERBUND AG
BMW Motoren GmbH
voestalpine Stahl GmbH
Autobahnen- und Schnellst
traßen-Finanzier
SIBUR International GmbH
ÖBB-Infrastruktur Aktieng
gesellschaft
Siemens Aktiengesellschaf
ft Österreich
A1 Telekom Austria Aktien
ngesellschaft
STRABAG AG
REWE International Lager-
- und Transportg
Münze Österreich Aktienge
esellschaft
Österreichische Post Akti
iengesellschaft
Salzburg AG für Energie,
Verkehr und Tel
Tech Data Service GmbH
LKW WALTER Internationale
e Transportorgan
Merkur Warenhandels-Aktie
engesellschaft
Shell Austria Gesellschaf
ft m.b.H.
ÖBB-Personenverkehr Aktie
engesellschaft
KELAG-Kärntner Elektrizit
täts-Aktiengesel
Sandoz GmbH
TIWAG-Tiroler Wasserkraft
t AG
Herba Chemosan Apotheker-
-AG
Red Bull GmbH
Rail Cargo Austria Aktien
ngesellschaft
VERBUND Hydro Power GmbH
RHI AG
Österreichischer Rundfunk
k
Julius Blum GmbH
VA Intertrading Aktienges
sellschaft
RWA Raiffeisen Ware Austr
ria Aktiengesell
CASTROL Austria GmbH
Montanwerke Brixlegg Akti
iengesellschaft
WIEN ENERGIE Vertrieb Gmb
bH & Co KG
ÖBB-Produktion Gesellscha
aft mbH
SCHENKER & CO AG
Bundesimmobiliengesellsch
haft m.b.H.
T-Mobile Austria GmbH
Energie AG Oberösterreich
h Trading GmbH
INTERSPAR Gesellschaft m.
.b.H.
AMAG metal GmbH
Mondi Paper Sales GmbH
voestalpine Rohstoffbesch
haffungs GmbH
WIENER NETZE GmbH
METRO Cash & Carry Österr
reich GmbH
JAF ZENGERER GmbH
LIEBHERR-WERK NENZING GMB
BH
OeMAG Abwicklungsstelle f
für Ökostrom AG
BMW Vertriebs GmbH
Steiermärkische Krankenan
nstaltengesellsc
Samsung Electronics Austr
ria GmbH.
Berglandmilch eGen
EVN Energievertrieb GmbH
& Co KG
GENOL Gesellschaft m.b.H.
. & Co KG
WIENER LINIEN GmbH & Co K
KG
Energie Steiermark Techni
ik GmbH
OMV Austria Exploration &
& Production Gmb
Lenzing Aktiengesellschaf
ft
Importkohle Gesellschaft
m.b.H.

Earnings forecasts to GDP



Comparison of ABM simulations with firm-level data (black), AR(1) (blue), DSGE (red), and observed Eurostat data for Austria (dashed line) for a forecast horizon of 12 quarters.

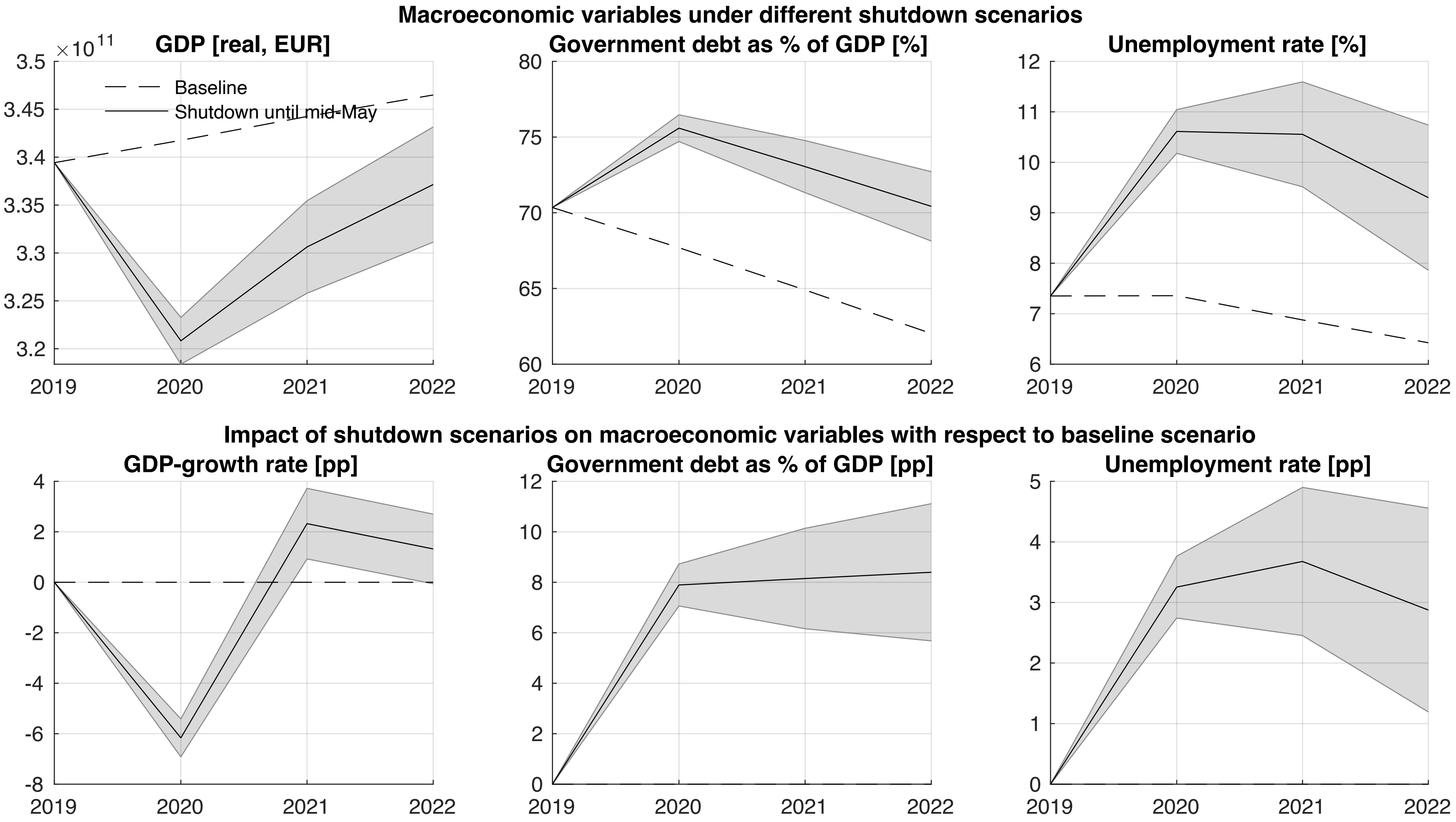
Flash projections in the COVID-19 pandemic in Austria

with Elena Rovenskaya, Jesus Crespo Cuaresma, Serguei Kaniovski, and Michael Miess

Flash projections in the COVID-19 pandemic in Austria

- Parameters of the model are calibrated with Austrian data (as of 2019Q4): national accounts, census, firm-level data, input-output tables
- The COVID-19 shock is calibrated using labor market data (AMS), assumption on the use of short-time work and forecasts by Oxford Economics (imports / exports):
    - AMS data for March 2020 (by sector) + assumption that approx. 65% of companies use short-time work
    - April 2020 forecasts for Austrian imports and exports (Oxford Economics)

Projections vs. Benchmark



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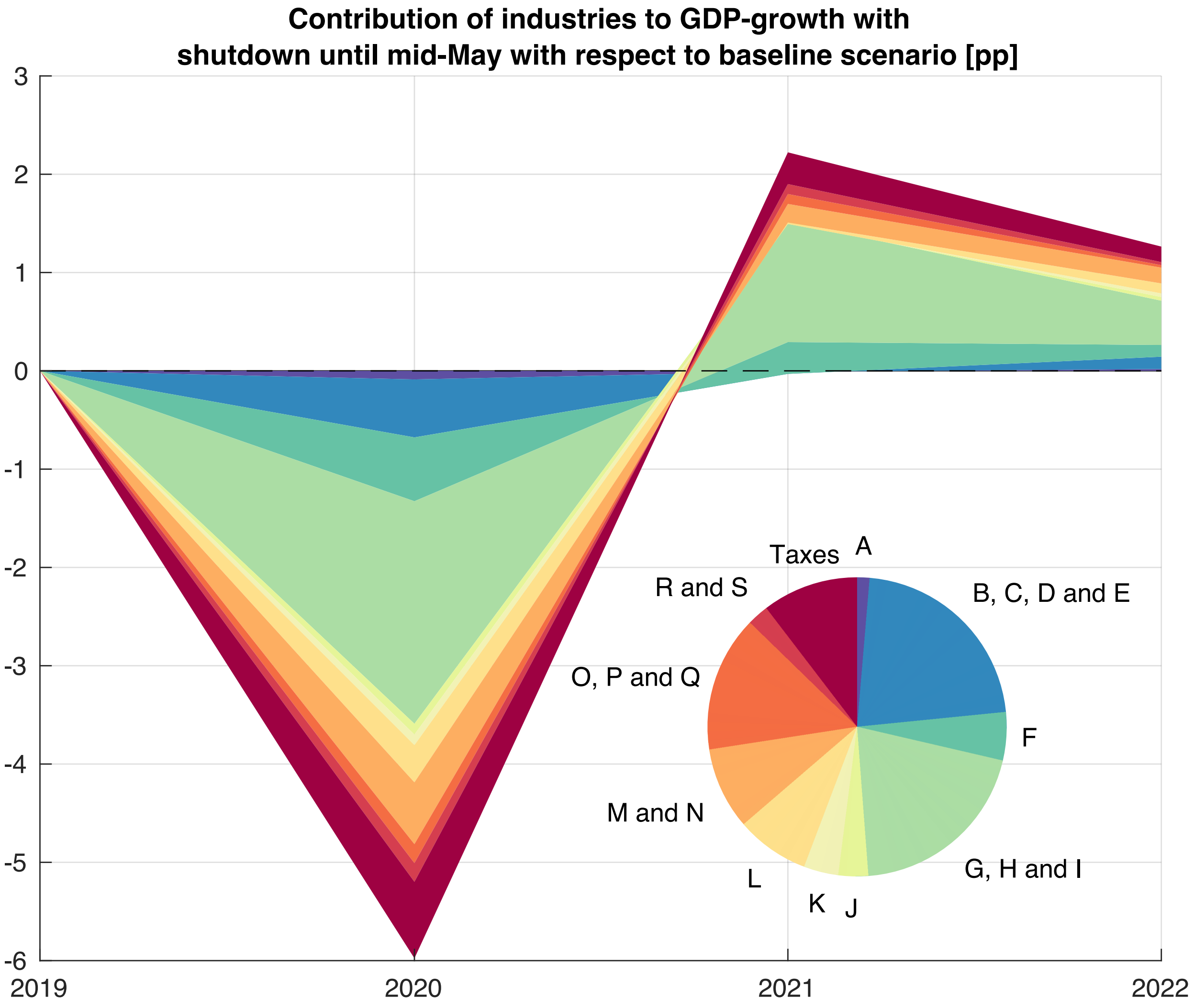
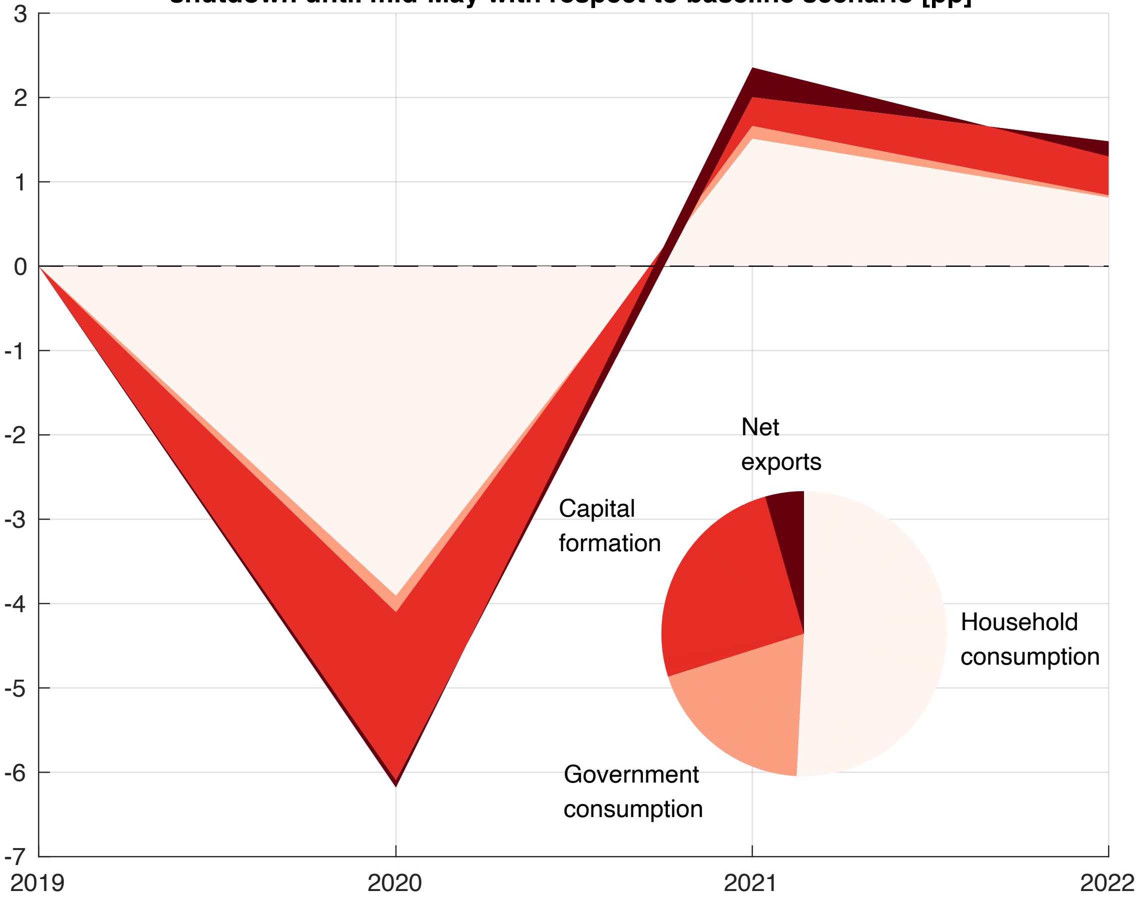
Projections vs. Benchmark



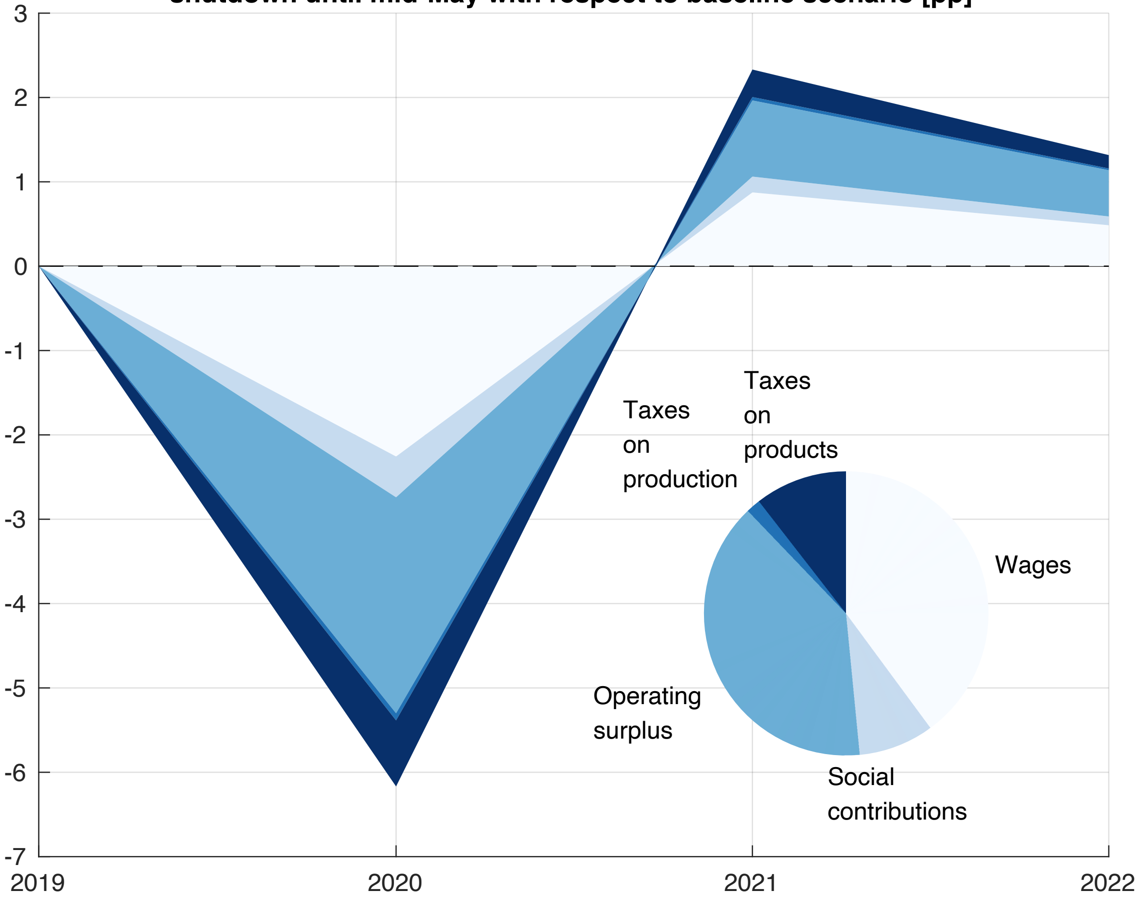
Contribution is shown of the sectors Agriculture, forestry and fishing (A); Industry (except construction) (B, C, D and E); Manufacturing (C); Construction (F); Wholesale and retail trade, transport, accommodation and food service activities (G, H and I); Information and communication (J); Financial and insurance activities (K); Real estate activities (L); Professional, scientific and technical activities, as well as administrative and support service activities (M and N); Public administration, defence, education, human health and social work activities (O, P and Q); Arts, entertainment, and recreation, as well as other service activities (R and S).

Projections vs. Benchmark

Contribution of expenditure components to GDP-growth with shutdown until mid-May with respect to baseline scenario [pp]



Contribution of income components to GDP-growth with shutdown until mid-May with respect to baseline scenario [pp]



Application: Post-pandemic inflation in Canada

with Cars Hommes, Jakob Grazzini, Mario He, Melissa Siqueira, and Yang Zhang

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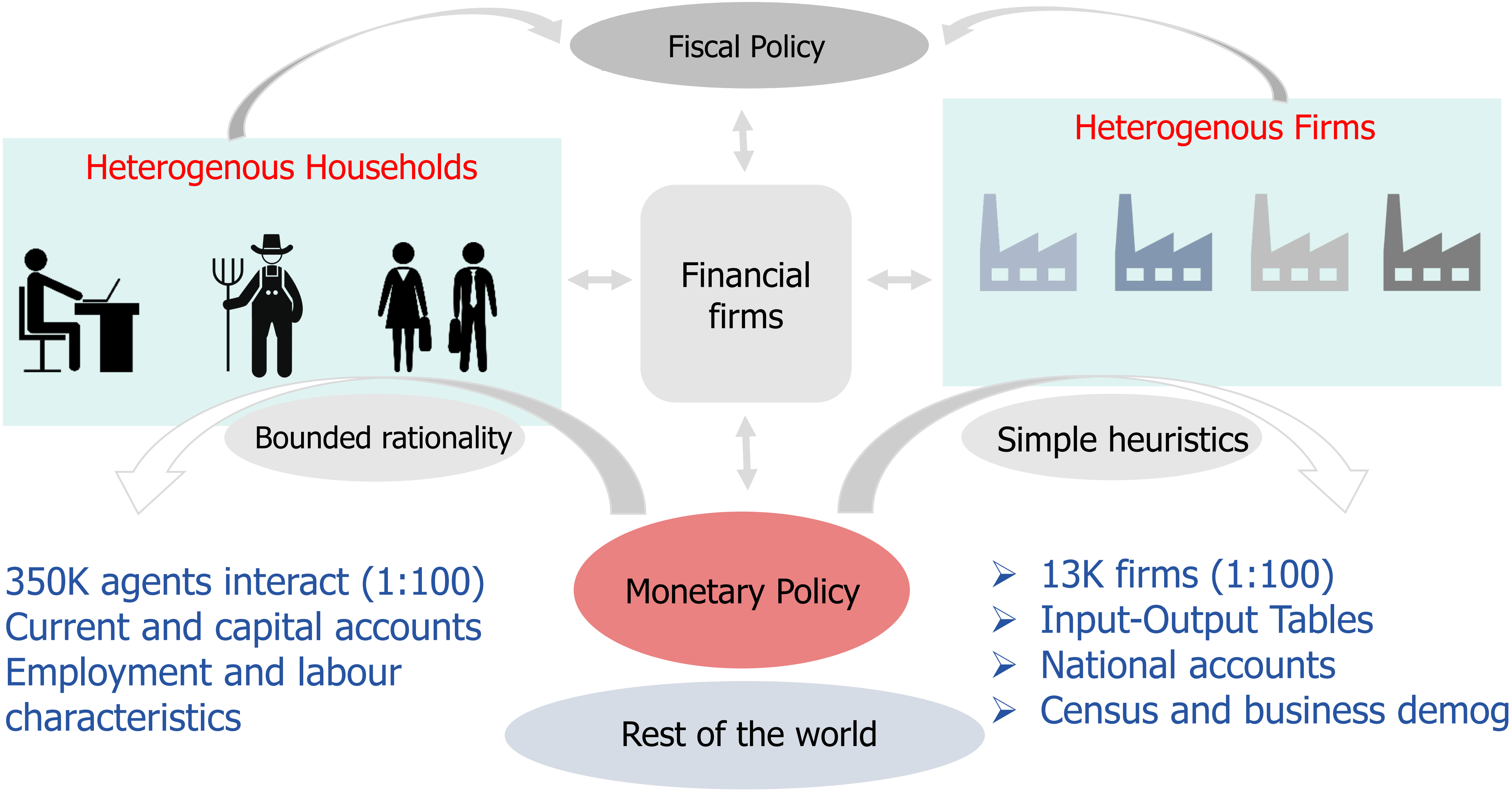
Disclaimer: The views expressed in this presentation are solely those of the authors and may differ from official Bank of Canada views. No responsibility for them should be attributed to the Bank of Canada.

Next-generation Agent-based Model of Canada

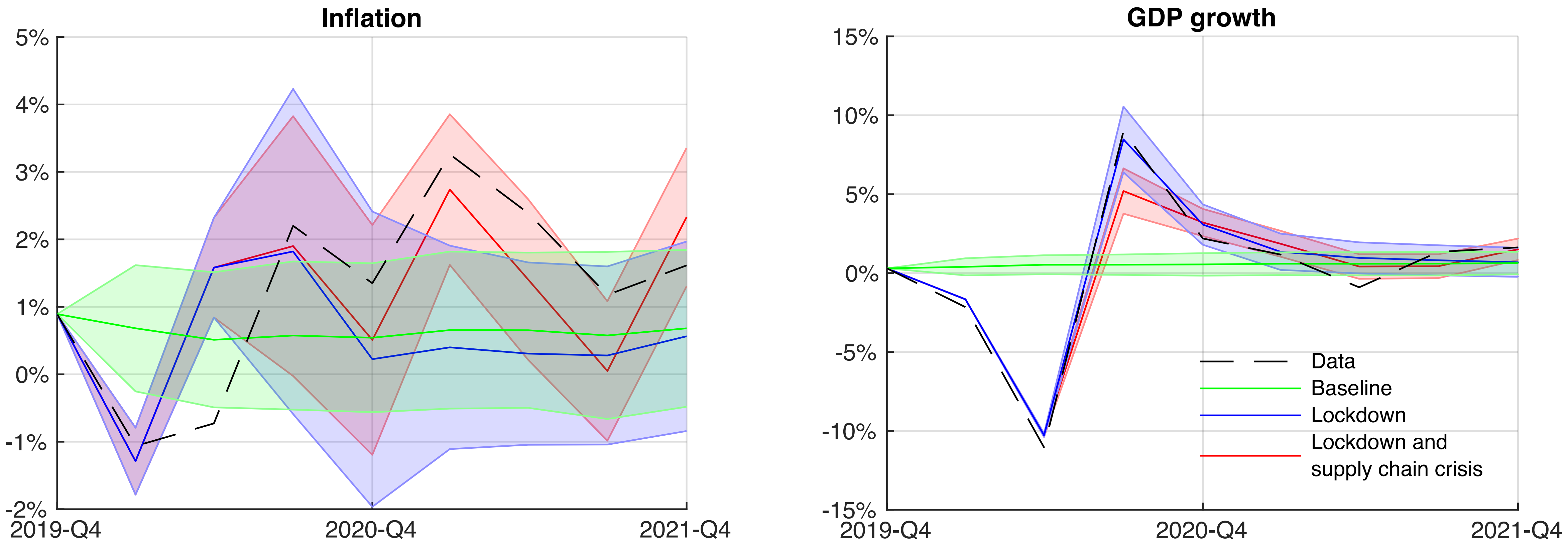


- 350K agents interact (1:100)
- Current and capital accounts
- Employment and labour characteristics

- 13K firms (1:100)
- Input-Output Tables
- National accounts
- Census and business demography

Hommes et al. (2022)

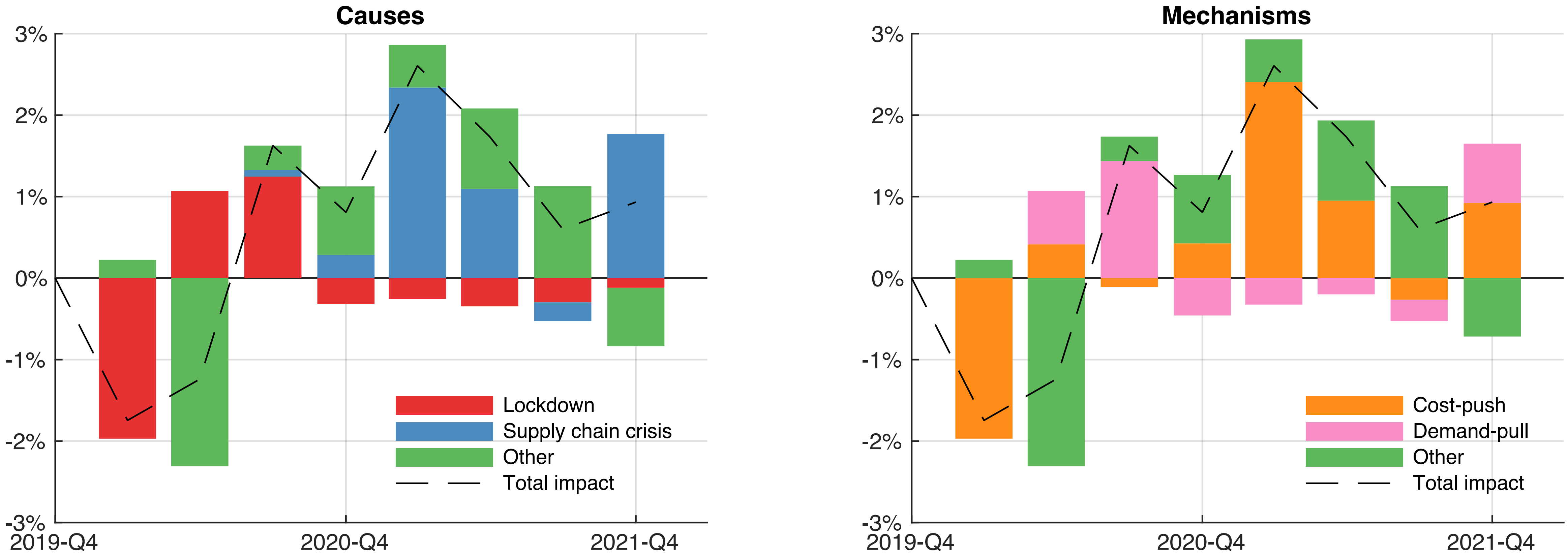
Post-pandemic inflation in Canada is captured well by the ABM



Impact of the Lockdowns and the Supply Chain Crisis on Inflation and GDP growth in Canada.

Grazzini et al. (2023)

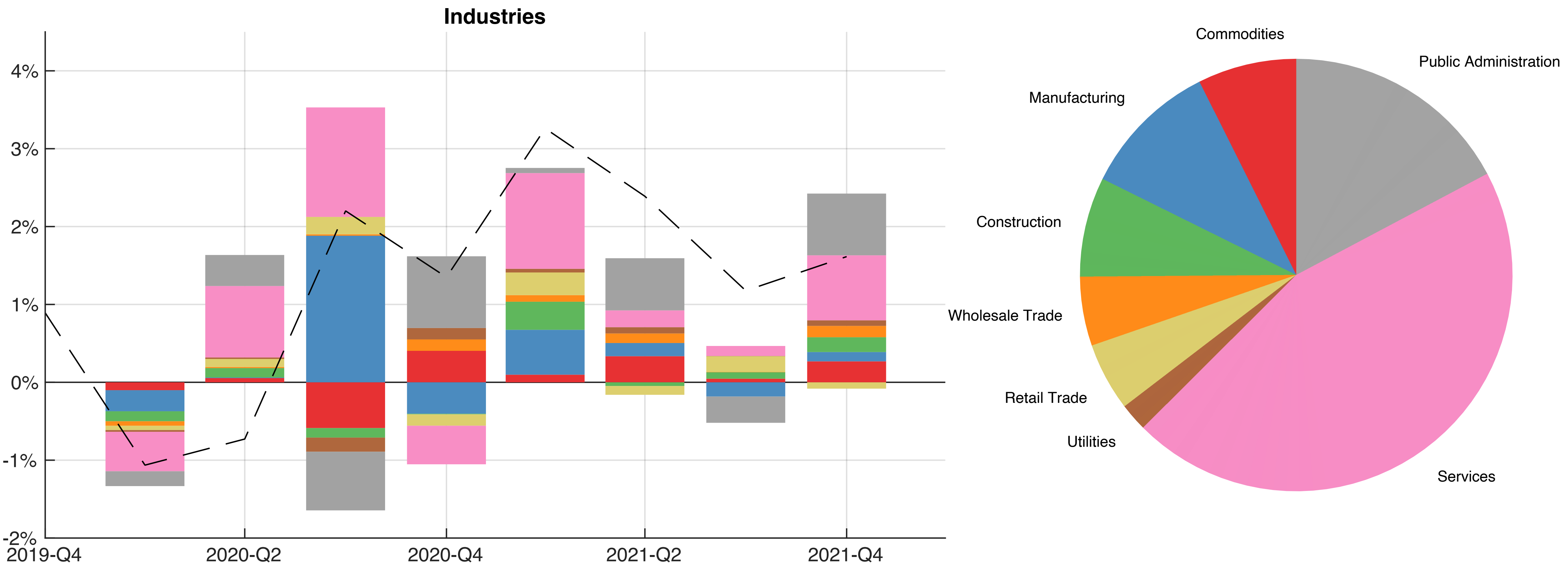
Marginal impact of causes and mechanisms on inflation



Marginal impact of causes and mechanisms on Inflation in Canada.

Grazzini et al. (2023)

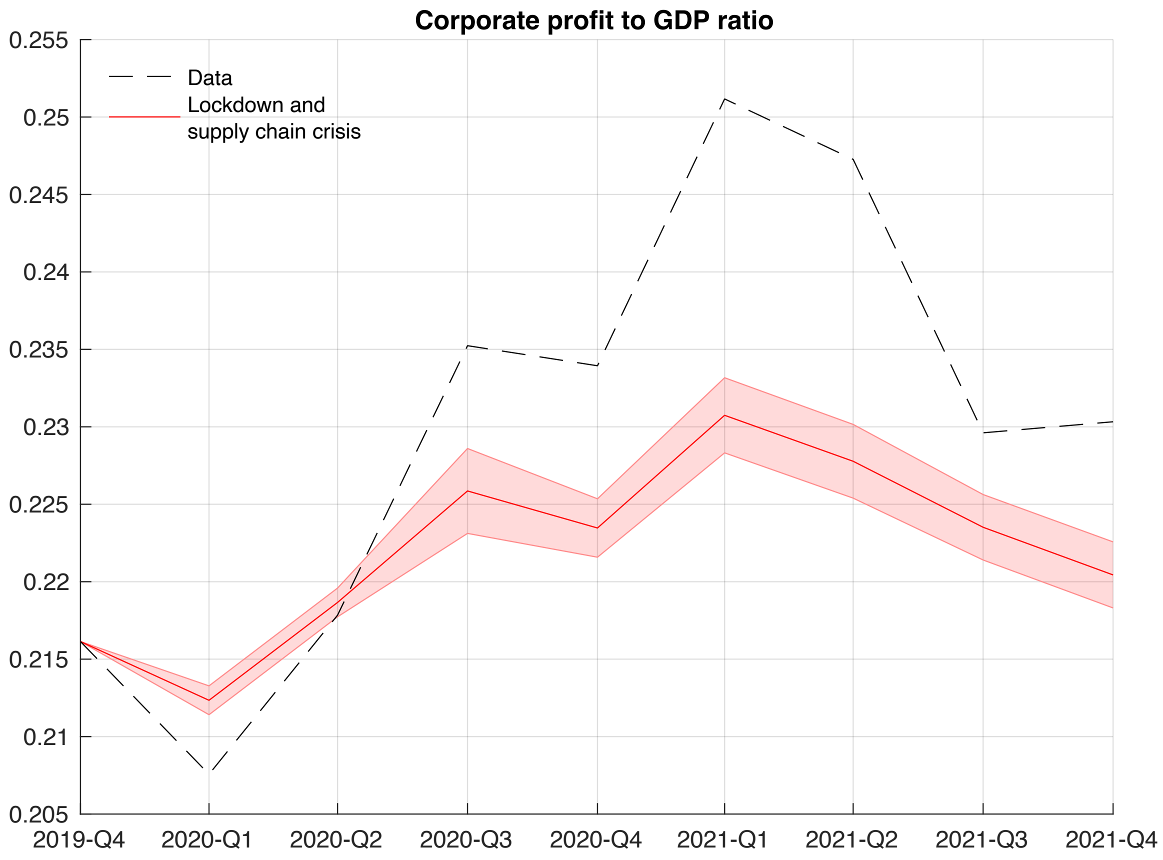
Marginal impact of Industry sectors on inflation



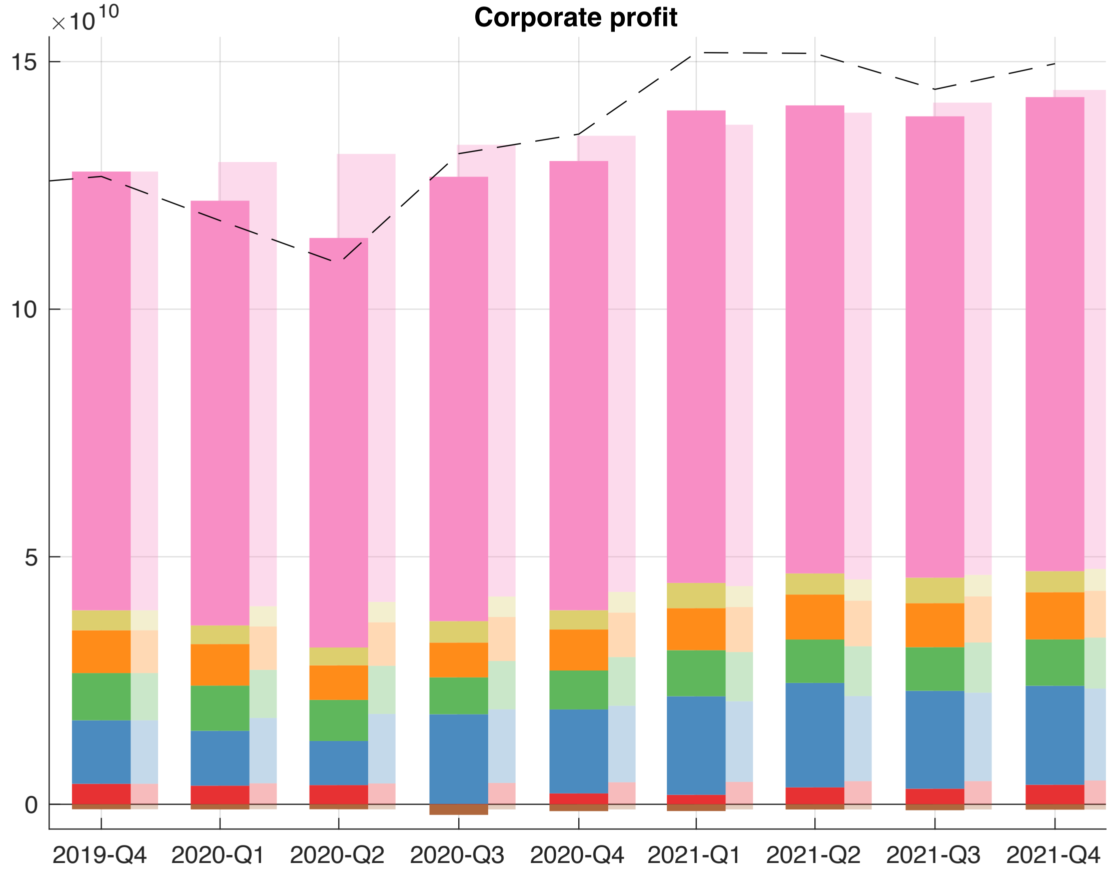
Marginal impact of industries on inflation. The right panel shows the share of GDP by industry and provides the legend of the left panel.

Grazzini et al. (2023)

Corporate profits in Canada



Corporate profits to nominal GDP ratio.



Nominal corporate profits in Canada (dashed line), in the lockdown and supply chain crisis scenario (foreground bars) and in the baseline scenario (background bars).

Grazzini et al. (2023)

Application: Financial crisis in the euro area

with Cars Hommes

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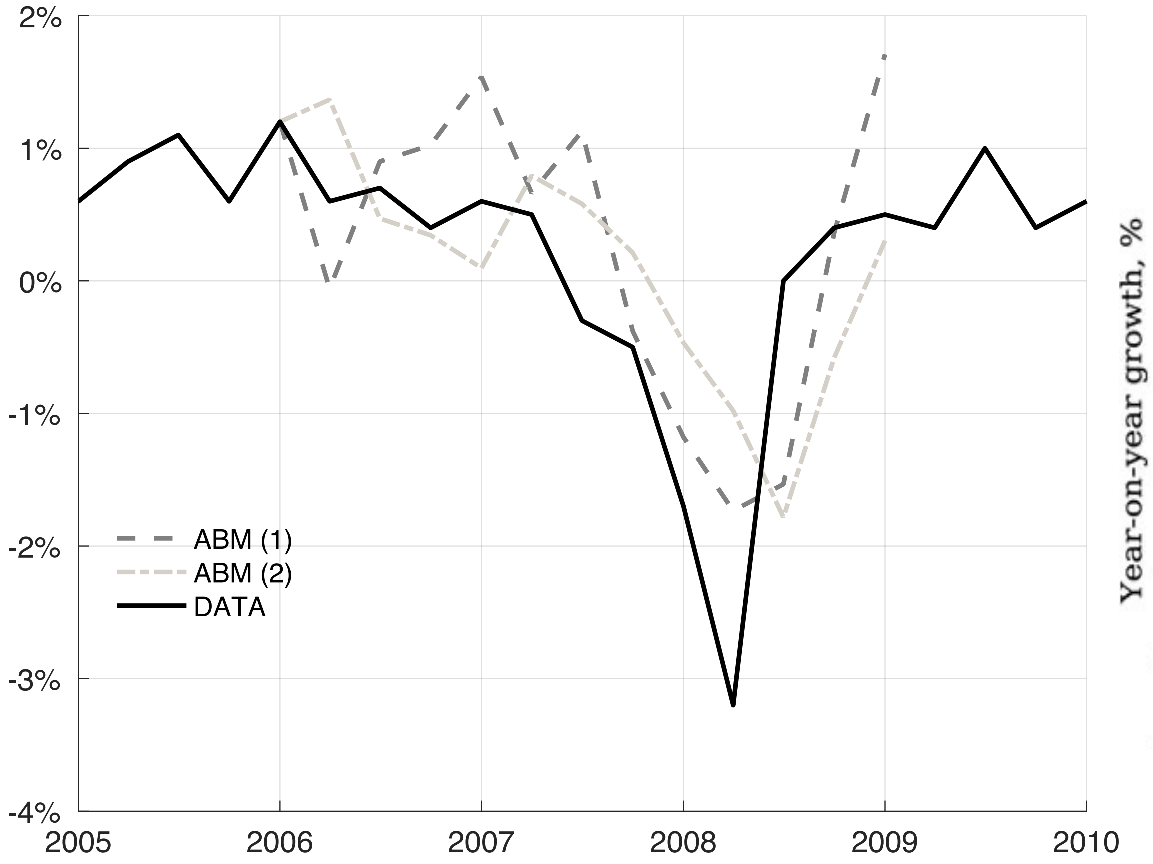
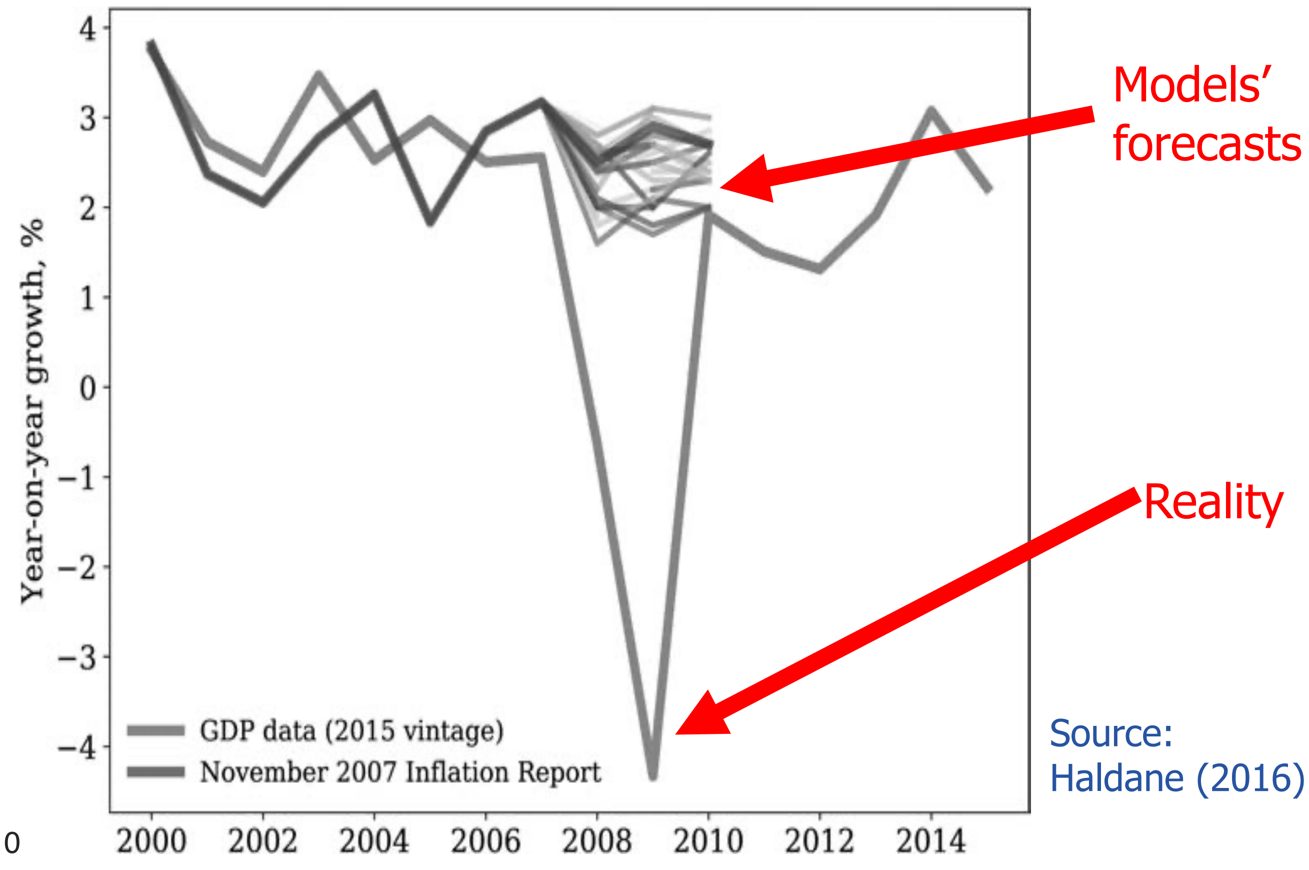
Financial crisis of 2007-2008 in the euro area

ABM GDP forecasts from the last quarter of 2006



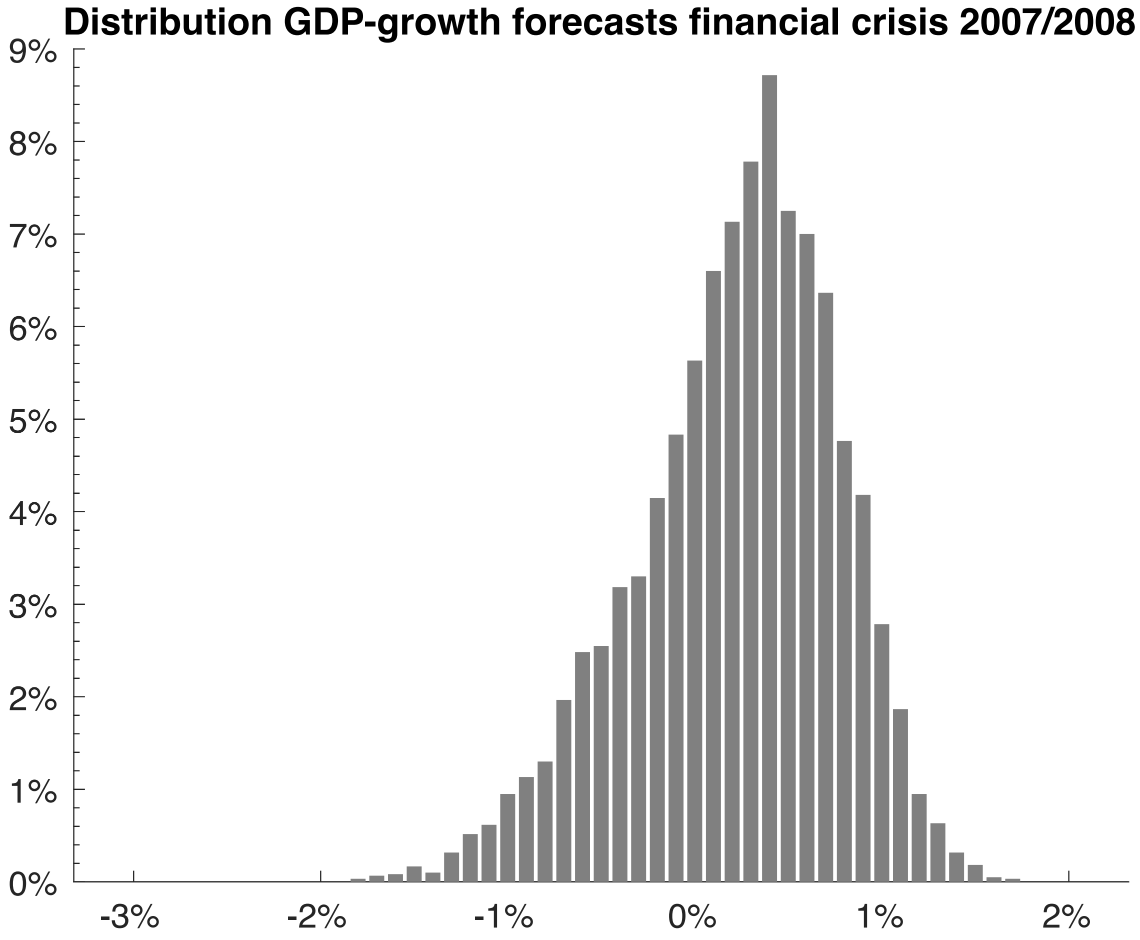
UK GDP forecasts in 2007

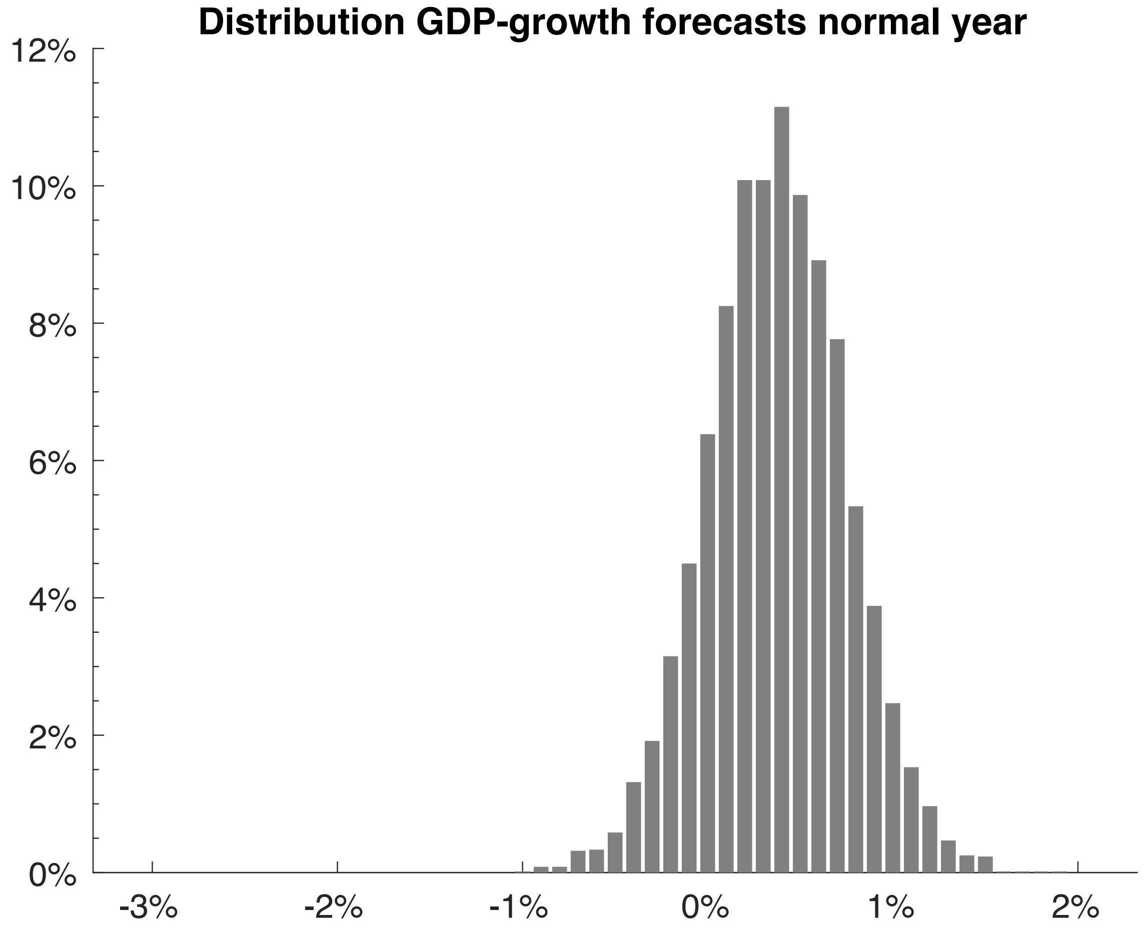


Source: Haldane (2016)

Comparison of ABM simulations (dashed lines) and observed Eurostat data for the euro area (black line) for a forecast horizon of 12 quarters.

Financial crisis of 2007-2008 in the euro area





Histograms of ABM quarterly GDP-growth rates in the euro area for a "normal" year and the financial crisis of 2007/2008.

Hommes & Poledna (2023)

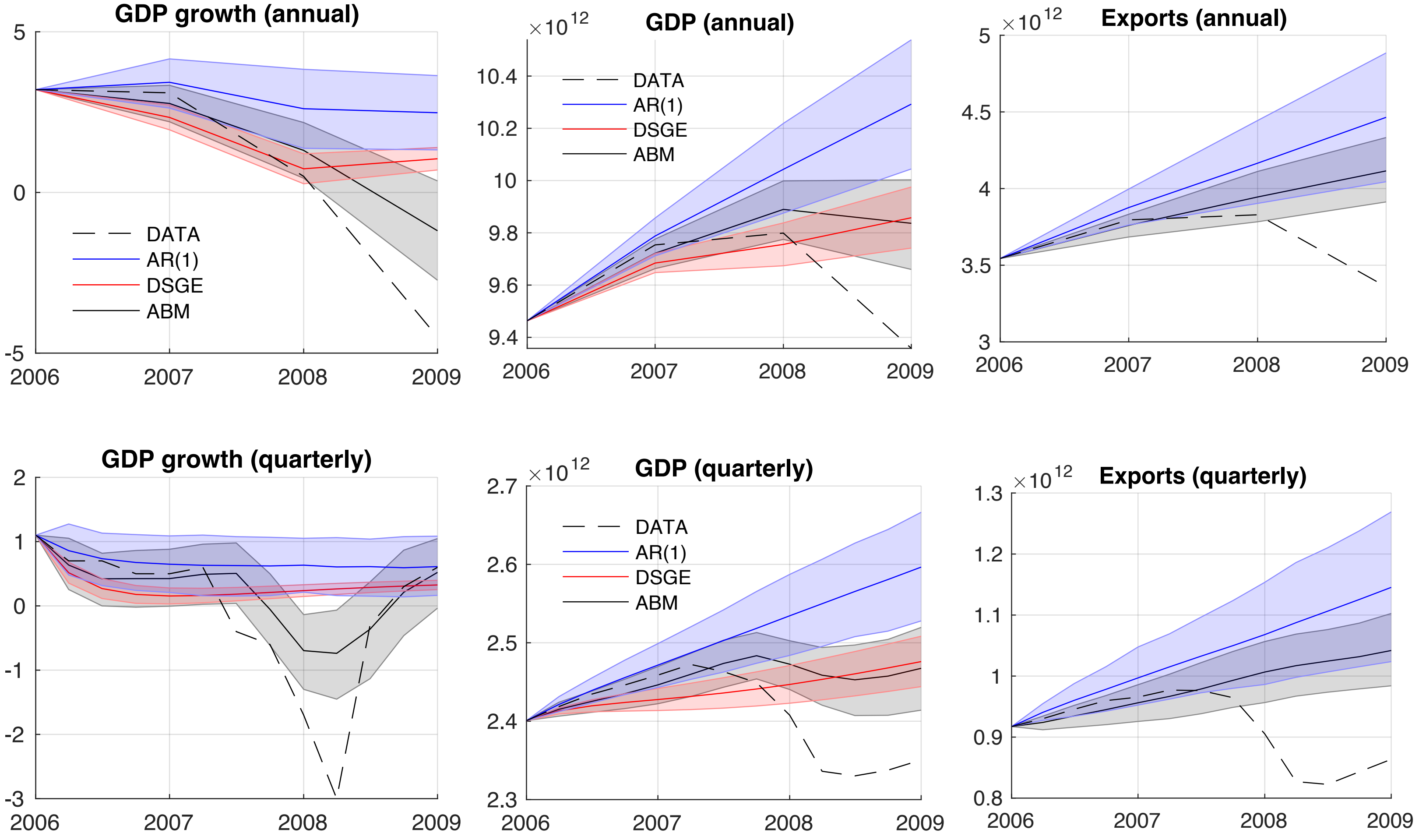
Out-of-sample forecast performance during the financial crisis of 2007-2008

	GDP	Inflation	Euribor	Government consumption	Exports
VAR(1)	*RMSE-statistic for different forecast horizons*				
1q	0.72	0.21	0.11	0.33	2.19
2q	1.72	0.28	0.19	0.45	5.15
4q	3.66	0.31	0.34	0.65	10.69
8q	6.35	0.29	0.5	0.96	17.75
12q	7.99	0.28	0.52	1.62	20.99
ABM	*Percentage gains (+) or losses (-) relative to VAR(1) model*				
1q	-19.5 (0.88)	6.6 (0.16)	-34.9 (0.82)	-86.2 (0.88)	-50.2 (0.87)
2q	-11.5 (0.90)	8.2 (0.17)	-36.7 (0.81)	-43.2 (0.93)	-20.4 (0.86)
4q	-7.7 (0.85)	6.2 (0.11)	-31.3 (0.82)	9.9 (0.37)	1.3 (0.38)
8q	-4.9 (0.91)	4.8 (0.25)	-20.1 (0.92)	-26.5 (0.76)	17.5 (0.11)
12q	-5.1 (0.90)	0.4 (0.40)	-6.1 (0.89)	-45.1 (0.97)	29.5 (0.00)
ABM (with financial frictions)	*Percentage gains (+) or losses (-) relative to VAR(1) model*				
1q	-58.8 (0.88)	-4.4 (0.57)	-51.4 (0.85)	-18.9 (0.94)	-59.2 (0.87)
2q	-26.9 (0.87)	28.2 (0.13)	-51.9 (0.84)	-10.2 (0.73)	-25 (0.86)
4q	-5.9 (0.89)	8.9 (0.08)	-38.3 (0.85)	4.6 (0.44)	-0.7 (0.58)
8q	32.5 (0.03)	15.4 (0.17)	-12.2 (0.99)	-20.3 (0.97)	16 (0.12)
12q	52.8 (0.00)	5.6 (0.13)	14.1 (0.01)	-13.9 (0.92)	29.8 (0.00)

Out-of-sample forecast performance for different forecast horizons of the ABM in comparison to the benchmark DSGE model of Smets and Wouters (2007) estimated for the subsample from 2007:Q1 to 2008:Q4 of the euro area.

Hommes & Poledna (2023)

Financial crisis of 2007-2008 in the euro area

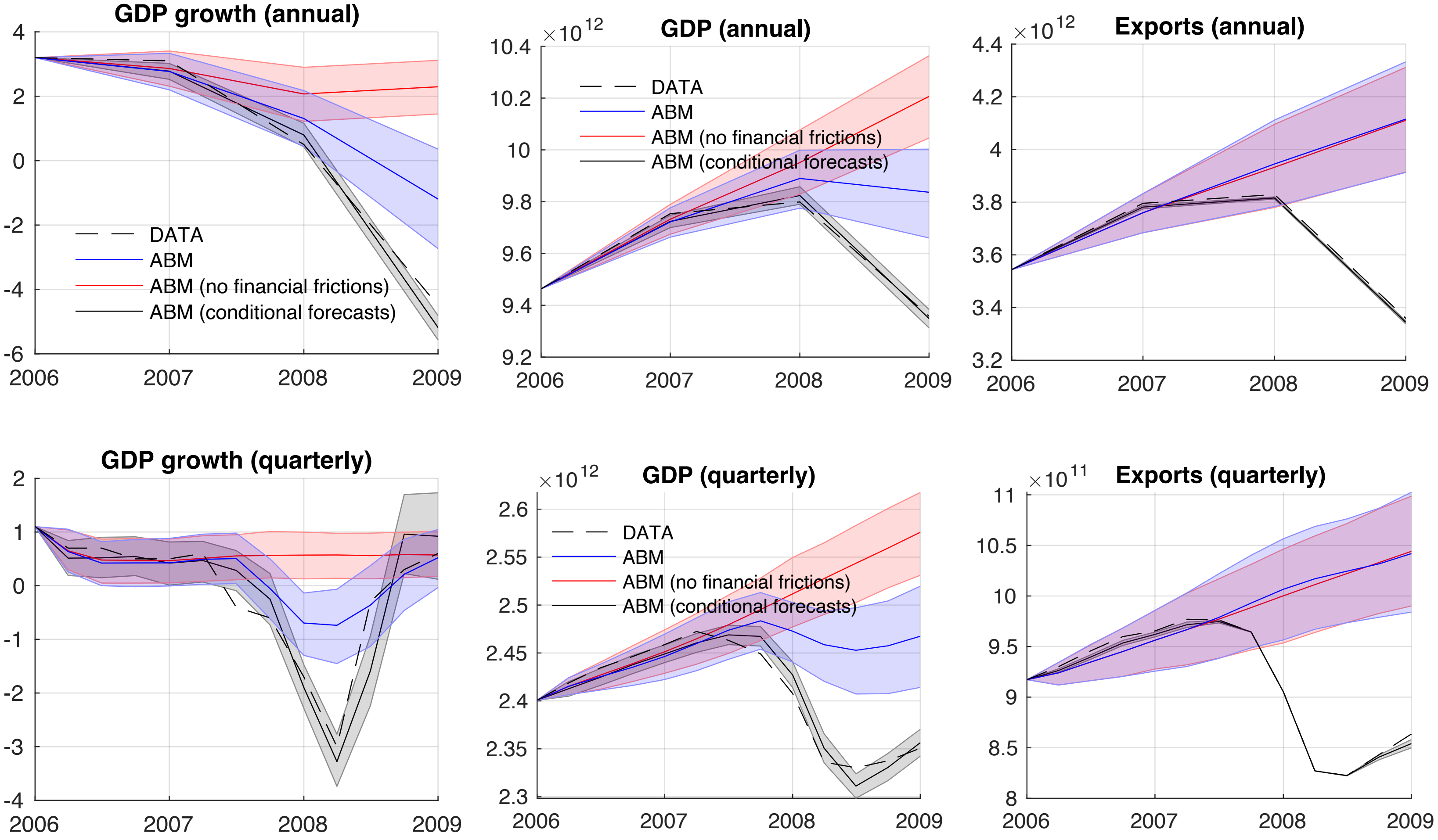


Comparison of ABM simulations (black), AR(1) (blue), DSGE (red), and observed Eurostat data for the euro area (dashed line) for a forecast horizon of 12 quarters.

Hommes & Poledna (2023)

Financial crisis of 2007-2008 in the euro area

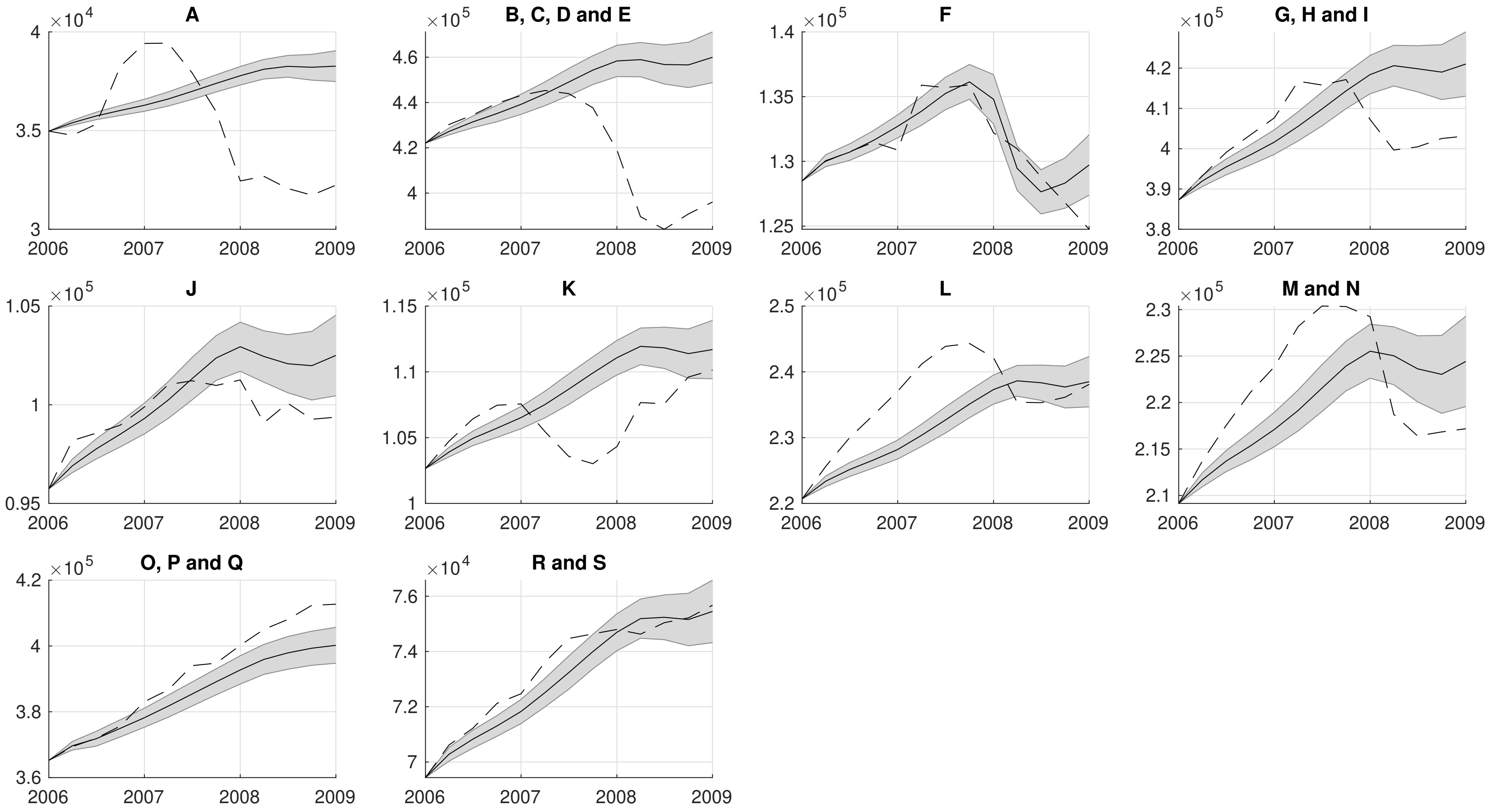
with (forward-looking) expectations for a global downturn



Comparison of ABM simulations (blue), ABM without financial frictions (red), conditional forecasts (on exports) of the ABM (black), and observed Eurostat data for the euro area (dashed line) for a forecast horizon of 12 quarters.

Hommes & Poledna (2023)

Sectorial decomposition during the financial crisis of 2007-2008 in the euro area

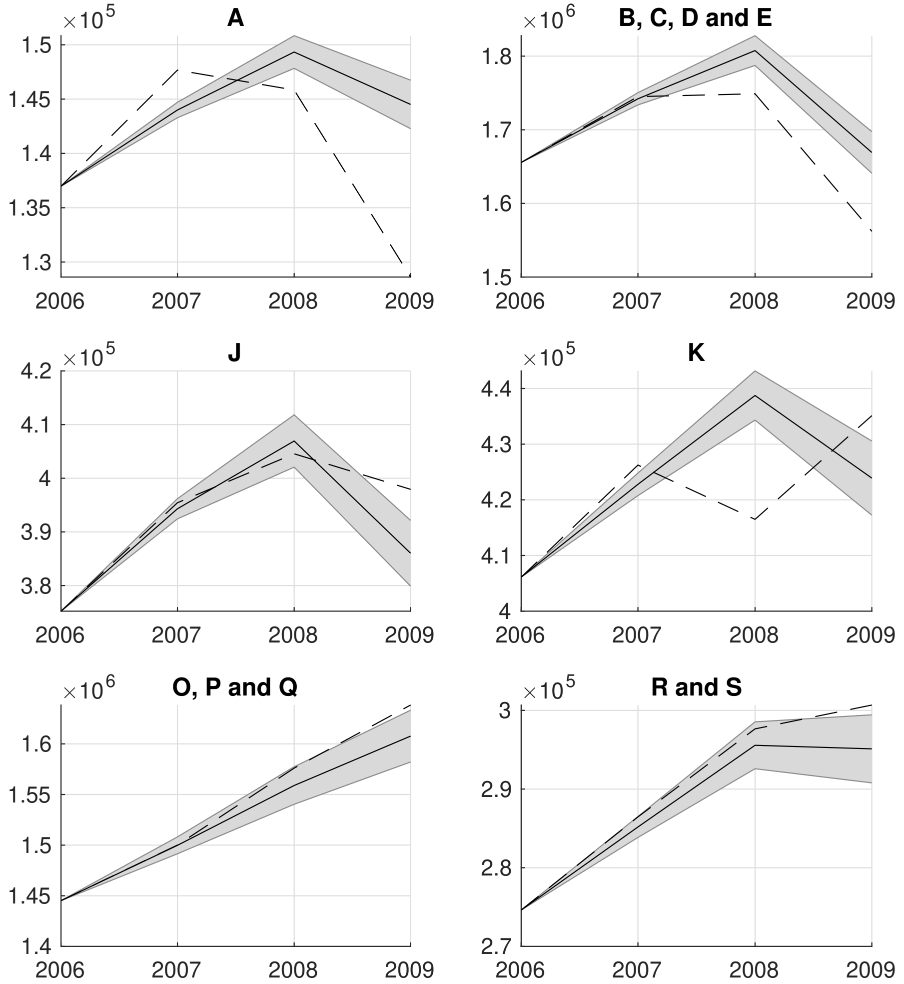


Sectoral decomposition ABM simulations and observed Eurostat data for the euro area (dashed line) for a forecast horizon of 12 quarters.

Hommes & Poledna (2023)

Sectorial decomposition during the financial crisis

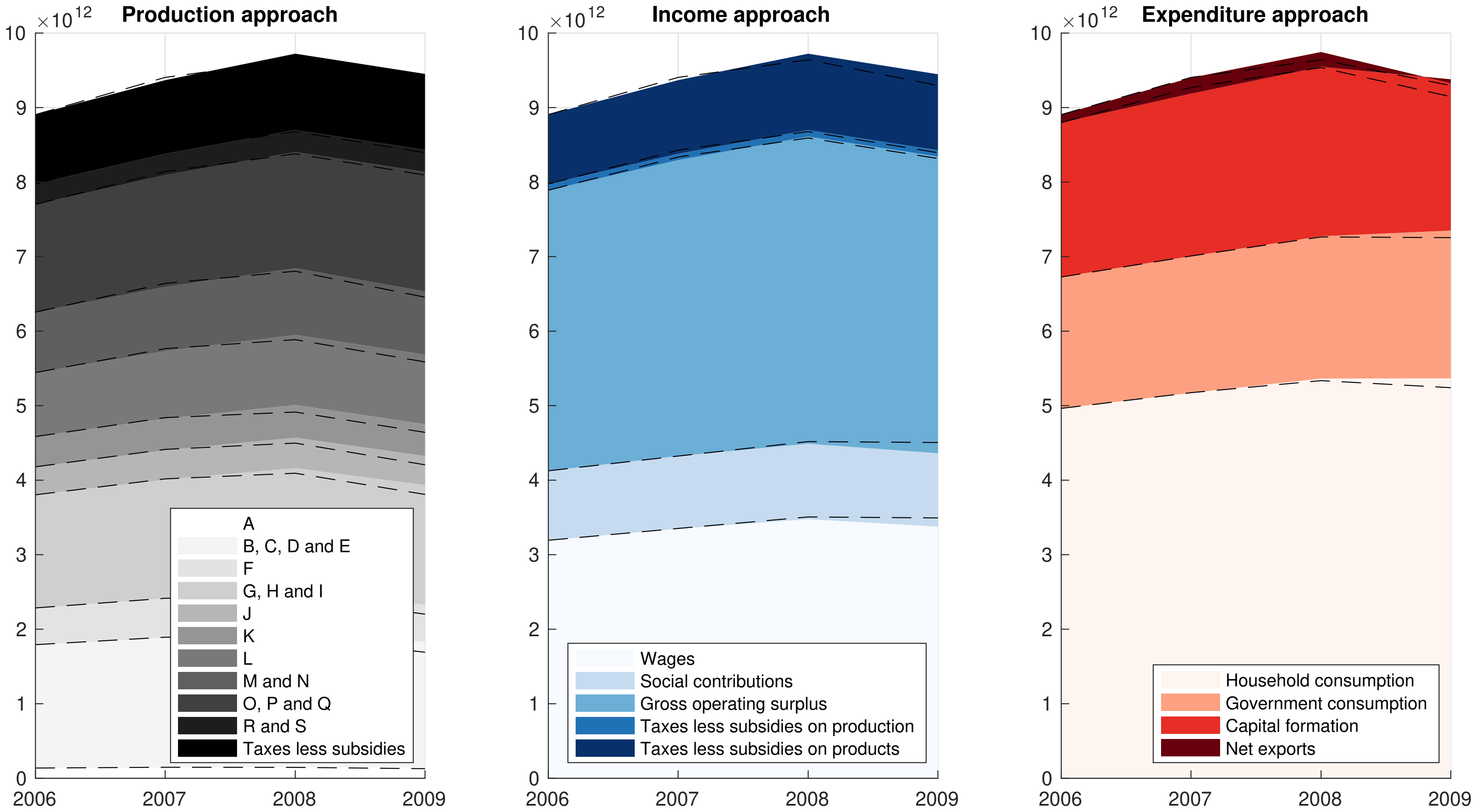
with (forward-looking) expectations for a global downturn



Sectoral decomposition ABM (conditional forecasts) and observed Eurostat data for the euro area (dashed line) for a forecast horizon of 12 quarters.

Hommes & Poledna (2023)

Structural change after the financial crisis of 2007-2008 in the euro area



GDP determined with production approach (grey), income approach (blue), and expenditure approach (red) from ABM simulations and observed Eurostat data for the euro area (dashed line) for a forecast horizon of 12 quarters.

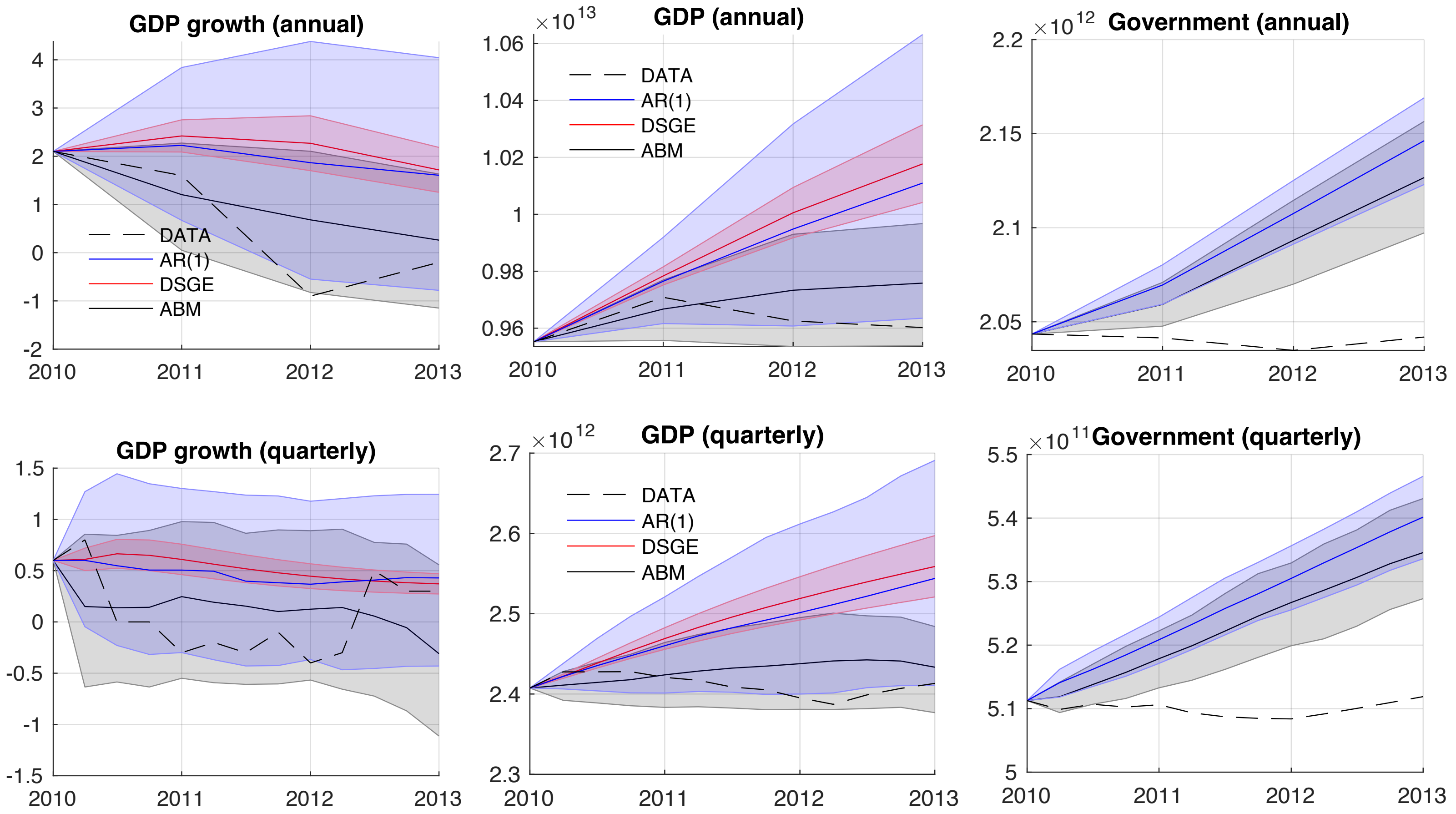
Hommes & Poledna (2023)

Out-of-sample forecast Performance during the European debt crisis

	GDP	Inflation	Euribor	Government consumption	Exports
VAR(1)	*RMSE-statistic for different forecast horizons*				
1q	0.54	0.14	0.05	0.37	1.35
2q	1.19	0.1	0.1	0.63	2.9
4q	2.84	0.15	0.23	1.24	7.02
8q	6.15	0.2	0.54	2.52	14.53
12q	7.77	0.21	0.67	3.55	18.32
ABM	*Percentage gains (+) or losses (-) relative to VAR(1) model*				
1q	28 (0.06)	13.3 (0.19)	13.9 (0.08)	41.4 (0.00)	-33.1 (0.77)
2q	38.7 (0.00)	8.3 (0.26)	13.1 (0.22)	9.2 (0.19)	13.7 (0.26)
4q	45.7 (0.00)	-3 (0.56)	32.4 (0.00)	-14.9 (0.94)	50.1 (0.00)
8q	56.4 (0.05)	7.4 (0.22)	66.9 (0.04)	-17.3 (0.86)	69.5 (0.00)
12q	59.8 (0.00)	8.4 (0.02)	71.4 (0.00)	-10.6 (0.98)	64.4 (0.00)
ABM (with financial frictions)	*Percentage gains (+) or losses (-) relative to VAR(1) model*				
1q	21.3 (0.19)	-29.9 (0.85)	-13.6 (0.87)	51.2 (0.00)	-26.1 (0.72)
2q	40.5 (0.00)	-42.1 (0.83)	-10.4 (0.65)	18.5 (0.03)	16 (0.22)
4q	56.8 (0.00)	-29.9 (0.99)	26.3 (0.11)	-4.4 (0.72)	50.3 (0.00)
8q	72.3 (0.04)	-11.7 (0.86)	77.1 (0.03)	-11.5 (0.82)	69.6 (0.00)
12q	74.6 (0.00)	-6.6 (0.86)	86.7 (0.00)	-4.5 (0.84)	63.9 (0.00)

Out-of-sample forecast performance for different forecast horizons of the ABM in comparison to the benchmark DSGE model of Smets and Wouters (2007) estimated for the subsample from 2010:Q1 to 2012:Q4 of the euro area.

The European debt crisis

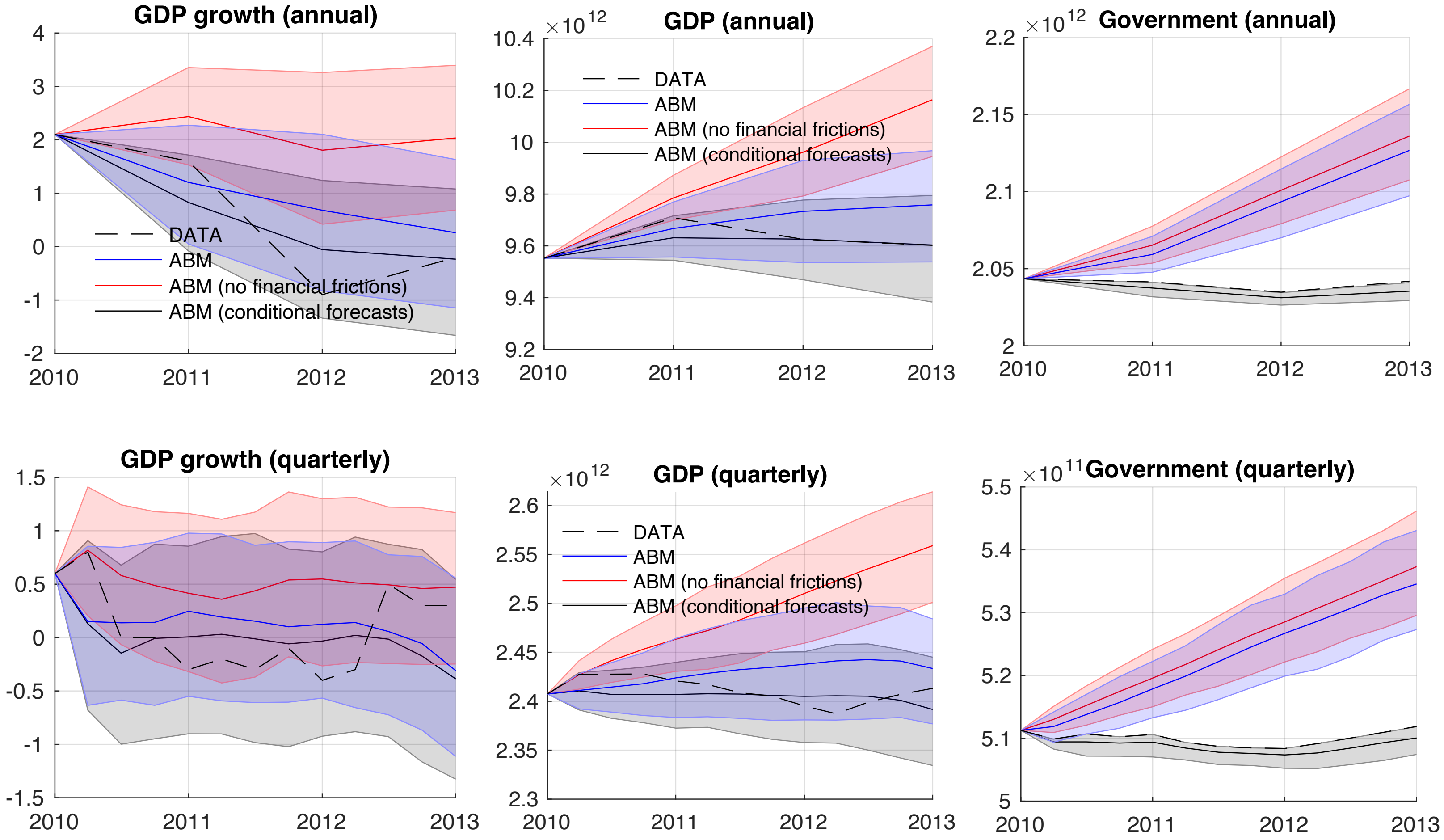


Comparison of ABM simulations (black), AR(1) (blue), DSGE (red), and observed Eurostat data for the euro area (dashed line) for a forecast horizon of 12 quarters.

Hommes & Poledna (2023)

The European debt crisis

with (forward-looking) expectations for government austerity



Comparison of ABM simulations (blue), ABM without financial frictions (red), conditional forecasts (on exports) of the ABM (black), and observed Eurostat data for the euro area (dashed line) for a forecast horizon of 12 quarters.

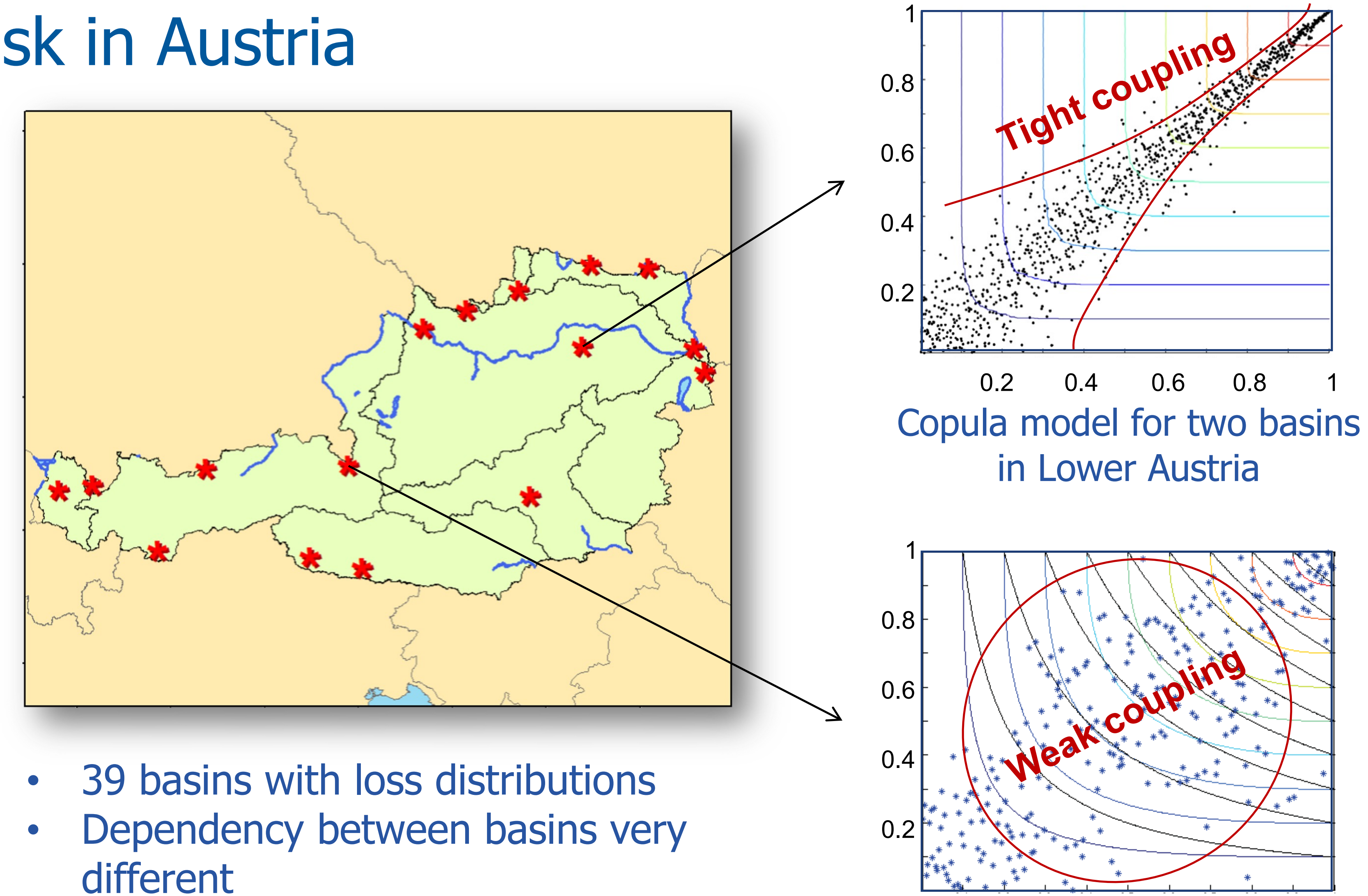
Hommes & Poledna (2023)

Application: Economic effects of natural disasters

Economic effects of natural disasters

- We study indirect disaster losses of natural disasters
- We couple the ABM with a catastrophe model (damage scenario generator) for flood events at a high resolution
- Projections are based on scenarios for three flood events:
    - 100-year flood event
    - 250-year flood event
    - 1500-year flood event

Flood risk in Austria



Copula model for two basins in Lower Austria

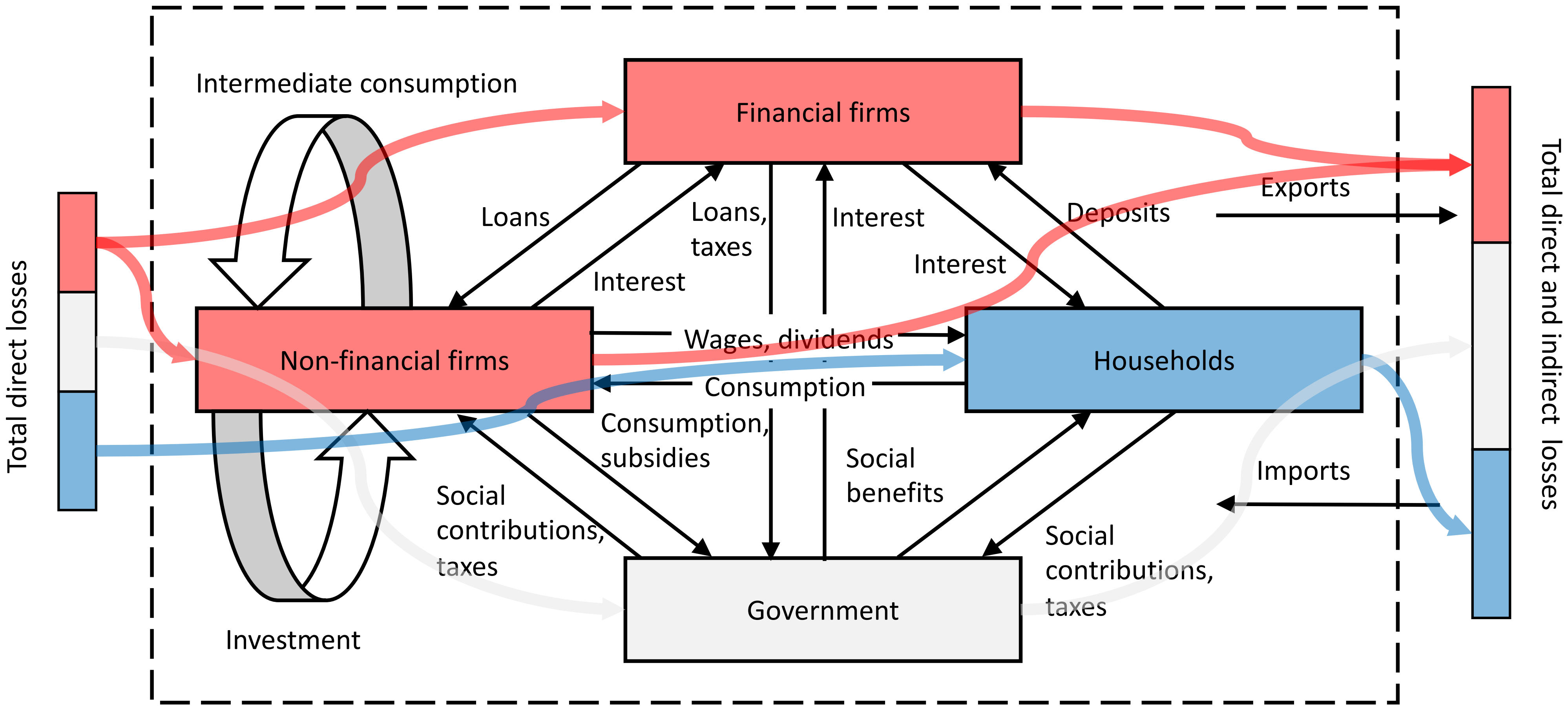
Copula model for two basins in Salzburg

- 39 basins with loss distributions
- Dependency between basins very different
- Copula models for all basins developed

Bachner et al. (2023)

Indirect losses from natural disasters

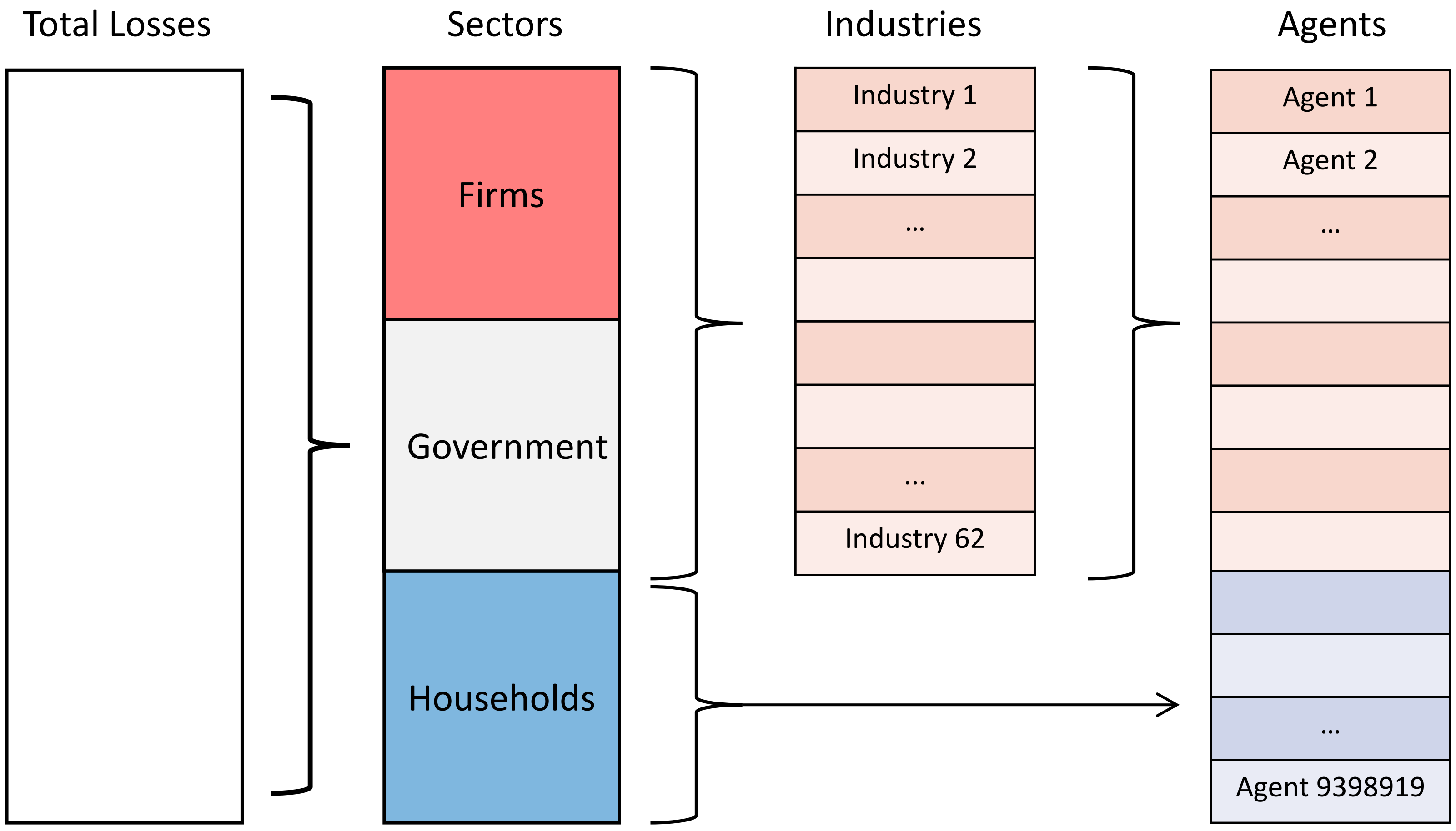
Agent-based model



Coupling with damage scenario generator to estimate indirect losses

Bachner et al. (2023)

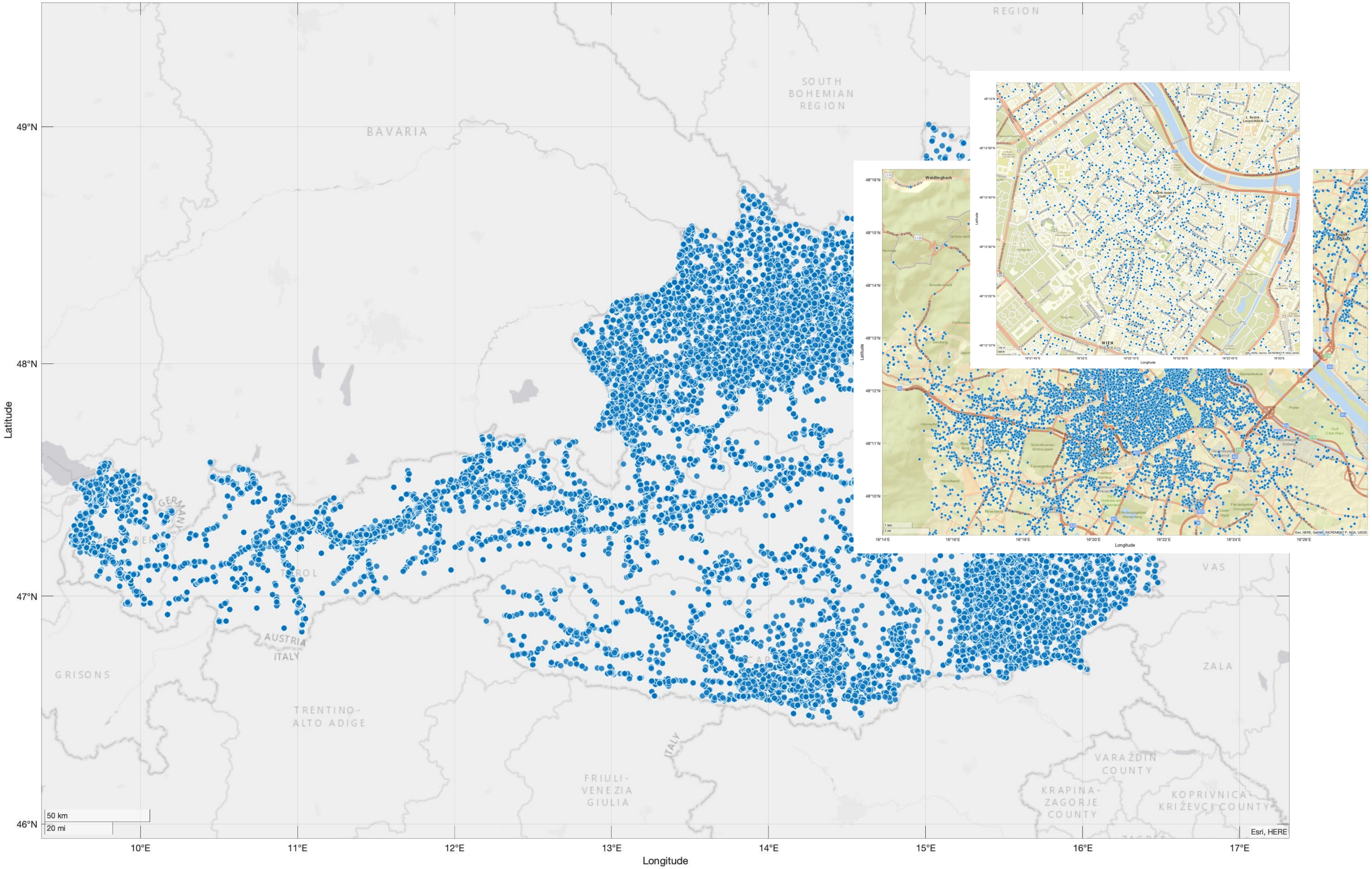
Indirect losses from natural disasters



Coupling with damage scenario generator to estimate indirect losses

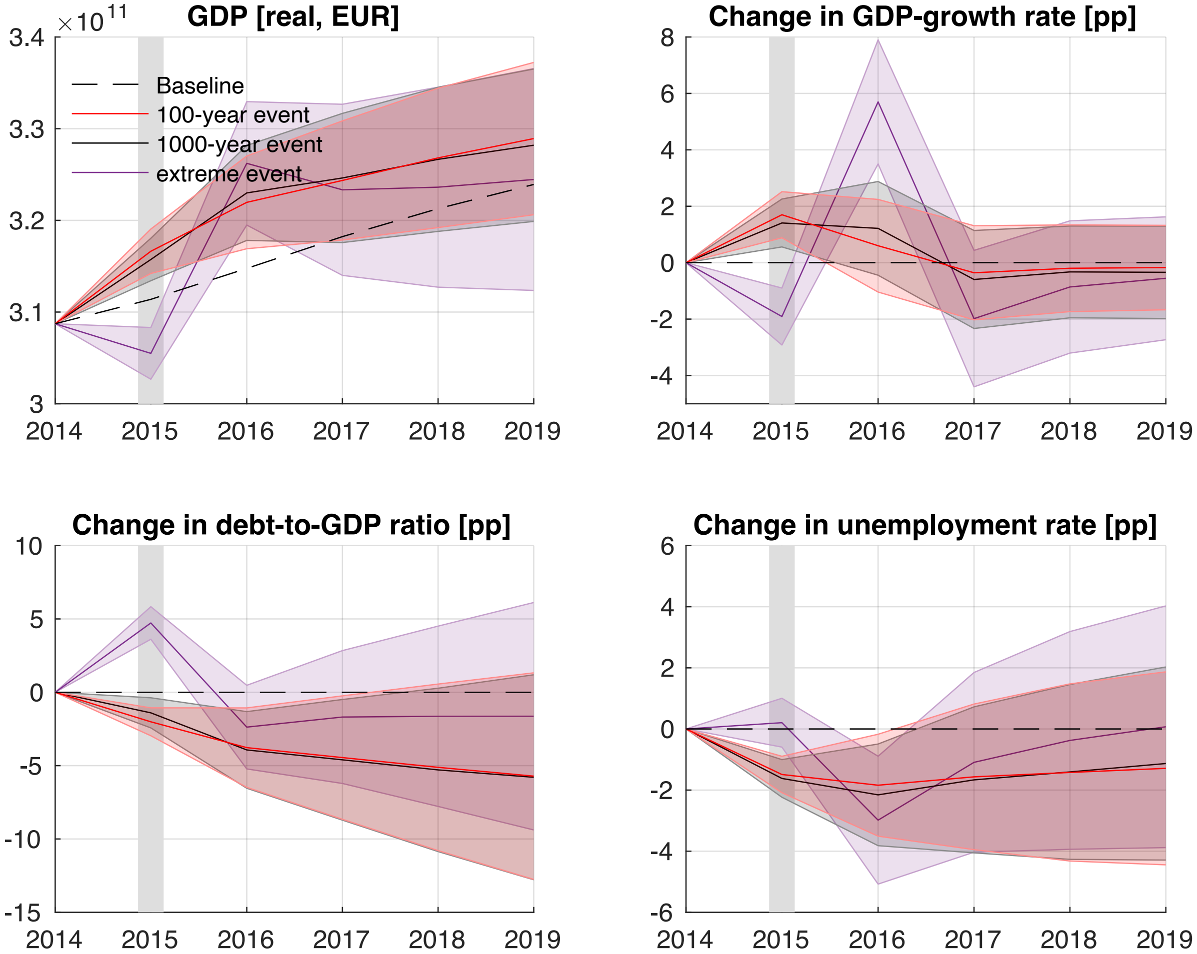
Bachner et al. (2023)

Geospatial location of firms in Austria used for flood scenarios



Geospatial location of firms in Austria used for the flood scenarios.

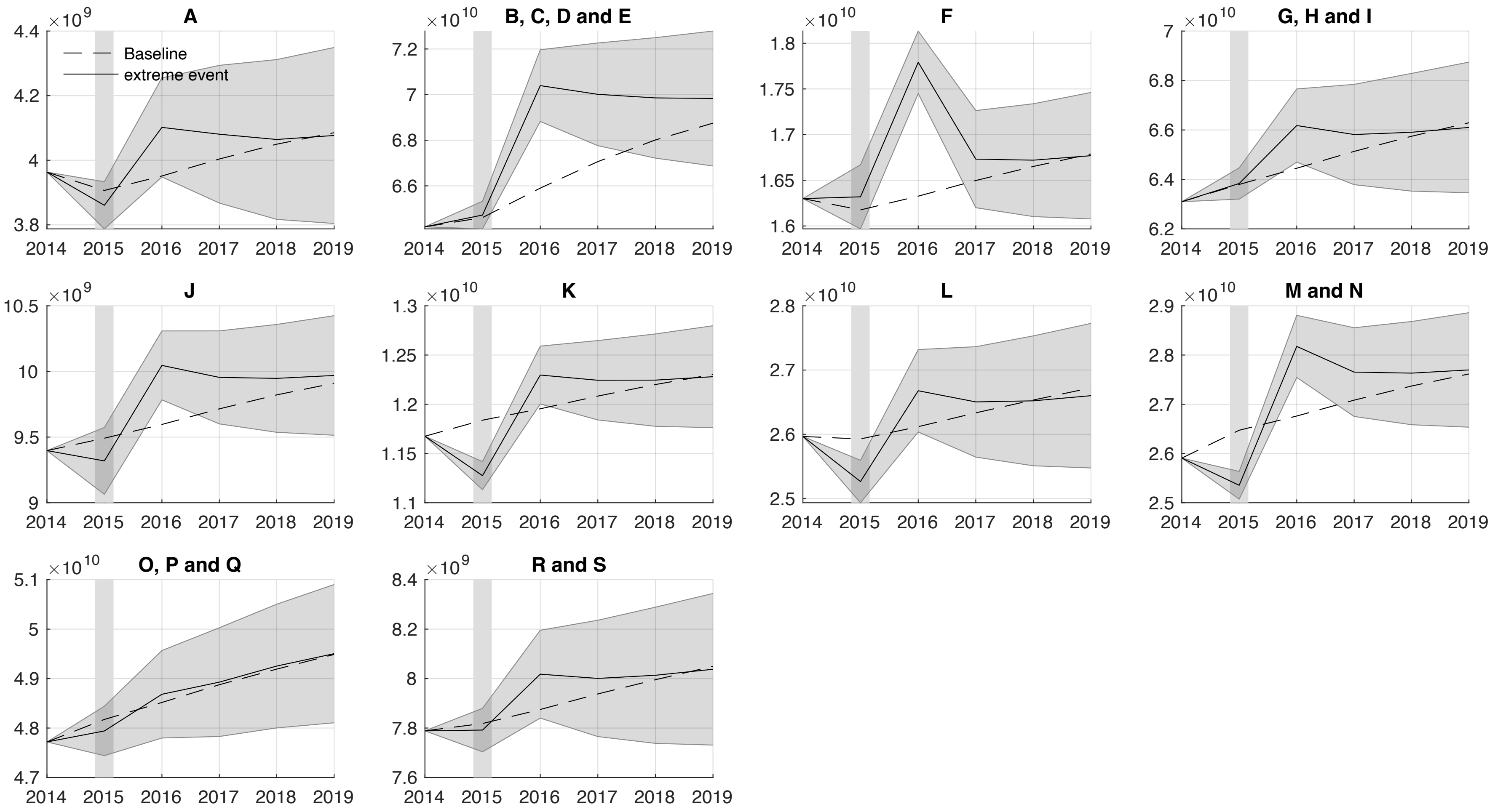
Indirect losses from natural disasters



Effects on economic growth of different flood events. Moderate events initially have positive economic effects on GDP growth, while catastrophic events have negative effects.

Bachner et al. (2023)

Indirect losses from natural disasters



Sectorial effects of the extreme event. Effects differ substantially across industries.

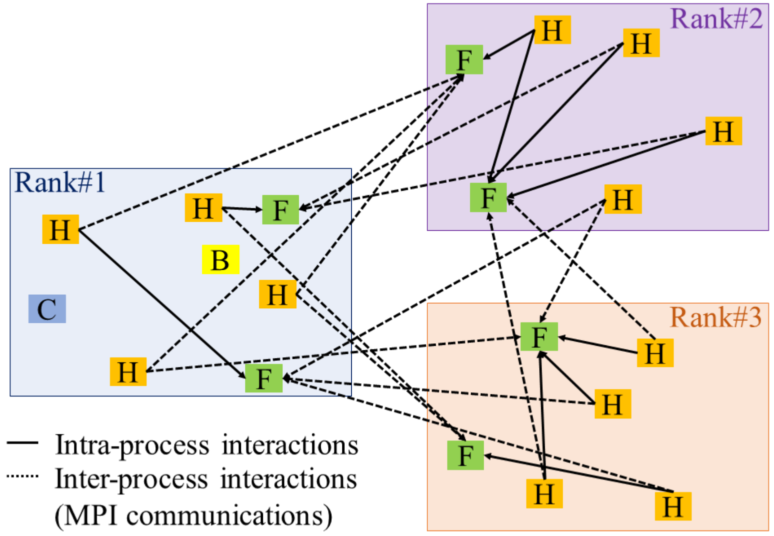
Bachner et al. (2023)

DMP implementation of the IIASA Macroeconomic ABM

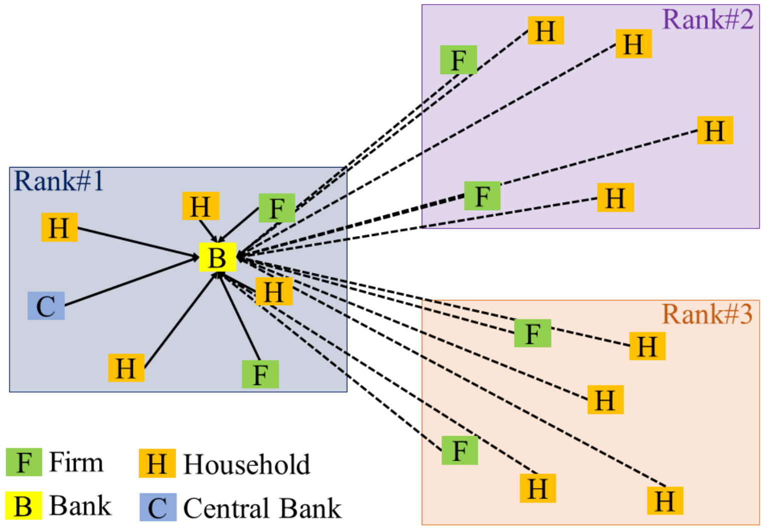
Challenges of developing a DMP-HPC implementation

- Shared memory implementations are not scalable due to random interactions among millions of agents
- Multiple interaction graphs make it a challenging task to implement a scalable **Distributed Memory Parallel** (DMP) extension
  - Agents interact over multiple graphs which are random and dense, and centralized Buying-selling, firms-workers, banks-customers, government-tax payers, etc.

Example of a dense graph with random links



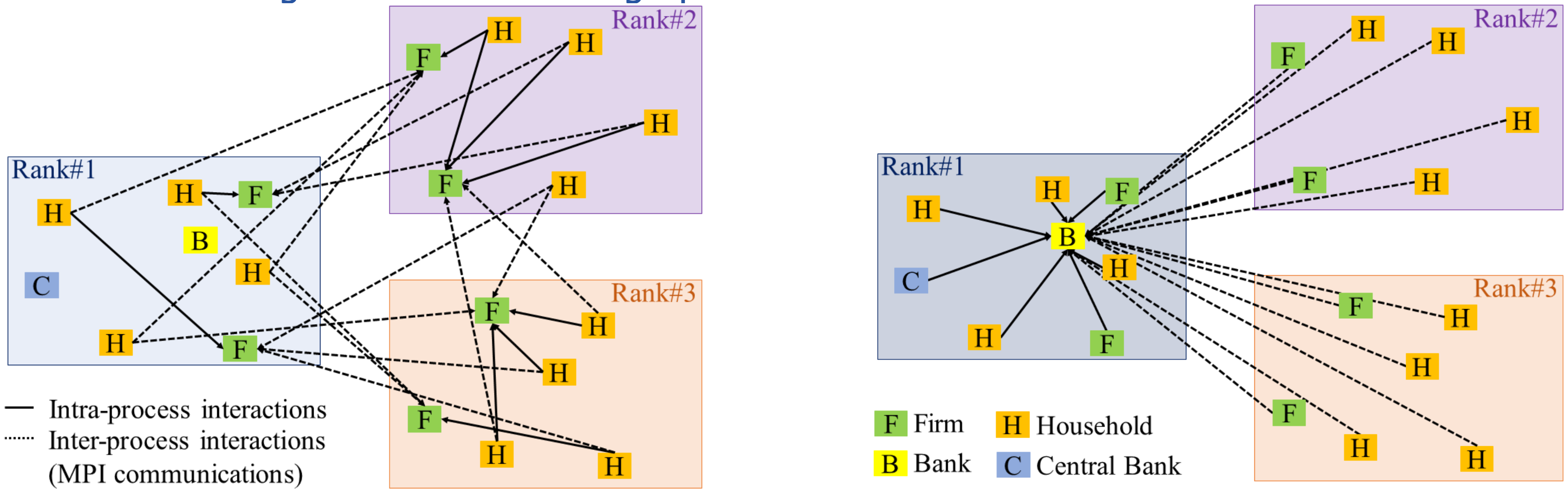
Example of a centralized graph



Gill et al. (2021)

Challenges of developing a DMP-HPC implementation

- Each interaction involves one or more communications among MPI-processes
  - Most of the interactions are bi-directional
    - Firms have to check the availability of goods and decide how much to sell
    - Banks have to estimate the risk and decide the amount to lend and the interest
  - Some of the interactions are sequential
    - A buyer visit another seller only if his demand is not satisfied, etc.
    - Produces **unknown number of communications** to random MPI-processes
- How can we partition the domain taking all the interaction graphs into account?



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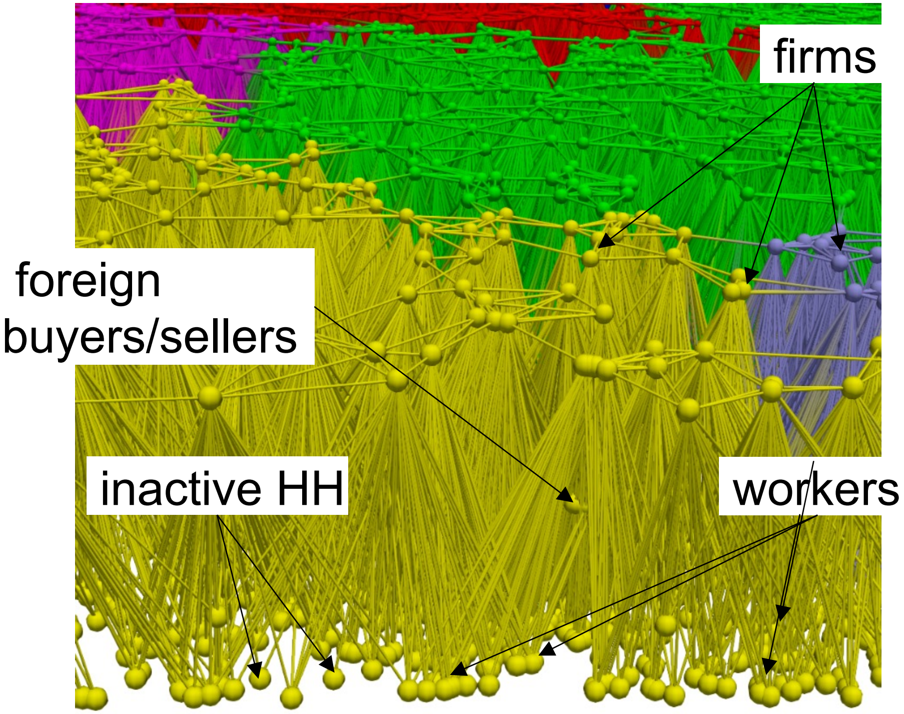
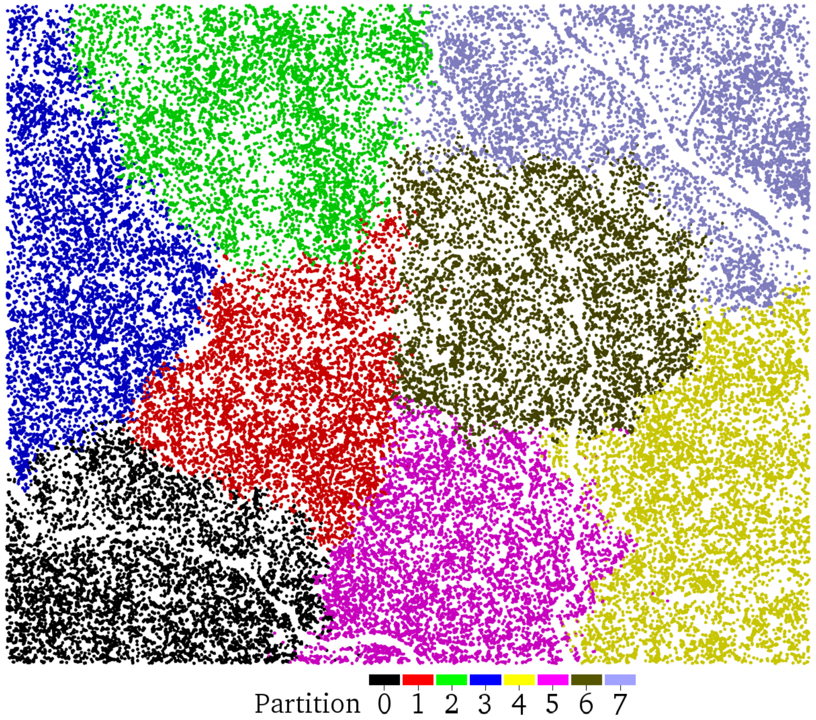
Distributed Memory Parallel (DMP) implementation

Graph to partition



Partitions

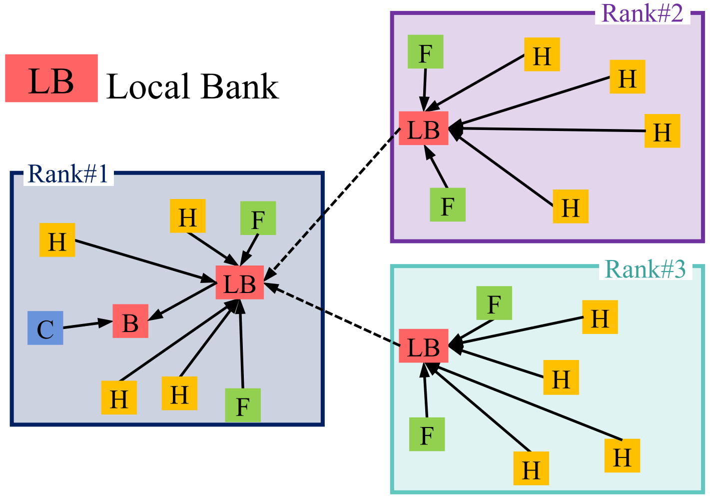


- Agents are partitioned based on a graph representing interactions between households and firms
- Nodes (i.e., agents) are assign a weight according to the amount of computation
- For example, workers are connected to the nearest firms according to available vacancies. Inactive households, etc. are connected with a lower link weight.

Gill et al. (2021)

Solutions for the centralized and dense random graphs

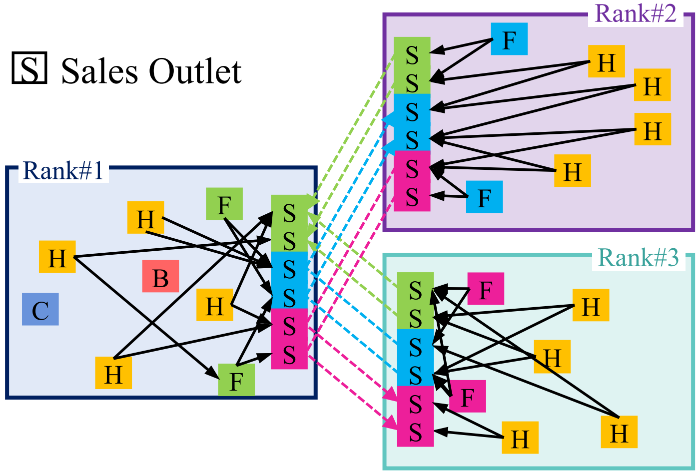
Centralized graphs



F Firm H Household B Bank C Central Bank

- Drastic reduction of communications by introducing local branches of banks and government entities
- Scalable

Dense graph with random links



Intra-process interactions (local load and store)

Inter-process interactions (MPI communications)

- Eliminated the involvement of unknown number of sequential communications to random ranks by Introducing sales-outlets
- Scalable, though communication intensive

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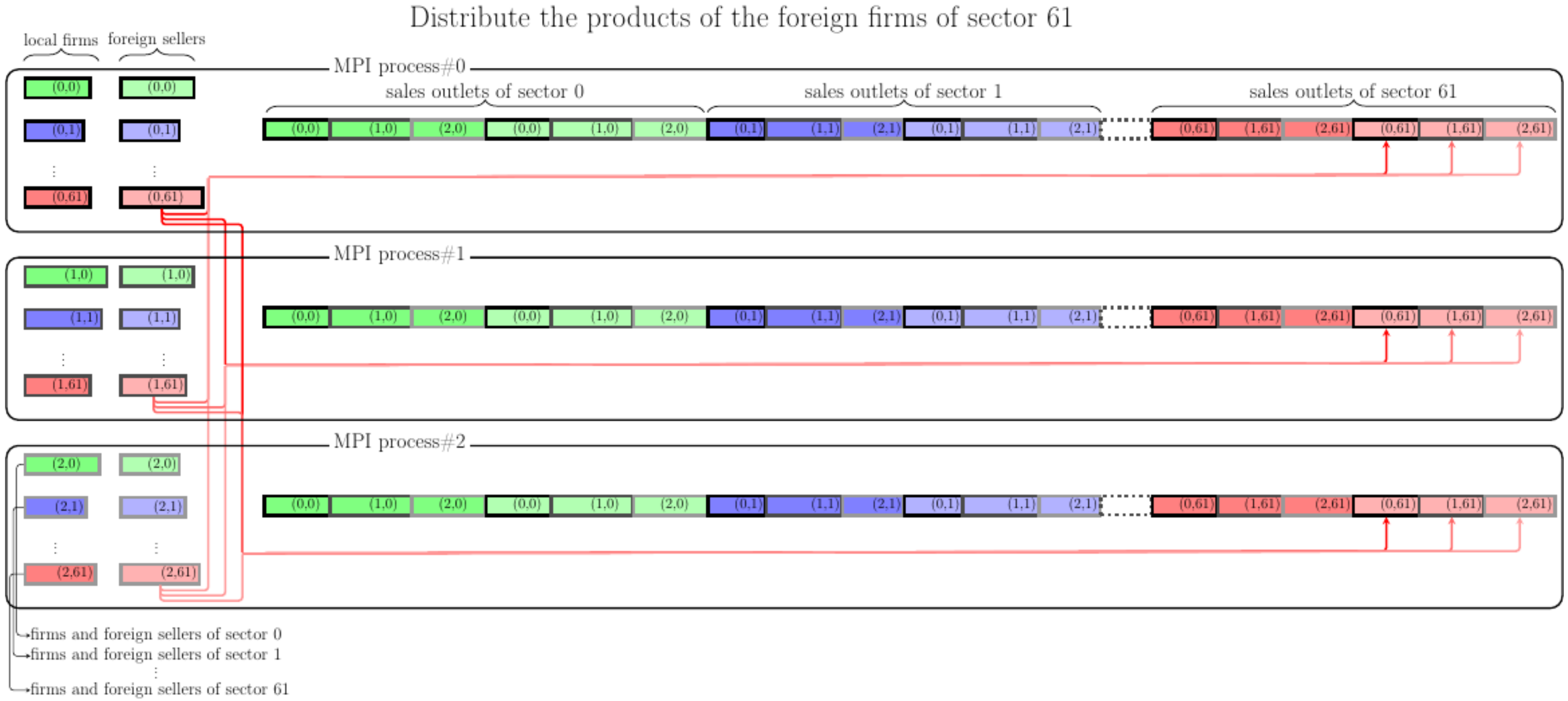
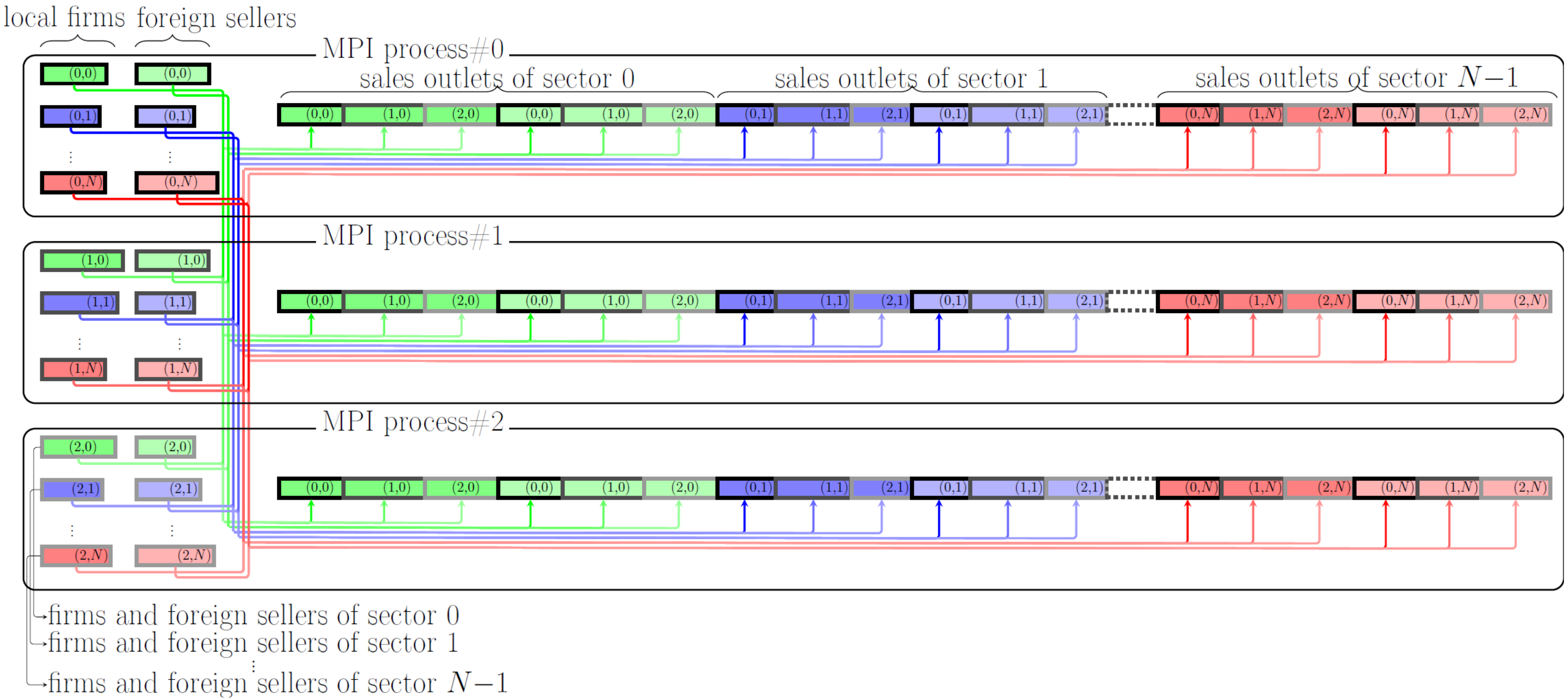
Reduction of communication with the latest MPI standard



- Poor scalability due to $2 \times N$ of calls to *MPI_Iallgatherv*()
  - N is the number of industries; for Japan $N=108$

Gill et al. (2021)

Reduction of communication with the latest MPI standard



- Used MPI_Ialltoallw()with user defined MPI data types to attain higher performance

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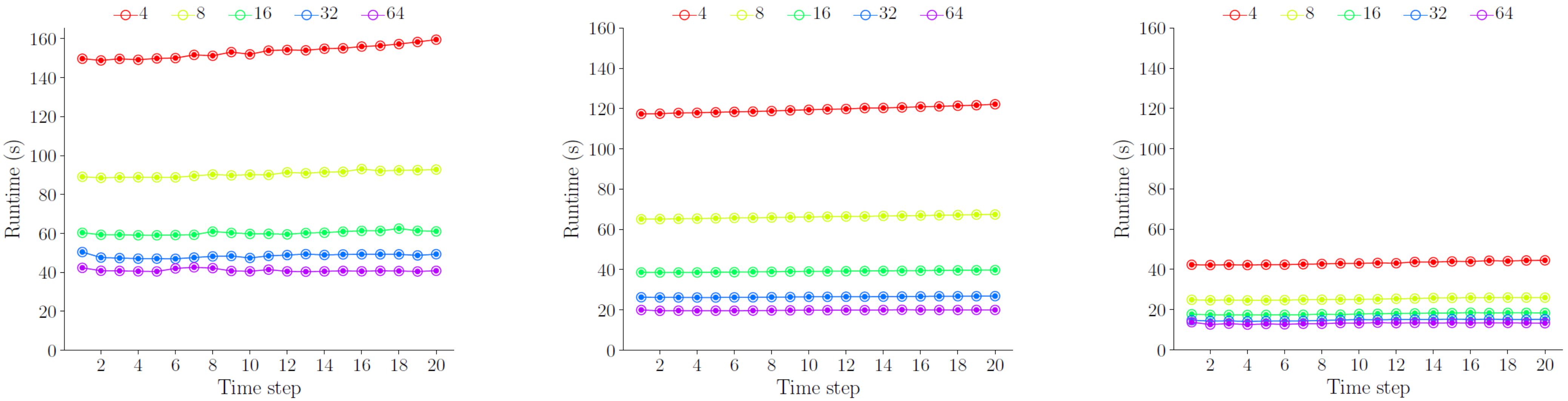
Reduction of serial computation time

Average runtime per period, with **10** million agents, at different stages



Primitive *draw_from_a_distribution*() Improved *draw_from_a_distribution*() Cache friendly data structures in *buy*()

- Significant improvements in computational performance are attained in three stages, by implementing cache friendly and low memory intensive algorithms and data structures

Gill et al. (2021)

Runtime and strong scalability

# MPI processes	Run-time per iteration(s)	Strong scalability
4	44.5	
8	26.0	85.7%
16	18.3	70.2%
32	15.2	60.2%
64	13.2	57.4%

Strong scalability = $\frac{T_n / T_m}{n/m}$, where $n \geq 2m$

Problem settings: 20 iterations with 10 million agents in Reedbush computer (The Univ. of Tokyo)

- Scalability is sufficient for simulating a **1-to-1 scale model of Japan, the U.S. or the euro area** with more than 300 million interacting agents
  - A single period with 100 million agents takes 38 seconds on 128 CPU cores.

Gill et al. (2021)