

JMAB 2.0: A Critical Update for the Macroeconomic Agent-based Model JMAB

Simon Hess

`simon.hess@uni-rostock.de`

University of Rostock

Research Article

Keywords: Agent based macroeconomics, Stock-flow consistent models, Business cycles, Bank regulation

Posted Date: September 28th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9726404/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

Title Page

Title

JMAB 2.0: A Critical Update for the Macroeconomic Agent-based Model JMAB

Name of the author

Simon Hess

Affiliation

University of Rostock, Rostock, Germany

Department of Economics: Chair of Money and Credit

Corresponding author

Simon Hess

simon.hess@uni-rostock.de

ORCID

0009-0000-4641-2623

Acknowledgements

I thank Alessandro Caiani for the extensive feedback on my paper, which helped me immensely to reconsider and clarify many of my points. Furthermore, I thank Doris Neuberger, Edoardo Beretta, and the participants of the economics seminar at the University of Rostock in 2023 for their valuable comments and questions.

JMAB 2.0: A Critical Update for the Macroeconomic Agent-based Model JMAB¹

Abstract

The agent-based stock-flow consistent model by Caiani et al. (2016, *Journal of Economic Dynamics and Control* (69), pp. 375–408) also known as the JMAB (Java Macro Agent-Based Toolkit) benchmark model can be considered as one of the most influential macroeconomic agent-based models. It replicates a variety of stylized economic facts, and many academic works rely on it. However, several shortcomings limit its applicability as a general benchmark model and policy analysis tool. Although the model was originally intended to be used in the field of banking regulation, it generates implausible outputs for several key variables of banks and other agents. In addition, it does not clearly converge to a long-term steady state. These issues mainly arise from misspecifications in agent mechanisms and incompatibilities of mechanisms with the model's internal structure. Moreover, some of the highlighted stylized facts on the micro level appear to be caused by model-specific mechanisms, rather than by their real-world counterparts, thereby implying spurious correlations. This paper identifies the main issues, proposes corrections, and integrates these solutions into an updated version, JMAB 2.0. The updated model produces more plausible and less volatile outputs, particularly for the banking sector, and therefore provides a more robust foundation for use as a general benchmark model and policy analysis tool.

JEL Codes: E03, E32, O30

Keywords: Agent based macroeconomics, Stock-flow consistent models, Business cycles, Bank regulation

¹ The corresponding author of Caiani et al. (2016) responded to my points of critique and agrees on some of them, but argues that many points, which I consider to be errors or misspecifications are instead limitations, that are common in the agent-based literature, such as the backward-looking expectations of agents. Furthermore, the corresponding author notes that many points already have been addressed in subsequent studies, such as firm's investment behavior in Fierro et al. (2022) and the banking system in Schasfoort et al. (2017). The corresponding author does not share the critique regarding the deposit interest rate, bank's demand for bonds, the exclusion of CAPEX from bank's loan approval decision, and the spurious correlation in the heterogeneous market shares of firms. The editor-in-chief of the journal in which the original model was published also responded to the issues and concluded that they were not fundamental enough to require the publication of a correction note. This is why the present paper includes, for example, a corrected version of the original calibration equation system.

1 Introduction

The financial crisis of 2008/2009 was also accompanied by a crisis in economic modeling. The state-of-the-art Dynamic Stochastic General Equilibrium (DSGE) models were unable to predict the crisis, mainly due to their lack of incorporation of the financial sector. As a result, academic focus shifted towards improving existing models by incorporating financial frictions, heterogeneity, bounded rationality, deep downturns, and disasters (Dosi & Roventini, 2019). At the same time, alternative modeling techniques such as Stock-Flow Consistent Models, Agent-Based Models (ABMs), and System Dynamics approaches, which include these features by default, gained attention. Especially, ABMs have received growing interest in recent years.

Most ABMs in economics share common components (Dosi & Roventini, 2019): a population of heterogeneous agents (e.g., firms and households) progresses forward in time steps. Agents update their micro-variables based on programmed algorithms, and aggregate macro-variables are derived from individual ones. Agents' stochastic behavior leads to disequilibrium. In contrast, basic DSGE models feature a representative household and firm with rational expectations, described by a three-equation system for aggregate demand, supply, and monetary policy. These models assume a general equilibrium where markets always clear and rely on exogenous shocks to create economic fluctuations.

ABMs offer various advantages over aggregated equilibrium models (Heckbert et al., 2010; Turrell, 2016). The most important one is emergent behavior: Individual agents' interactions create the macroeconomic outcome, which can be useful to model causal relationships between the micro- and macro-level. This is accompanied by agent heterogeneity, allowing for the study of redistributive policies for example. ABMs can also replicate stylized facts like fat-tailed distributions and model agent behaviors more realistically by assuming bounded rationality and relying on simple heuristics. On top of that, they can handle complex, non-linear systems with multiple equilibria. However, ABMs rely more on assumptions and face the Lucas critique. Generalizing results is also difficult, and model calibration can be challenging due to numerous parameters. Due to interdependence between parameters, it is not always clear which one produces a certain outcome, potentially leading to over-fitting and spurious correlations. Additionally, they can be harder for policymakers to interpret compared to statistical models.

In the past, various ABM families for macroeconomics have evolved with four main strains: the Keynes meets Schumpeter models (Dosi et al., 2010, 2017), the CATS models (Assenza et al., 2015; Gatti et al., 2005, 2011), the EURACE models (Dawid et al., 2012; van der Hoog &

Dawid, 2019), and the JMAB models, all originated from the JMAB benchmark model by Caiani et al. (2016), which this paper focuses on. This model is referred to as JMAB 1.0 in this paper. While all these models share common agent-based properties such as heterogeneity, disequilibrium, and internal business cycles, JMAB 1.0 stands out due to its stock-flow consistency and incorporation of a financial sector with credit money. Stock-flow consistency means that every flow in the economy affects one or more stocks (Stock-flow consistency), every financial liability of one agent is a financial asset of another, ensuring the net financial wealth of the economy is zero (Stock consistency), and every monetary flow originates from and ends somewhere (Flow consistency)(Nikiforos & Zezza, 2017). Violating this principle by introducing flows and stocks without origin can result in logically incoherent stock and flow dynamics. According to Caiani et al. (2016), incorporating stock-flow consistency ensures the logical coherence of the model, allowing for both logical and empirical validation. Another contribution of Caiani et al. (2016) is JMAB from a software engineering perspective. While existing ABMs such as EURACE are too complex to be accessible and reusable for new users, JMAB was intended to be a simple and flexible AB-SFC model which can be easily employed, adapted, and changed, especially for new users. Therefore, alongside their benchmark model Caiani et al. (2016) provide the JMAB software package with a documentation as a flexible, modular, object-oriented platform to create AB-SFC models. As Richiardi (2017) points out, DSGE models are homogenous and easy to implement due to the DYNARE software while ABMs in general need programming skills, code is often not reusable, and projects are not incremental. The JMAB platform could be the DYNARE-equivalent for ABMs.

The benchmark model has been successfully applied to various economic fields. So far, five papers have primarily relied on the original model with various extensions. Schasfoort et al. (2017) investigate monetary policy transmission by adding an interbank market to the model. Caiani et al. (2019) apply it to the study of inequality, extending it with technology (R&D investments) and different income classes, while Caiani et al. (2020) build on this extension to examine the effects of higher wages. Additionally, Kremer (2021) investigates contingent convertible bonds by introducing these bonds and new learning behaviors for investors. Finally, Fierro et al. (2022) study the economic effects of automation using the model.

At first glance, JMAB 1.0 appears solid, and the results it produces seem valid. At the macro level, it can reproduce a set of macroeconomic stylized facts. It shows autocorrelations close to real world ones and cross-correlations such as procyclicality of consumption, investment, inflation, and firm's leverage. Furthermore, it generates some economic dynamic. Fig. 1 (a)

depicts the real GDP of the JMAB 1.0 benchmark model. According to the authors, the model's dynamics can be classified into three phases: first, self-sustained growth, followed by a recession, and finally, a recovery to what the authors call a quasi-steady state—a steady state generated by the model dynamics that differs from the initial steady state. Furthermore, at the micro level, the model is also able to replicate a set of stylized facts. For instance, the market share of firms and banks tends to concentrate among a few firms over time, and the investment behavior of firms tends to be lumpy, meaning a few large investments are made instead of many small ones.

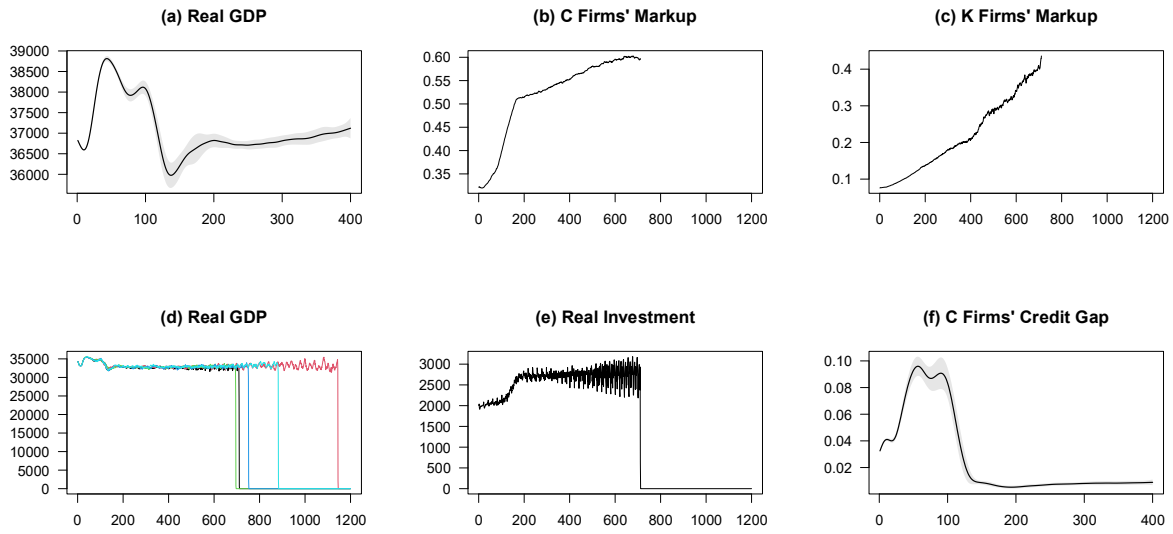


Fig. 1 Results of JMAB 1.0 for various variables. In (a) and (f) solid lines are averages, while shaded areas are standard deviations of all 100 simulation runs. In (b), (c), (d), and (e) each line represents one run in the model

However, after closer examination, the model shows various shortcomings. Table 1 in Appendix A contains a list of the main issues I identified in the model, which includes issues related to the model itself, to its calibration, to its implementation, and its validation. One of these issues affecting its long-term functionality is its method for expectation formation of firm's real sales since this method makes the markups of firms rise continuously. As Fig. 1 (b) shows, the initial markup for consumption firms was calibrated to 0.318857 but nearly doubles to 0.55 after 400 periods. Similarly, the initial markup for capital firms in Fig. 1 (c) was calibrated to 0.075 and almost triples to 0.2 over the same time span. As a result, the model crashes prematurely whenever the original runtime of 400 periods is extended. In Fig. 1 (d) the model's runtime is extended to 1200 periods to investigate its long-term behavior, and every single run crashes before the final period is reached. The investment mechanism of the model

also causes issues. Fig. 1 (e) demonstrates the aggregated investment of the model in a single run. There is a feedback-loop in the investment mechanism causing the volatility of investment to increase over time. The described quasi-steady state therefore only exists in the statistical average over all these volatile runs, but the model itself becomes less steady over time. There are also several issues with the banking system. This includes the omission of the central bank's policy rate in the deposit interest rate determination, the incorrect calibration of the probability of default of firms, and the loan approval decision, which does not consider any funding costs of the loan. These lead to an implausible behavior of the credit gap of firms, as shown in Fig. 1 (f). The credit gap starts at a ratio of 0.04 of total loans in the first period despite there is no credit gap in the calibrated steady state. All these issues limit the model from fulfilling its intended purpose of being used as a benchmark model for policy analysis and may lead to misleading results, if uncritically applied to certain fields, such as banking regulation. Moreover, the proposed validation methods by Caiani et al. (2016) exhibits limitations in detecting these issues. Several key variables in the banking sector are left out of the validation. In addition, some of the highlighted stylized facts in the validation on the micro level—namely the concentrated market shares of firms and lumpy investment patterns—appear to be caused by model-specific mechanisms, rather than by their real-world counterparts, implying spurious correlations.

The contribution of this paper is twofold. First, it reveals the shortcomings in the JMAB 1.0 model, and second, it provides a revised alternative, JMAB 2.0, which generates more plausible and less volatile outputs. JMAB 2.0 builds on JMAB 1.0 but introduces fundamental differences in agent behaviors. Beyond that, a set of basic standards is presented, which intends to improve the publication and validation of future ABMs.

The structure of this paper is as follows: Section 2 outlines the main issues with JMAB 1.0 and offers working solutions to these. Section 3 shows the remaining components of the JMAB 2.0 model, followed by the calibration in Section 4. Section 5 presents the results of the revised model, while Section 6 discusses the findings. Section 7 concludes the paper.

2 The Main Issues with JMAB 1.0 and Solutions

This section, first, provides an overview of JMAB 1.0, which also contains the alterations of JMAB 2.0. Second, it outlines the main issues with JMAB 1.0, along with suitable solutions included in JMAB 2.0. Issues exist with firms' sales expectations, price and wage expectations, firm pricing, firm investment, the banking sector, and other mechanisms.

2.1 Model Overview

The agent population of the JMAB 1.0 model consists of six types of agents: households h , consumption firms c , capital firms k , banks b , a government g and a central bank cb . When terms apply to both consumption and capital firms they are denoted with x . These agents produce or hold seven types of stocks: consumption goods C , capital goods K , bank loans L , bank deposits D , government bonds B , central bank advances (central bank loans) A , and reserves (central bank deposits) R . JMAB 2.0 newly introduces interbank (IB) loans IBL and interbank borrowing IBB , which is the liability of the interbank loan.

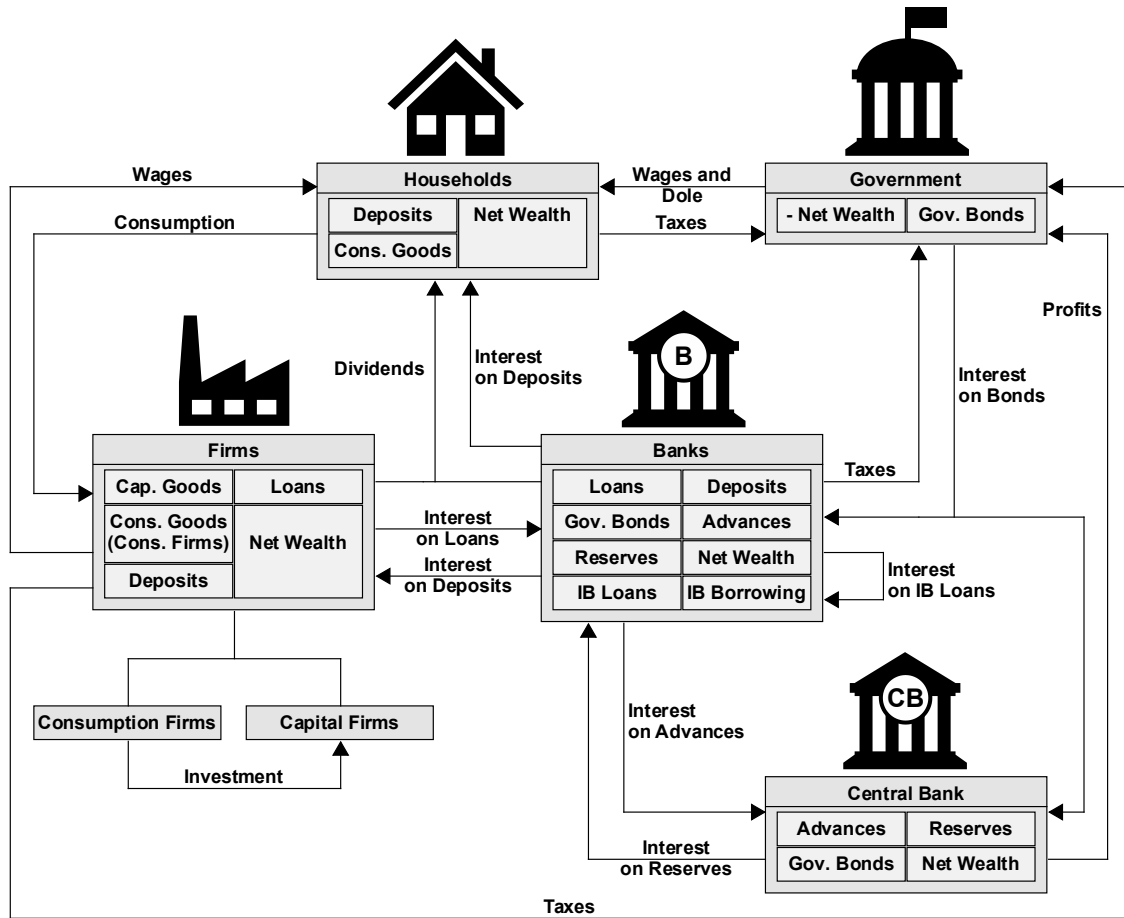


Fig. 2 Agents in JMAB 1.0/2.0 with stocks and financial flows

Consumption firms produce consumption goods, invest in capital goods, take loans from banks, and employ households. Capital firms produce capital goods, take loans, and employ households. Households buy consumption goods, while banks grant loans, purchase government bonds, and create and manage deposits for firms and households. The government employs households and issues bonds. The central bank grants advances to banks, purchases government bonds, and creates and manages the reserves of banks and the government. In

JMAB 2.0 banks additionally grant and take interbank loans among themselves. All types of agents with their stocks and financial flows are depicted in Fig. 2.

There are tax flows from all agents except for the central bank to the government as well as interest flows. They go from credit demanders to banks, from banks to deposit holders and from the government to bond holders. The government also provides dole to households. The profits of firms and banks are distributed as dividends among households. The profit of the central bank is transferred to the government.

The model progresses in discrete timesteps $t = 1, 2, 3, \dots, T$ with each timestep representing one quarter of a year. In each timestep, agents perform their activities in a predefined order. They follow certain strategies, interact with other agents in markets, and after each period, selected aggregated and micro-agent data is collected in reports.

The agents interact in seven markets: labor, consumption goods, capital goods, loans, deposits, bonds, and central bank advances. In JMAB 2.0 agents additionally interact in the market for interbank loans. Each market has its own matching mechanism. All markets are buyer-driven, where the buyer selects the supplier. Buyers are chosen in random order and assigned a number of randomly drawn matching suppliers ξ_x . The buyer preselects the supplier offering the lowest price (for consumption goods, capital goods, labor, and loans) or the highest price (for deposits). If the preselected supplier offers a lower price than the previous one (or a higher price for deposits), or if the previous supplier is out of stock, the buyer switches to the preselected supplier with a certain probability PS . In JMAB 1.0 this probability is a function of the distance between the price of the preselected supplier and the previous supplier. For the sake of simplicity, in JMAB 2.0 and the experiments related to 1.0 the probability is fixed. Buyers are matched with sellers as long as there is at least one active buyer and one supplier.

The code of the JMAB 2.0 model is publicly available.² JMAB 1.0 specific data and plots were generated either with the original model's code or with a simplified model. The full-scale JMAB 1.0 model is difficult to debug due to its lengthy program initialization, which required the creation of a simplified model only containing three types of agents (households, C firms and K firms) and two markets (consumption and capital) with fixed wages and no nominal growth. Plots, which are based on data created by the simplified model contain a note in their caption.

² See the data availability section for more information.

2.2 Expectations of Firm Sales

The centerpiece of the JMAB 1.0 model is the method used to compute expectations. At the start of each period, each agent forms expectations e for a generic variable z based on the past expectations and the actual past value:

$$z_t^{e^{SES}} = z_{t-1}^{e^{SES}} + \beta^{SES} (z_{t-1} - z_{t-1}^{e^{SES}}) \quad (1)$$

The method applied here is simple exponential smoothing (SES), which calculates expectations based on all past observed values with exponentially decaying weights. The β^{SES} variable is the smoothing parameter. The larger this parameter, the more weight is given to the most recent past values when computing the next expected value. In JMAB 1.0, SES expectations are formed for firms' real sales, firms' nominal wages, and households' nominal consumption prices.

At first glance, this method appears to provide a simple and promising approach for computing expectations for all agents. However, closer examination reveals several shortcomings. The first issue arises in firms' expectations of real sales, where the exponential smoothing method is incompatible with the inventory-based pricing strategy.

In JMAB 1.0, the markup (and therefore the price) $mu_{x,t}$ of firms is adjusted using an adaptive heuristic based on the past inventory-to-sales ratio and the desired inventory-to-sales ratio v . If the remaining inventories from the last period are lower than desired, the markup is increased. If they are higher, the markup is decreased:

$$mu_{x,t} = \begin{cases} mu_{x,t-1} + FN & \text{if } \frac{inv_{x,t-1}}{s_{x,t-1}} \leq v \\ mu_{x,t-1} - FN & \text{if } \frac{inv_{x,t-1}}{s_{x,t-1}} > v \end{cases} \quad (2)$$

FN is a random number drawn from a Folded Normal distribution with parameters μ_{FN} and σ_{FN}^2 .

The precondition for this inventory-based pricing strategy in combination with exponential smoothing method to work properly and keep markups at a steady-state level is that sales of firms must be distributed perfectly symmetrical around the mean and the median has to be on the same level as the mean. Otherwise, firms tend to over- or underestimate their sales which leads to falling or raising markups. This is exactly the case with JMAB 1.0. Fig. 3 (a) shows the actual and expected sales of a single firm in a configuration of JMAB 1.0 with the

probability to switch set to the excessive value of 0.5, revealing that firms' sales are clearly asymmetrical. While most sales cluster around 300, there are occasional downward spikes. These spikes cause the expectations to remain below the actual values most of the time, leading firms to consistently underestimate sales, which, in turn, results in increasing markups and finally makes the simulation crash. The two key parameters contributing to this asymmetry are the probability of households switching suppliers and the target inventory-to-sales ratio.

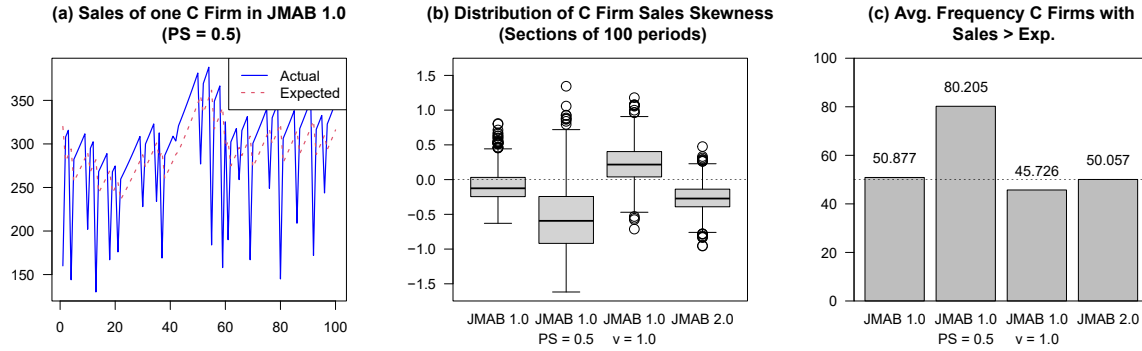


Fig. 3 Results of consumption market experiments with various expectation mechanisms and configurations. (b) and (c) show the data of a single run with 1000 periods. All data was created by the simplified JMAB 1.0 model

Fig. 3 (b) illustrates the sales skewness distribution of a single run in the model, with all sales of each firm segmented into sections of 100 periods (of 1000 periods in total) across various parameter settings. The segmentation was performed to minimize the influence of outliers. In addition, Fig. 3 (c) shows the average frequency of firms with sales exceeding expectations. In all configurations, sales are skewed. With the probability to switch PS set to 0.5, most sales sections are strongly negatively skewed, causing around 80 out of 100 firms on average to underestimate their sales. Even in the standard JMAB 1.0 configuration, a similar but less extreme pattern emerges, with slightly negatively skewed sales sections and 50.877 out of 100 firms on average underestimating sales. When the inventory-to-sales ratio v is set to 1.0, the behavior reverses, sales sections become positively skewed, and firms begin overestimating their sales (only 45.726 out of 100 on average underestimating). To produce the results in Fig. 3, the JMAB 1.0 expectation mechanism is combined with the JMAB 2.0 pricing mechanism for comparability.

Due to the inadequacy of exponential smoothing in predicting sales, JMAB 2.0 uses a simpler rule-based (RB) heuristic which is capable of error correction and is commonly found in other

ABMs. With this heuristic, the expectation increases when past sales exceed the past expectation, and vice versa:

$$s_{x,t}^{eRB} = \begin{cases} s_{x,t-1}^{eRB} + \alpha_x^s LN & \text{if } s_{x,t-1} > s_{x,t-1}^{eRB} \\ s_{x,t-1}^{eRB} - \alpha_x^s LN & \text{if } s_{x,t-1} < s_{x,t-1}^{eRB} \end{cases} \quad (3)$$

LN is a random number drawn from a lognormal distribution with the median μ_{LN} and the variance σ_{LN}^2 . A lognormal distribution is used for all JMAB 2.0 mechanisms because it better aligns with empirical data. α_x^s is a fixed adaptive parameter ensuring that the step-size of each adjustment remains consistent. Similar mechanisms, such as those by Dawid and Gatti (2018) and Assenza et al. (2015) were tested but exhibited issues with percentage-based adjustments of expectations where sales were adjusted as $s_{x,t-1}^{eRB}(1 + LN)$.³

As Fig. 3 (c) shows, this method predicts expectations better, even with a more negatively skewed sales distribution than JMAB 1.0. This is due to the error correction capability of the method, which adjusts expectations in the same direction as the sales trend.

2.3 Expectations of Wages and Prices

The second issue with exponential smoothing arises from its application to variables with a persistent upward trend in the expectation formation of firms and households. Firms form expectations on nominal wages to determine their prices and credit demand while households form expectations on nominal consumption prices to determine their real desired consumption. Since households in the model increase their wage more often than they decrease it there is persistent nominal growth in the model. Simple exponential smoothing, however, is not suited to deal with this trend and therefore appears to be a misspecification in this context. Fig. 4 shows the expected and actual values of the wage of one consumption firm and the consumption good price of one household. As can be seen since exponential smoothing only considers the past values it is not able to predict the grown nominal values correctly. The predicted values are below the actual ones most of the time. Considering inflation this implies that households almost always expect negative inflation rates what is in stark contrast to

³ For instance, an expectation of 320 multiplied by 1.01 results in 323.2. If the firm later lowers its expectation by multiplying 323.2 by 0.99, the result is 319.968, which is lower than the original 320, causing the firm to underestimate sales again. This issue does not arise when using a fixed adjustment parameter, i.e., $s_{x,t-1}^{eRB} + \alpha_x^s LN$.

empirical data (University of Michigan 2024). In consequence, this has the same effect as an external shock and contributes to the deviation from the steady state when the model is running. Households consume more than they would do with the actual higher consumption price. Firms set their prices lower and request less credit since their wage expectation is below the actual value.

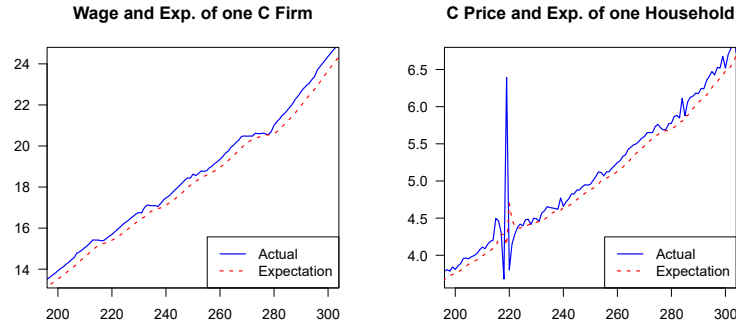


Fig. 4 Actual and expected values of wages and C Prices of one respective agent in JMAB 1.0

To cope with this problem there are three potential solutions: First, agents could form expectations on the inflation rate and wage growth rate instead of the price and wage. Second, agents could utilize double exponential smoothing for their expectations which considers trends in data, like the nominal growth in the model. The third option would be to use no expectation at all and take the actual values. For sake of simplicity, JMAB 2.0 uses no expectation for prices and wages. The order of agent activities is adjusted so that firms and households can consider the current wage and price for their behavior. Nevertheless, double exponential smoothing is utilized for almost all other expectations that agents are forming, like the return on real capital of consumption firms and EBIT of firms (see Sections 2.5 and 2.6.2).

2.4 Firm's Pricing

Furthermore, there are issues with the pricing mechanism in JMAB 1.0 and the interpretation of the results it produces. Caiani et al. (2016) identify a stylized fact in the model's output since the market share of firms tends to exhibit a high degree of heterogeneity and persistence.⁴ This is attributed to competition in consumption and capital markets. However, upon closer inspection, the underlying causes of this stylized fact differ between the model and the real

⁴ See Fig. 16 for a visual representation.

world, implying a spurious correlation. The actual driver of firm's market share in the model is the random parameter FN in the markup-setting equation (Eq. 2). Firms that draw lower values from the random number generator set lower prices, become more competitive, and attract more customers, while firms with higher numbers set higher prices, making them less competitive and leading to a loss of customers. These firms effectively price themselves out of the market without being able to counteract this trend, as they lack information on market prices. Empirical studies, however, suggest that firms are aware of their competitors' prices, and it is one of the most important factors in firms' pricing decisions (Fabiani et al., 2006). Heterogeneity arises from other factors. Hottman et al. (2016), for example, argue that firm heterogeneity mainly stems from differences in appeal (quality or taste), product scope, and average marginal costs. Thus, Caiani et al. (2016) spuriously link the market share of firms without any information on their competitors with market shares of firms with this information.

In JMAB 2.0, competitors' prices are a factor that must be considered. Existing ABM literature offers various quantity-price mechanisms that account for competitor prices, though each has its own shortcomings. A detailed comparison of the mechanisms by Dawid and Gatti (2018) and Assenza et al. (2015) with those of JMAB 1.0 and JMAB 2.0 is presented in Appendix B. I propose the following mechanism for firms' markups in JMAB 2.0:

$$mu_{x,t} = \begin{cases} \overline{mu}_{x,t-1} + \alpha_x^{mu} LN & \text{if } s_{x,t-1} > s_{x,t-1}^{eRB} \\ \overline{mu}_{x,t-1} - \alpha_x^{mu} LN & \text{if } s_{x,t-1} < s_{x,t-1}^{eRB} \end{cases} \quad (4)$$

Firms choose a markup higher than the average if past sales exceeded expectations, and a markup lower than the average if past sales are below expectations. The average markup $\overline{mu}_{x,t-1}$ is approximated by capital firms by rearranging Eq. (6) from the last period for the markup and replacing the price with the average price. Consumption firms do the same with Eq. (8).

Additionally, there is a potential issue with the pricing mechanism in JMAB 1.0. The price is determined by a markup on variable costs:

$$p_{x,t} = (1 + mu_{x,t})vc_{x,t} \quad (5)$$

Where $mu_{x,t}$ is the markup and $vc_{x,t}$ represents the variable costs. This mechanism, however, does not account for changes in fixed costs, which may be necessary when analyzing price shocks in capital goods or changes in monetary policy. If a firm's fixed costs exceed the growth

rate, it cannot cover those increases. In JMAB 2.0, capital firms set the prices of their goods by applying a non-negative markup $mu_{k,t}$ on their unit costs:

$$p_{k,t} = (1 + mu_{k,t})uc_{k,t} \quad (6)$$

The unit costs for capital firms are defined as labor costs plus the interest paid on loans in the last period, divided by the desired output:

$$uc_{k,t} = \frac{\sum_{n \in N_{k,t}} W_{n,t} + i_{k,t-1}^L L_{k,t-1}}{y_{k,t}^d} \quad (7)$$

where $W_{n,t}$ is the wage of employee n of firm k , $i_{k,t-1}^L$ the interest rate on the previous loan stock $L_{k,t-1}$, and $y_{k,t}^d$ is the desired output.

Consumption firms use the normal-cost pricing method according to Godley and Lavoie (2007) to set their prices independently of their capacity utilization. Their prices are constituted by a non-negative markup on their normal unit costs:

$$p_{c,t} = (1 + mu_{c,t})nuc_{c,t} \quad (8)$$

Normal unit costs are defined as the costs a consumption firm incurs when operating at full capacity. Full capacity output (normal output) is defined as $y_{c,t}^n = K_{c,t} cu_c^T$. Normal unit costs are calculated by dividing labor costs, interest paid, and amortization by the normal output:

$$nuc_{c,t} = \frac{\sum_{n \in N_{c,t}} W_{n,t} + i_{c,t-1}^L L_{c,t-1} + \sum_{k \in K_{c,t-1}} (k^k p^k) \frac{1}{\kappa}}{y_{c,t}^n} \quad (9)$$

where p^k is the price of one batch of capital goods k^k of the firm's previous capital stock $K_{c,t-1}$, and κ the capital duration.

2.5 Firm's Investment

To investigate the cause of the high volatility in investments and the unsteady state in the long run, the investment function of JMAB 1.0 needs to be examined. In JMAB 1.0, each consumption firm aims to reach a desired productive capacity growth $g_{c,t}^d$, based on the previous period's rate of return $r_{c,t-1}$ and the desired rate of capacity utilization $cu_{c,t}^d$:

$$g_{c,t}^d = \omega^r \frac{r_{c,t-1} - r_c^T}{r_c^T} + \omega^{cu} \frac{cu_{c,t}^d - cu_c^T}{cu_c^T} \quad (10)$$

where r_c^T is the target rate of return, and cu_c^T is the target capacity utilization. Both variables are exogenously given. ω^r and ω^{cu} represent the weights assigned to the rate of return and

capacity utilization, respectively. $cu_{c,t}^d$ is the capacity utilization necessary to produce the desired output of the firm as will be outlined in Section 3.2.2.

The rate of return $r_{c,t}$ is defined as operating cash flows divided by the nominal value of capital:

$$r_{c,t} = \frac{OCF_{c,t}}{\sum_{k \in K_{c,t-1}} (k^k p^k) (1 - \frac{age_{k,t-1}}{\kappa})} \quad (11)$$

where $age_{k,t-1}$ indicates the age of capital goods, and $OCF_{c,t}$ represents the operating cash flows for the consumption firm. $OCF_{x,t}$ is calculated as after-tax profits plus capital amortization costs (for consumption firms only), minus changes in inventories and principal repayments.

The real demand for capital goods $i_{c,t}^d$ can be derived by subtracting the residual capital $k_{c,t-1}^{res} = \sum_{k \in K_{c,t-1}, age_k < \kappa-1} k^k$, which is the capital stock left from the previous period in the next period, from the desired capital:

$$i_{c,t}^d = k_{c,t-1} (1 + g_{c,t}^d) - k_{c,t-1}^{res} \quad (12)$$

where $k_{c,t-1}$ is the previous real capital stock. Finally, the nominal demand for capital goods $I_{c,t}^d$ can be obtained by multiplying $i_{c,t}^d$ by the price from the selected capital goods supplier:

$$I_{c,t}^d = i_{c,t}^d p_{k,t} \quad (13)$$

This investment function has several flaws at both the micro and macro levels. One issue at the micro level lies in Eq. (12). Caiani et al. (2016) state to have implemented lumpy investments in their model without explicitly doing so. Lumpiness typically arises from fixed adjustment costs (Caballero et al., 1995). For example, a new production plant is usually bought only once over several periods due to the fixed costs of that purchase. However, the investment behavior of firms in JMAB 1.0 is not related to this lumpiness and therefore again implies a spurious correlation. Instead, it results from a feedback-loop between the investment variable and residual capacity in Eq. (12). Fig. 5 (a) illustrates the simplified JMAB 1.0 model with only two consumption firms, where the desired output of each firm alternates between 16800 and 15200, keeping the term $K_{c,t}(1 + g_{c,t}^d)$ in the equation relatively constant. The capacity weight is set to 0.02, as in Caiani et al. (2016), while the profit rate weight is set to 0. One firm has a desired output of 16800 in $t=1$, leading to an investment of 1020 capital goods. For the first 20 periods, investment remains between 1020 and 980, in line with the alternating output, and residual capacity alternates between 19000 and 19020. However, after 20 periods, residual

capacity decreases due to increased investment in $t=1$, so the firm increases its investment by 40 units to balance out the reduction in capacity. This, in turn, reduces the residual capacity again at $t=40$, forcing further increases in investment. This process continues until investment fluctuates between 2000 and 0. Another factor contributing to this behavior is that every firm has an equal amount of capital of each age in the steady state. If firms had capital of only one age they would invest once per 20 periods without the feedback-loop building up over time.

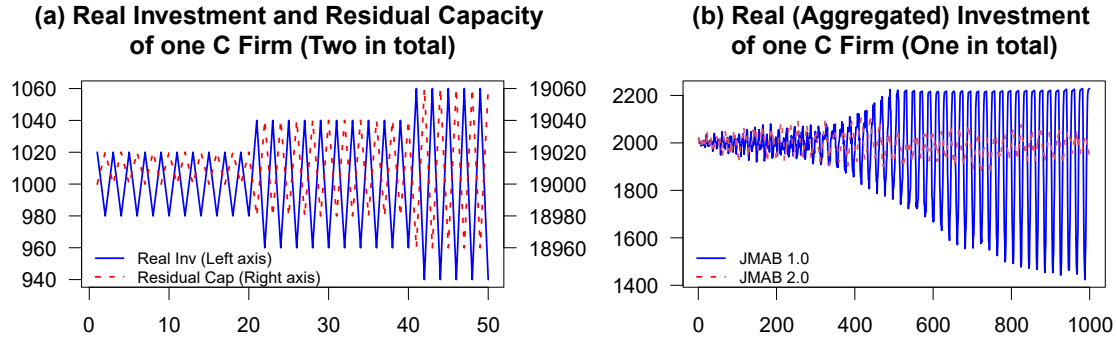


Fig. 5 Experiments with JMAB 1.0 and 2.0 investment mechanisms. All data was created by the simplified JMAB 1.0 model. In all experiments the expectation and pricing mechanisms of JMAB 2.0 were used

The investment mechanism on the micro level only affects investment volatility of a single firm, not the aggregated level, since the fluctuations of multiple firms balance each other out. However, the feedback-loop also affects the macro level. Fig. 1 (e) earlier showed that JMAB 1.0 produces implausible results concerning aggregate investment, with investment volatility increasing exponentially, which contradicts empirical evidence. This malfunction can be explained by the feedback-loop that emerges when aggregate consumption deviates from its steady state, caused by the stochastic elements in the agent's adjustment processes or rounding behavior of the programming language. If two firms, for example, want to produce 32000 goods in total, one firm 16000.5 while the other 15999.5, both are rounded to the next bigger integer, so that firms produce 32001 goods in total. This would lead to higher investment, employment and consumption, which in turn leads to higher production and starts the circle again. This feedback-loop would continue indefinitely but is ultimately constrained by the wear of capital goods, which is limited per period if the capital stock stays on one level. In Fig. 5 (b) this behavior is reproduced in the simplified JMAB 1.0 model with an economy consisting of only one consumption firm to eliminate the effects of the feedback-loop on the micro level shown in Fig. 5 (a). The investment is artificially increased above the steady (2020 instead of

2000) state level at $t=1$ to start the feedback-loop. This one deviation creates an exponentially increasing volatility over the entire timespan. The investment cycles are 20 periods long like on the micro level, but investment does not fluctuate between each period to the same degree. Thus, the investment behavior is incompatible with the model's internal structure if the objective is to achieve a long-term (quasi) steady state.

Another issue concerns a misspecification in the inclusion of the target profit rate in Eq. (10). For their investment function Caiani et al. (2016) adopt later generation Post-Keynesian macroeconomic growth models which define investment as a function of the profit rate and rate of capacity utilization (Dutt, 1984; Rowthorn, 1981). From a macroeconomic perspective this may be reasonable since increased profits increase internal funding capabilities for new projects and higher expected profits leads to more investment. However, at the micro level of the model, where firms face only a single investment opportunity, the inclusion of a target profit rate appears inappropriate. While it may be plausible for firms with profit rates below their target to reduce capacity, the behavior implied for firms with profit rates above their target is less convincing. In such cases, firms expand capacity in a way that appears unnecessary, effectively creating excess capacity in order to bring the profit rate back toward its target, which contradicts empirical evidence. Second, in the model where all firms face the same fixed external economic conditions (e.g. interest rates and taxes) both the capacity utilization and the profit rate depend on the specific sales of the firm making the profit rate redundant.⁵ Third, it may be argued that the profit rate has its viability in reflecting changing external economic conditions such as changes in interest rates or tax rates. Reissl (2021), for example, makes this explicit by replacing the profit rate with the current interest rate on loans. However, this again lacks a microeconomic foundation. A decrease in interest rates may increase investment on the macroeconomic level but on the micro level it would just build up excess capacity and reduce profits. Overall, the use of the profit rate in this context lacks a clear economic rationale and turned out inappropriate for modeling firms' microeconomic investment behavior.

The investment function of JMAB 2.0 should have a more solid empirical foundation. A survey by Graham and Harvey (2001) suggests that the internal rate of return and the Net Present Value (NPV) method are the most common capital budgeting techniques. Therefore, the latter is used for JMAB 2.0 to assess the profitability of investment. Furthermore, investment of the

⁵ The same argument is made by Bhaduri and Marglin (1990) for the macro level. The authors therefore suggest using the share of profit in national income instead of the profit rate.

current period is based on investment of the previous period and is adjusted in fixed steps instead of being derived from the difference between the desired and residual capacity. This prevents the high volatility on the micro and macro level.

Thus, in JMAB 2.0 firms increase their investment if the desired capacity exceeds their current capacity and the NPV of the current capacity is greater than 0. Conversely, if the desired capacity is below the current capacity or the NPV is zero or negative, investment is reduced:

$$i_{c,t} = \begin{cases} i_{c,t-1} + \alpha_c^i LN & \text{if } k_{c,t}^d > k_{c,t-1} \text{ and } NPV_{c,t} > 0 \\ i_{c,t-1} - \alpha_c^i LN & \text{if } k_{c,t}^d < k_{c,t-1} \end{cases} \quad (14)$$

where the desired capacity is calculated as $k_{c,t}^d = y_{c,t}^d / cu_c^T$. $NPV_{c,t}$ is calculated by summing up the discounted future cash flows of one capital unit and subtracting the investment cost, which is the price of one capital unit:

$$NPV_{c,t} = \sum_{n=1}^{\kappa} \frac{RORK_{c,t+n}^{eDES}}{(1 + WACC_{c,t})^n} - p_k \quad (15)$$

The future cash flow is calculated based on the expected return on real capital $RORK_{c,t+n}^{eDES}$, which is the double exponentially smoothed expectation of unlevered free cash flow divided by the capital stock, $RORK_{c,t} = UFCF_{c,t} / k_{c,t}$. Unlevered free cash flow is defined as profits minus interest payments, amortization, and investment.

Double exponential smoothing is utilized to account for the nominal increasing trend in the cash flow. For a generic variable z_t , the double exponentially smoothed expectation z_t^{eDES} is calculated as follows:

$$lvl_t = \beta z_{t-1} + (1 - \beta)(lvl_{t-1} + trd_{t-1}) \quad (16)$$

$$trd_t = \gamma(lvl_t - lvl_{t-1}) + (1 - \gamma)trd_{t-1} \quad (17)$$

$$z_t^{eDES} = lvl_t + trd_t \quad (18)$$

$$z_{t+n}^{eDES} = lvl_t + n trd_t \quad (19)$$

where lvl_t and trd_t represent the level and trend, and β and γ are the respective smoothing parameters for the level and trend.

The discount factor used to calculate the NPV is the weighted average cost of capital (WACC), calculated as follows:

$$WACC_{c,t} = \overline{ROE}_{c,t-1} \overline{ER}_{c,t-1} + \overline{r}_{b,t-1}^L (1 - \overline{ER}_{c,t-1}) \quad (20)$$

where $\overline{ROE}_{c,t-1}$ is the average return on equity, $\overline{ER}_{c,t-1}$ is the average equity ratio of all consumption firms in the previous period, and $\overline{r}_{b,t-1}^L$ is the average interest rate on loans of all banks in previous period. Average values are used so that firms can compare themselves to the market.

As shown in Fig. 5 (b), this mechanism is much less volatile than the one in JMAB 1.0. Although a feedback-loop still exists, investment cannot rise or fall to infinity because the increase in investment is constrained by the limited step size in investment adjustment behavior. It should be noted that the mechanism does not implement lumpy investment by default. This could be implemented by introducing a threshold for the minimum capacity a firm wants to maintain, so firms would only invest every tenth or twentieth period. Caiani et al. (2016) also noted this in a footnote. However, this would require firms to start with unequal capital stocks to ensure that aggregate capital demand is not affected. This would contradict the model's calibration, where all agents start under the same conditions, and is therefore not considered for JMAB 2.0.

2.6 Banking Sector

In the banking sector there are issues with the loan approval decision, the probability of default of firms, the deposit interest rate, the loan interest rate, and the demand for bonds.

2.6.1 Loan Approval Decision

The loan approval process in JMAB 1.0 works as follows: A firm approaches a bank with a specific loan request L^d . The bank first calculates the firm's probability of default (Section 2.6.2) for one period. Then, it computes the potential revenues and losses for all possible default scenarios using a declining hazard rate (where the probability of default decreases over time) and derives an expected return. If the applicant has pledged collateral, a share of the expected loss can be recovered, and the expected return is increased. This share is described by the recovery rate δ_x which is the ratio between the discounted value of capital to the firm's total debt. For capital firms with no collateral $\delta_k = 0$ applies, while for consumptions firms $0 < \delta_c \leq 1$ applies. The whole process can be visualized using the payoff tree in Fig. 6 with η being the loan duration. If the expected return exceeds zero, the full loan amount is granted. Otherwise, the loan amount is reduced, and the bank recalculates the probability of default and

expected return until the loan amount can no longer be reduced. This can be expressed using the following recursive function, where $L_0 = L^d$:

$$L_{b,t}^s(L_n) = \begin{cases} 0 & \text{if } L_n = 0, \\ L_n & \text{if } r^e(L_n, i_{b,t}^L, PD_{x,t}(L_n), \delta_x) > 0, \\ L_{b,t}^s(L_n - L_0 1/100) & \text{else} \end{cases} \quad (21)$$

where $i_{b,t}^L$ is the loan interest rate of bank b and $PD_{x,t}$ is the firm's probability of default.

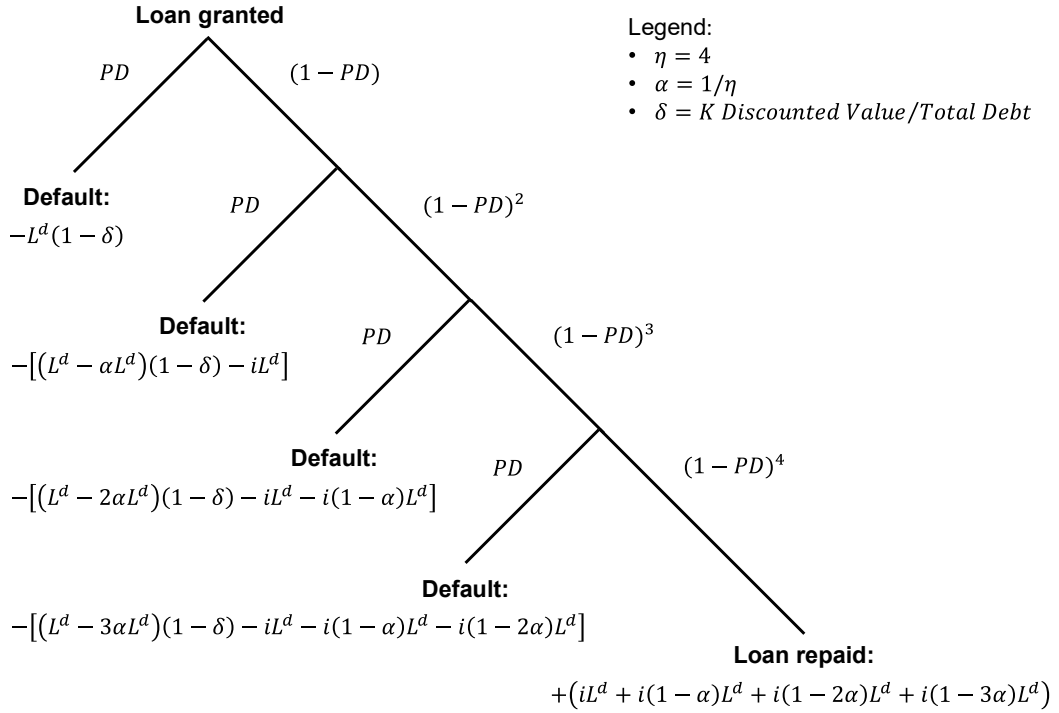


Fig. 6 Payoff tree of a hypothetical loan in JMAB 1.0. Revised version based on Caiani et al. (2016)

There are two issues with this mechanism. First, there is a misspecification since no financing costs are considered: while the positive interest yield of the loan is considered, the bank's financing costs, specifically deposit interest payments, are not accounted for. As a result, the bank may grant loans even when the effective return is negative, which would cause a real-world bank to go bankrupt quickly. In the model, this problem is overshadowed by the issues with the probability of default, which are addressed in the next section. The second issue is that the loan approval process is not implemented as described in the paper. In the implementation, the bank deducts interest payments from the expected loss in the first period $t + 1$ (First left branch in the payoff tree), even though no interest payments would be made if the borrower defaults early. Furthermore, there is a typesetting error in the payoff tree of Caiani et al. (2016) since no collateral is considered in the first left branch of the tree. This is corrected in Fig. 6.

To resolve the first issue, financing costs must be factored into the loan approval decision. I propose the following mechanism, in which all expected discounted cash flows of the loan are offset against all discounted expected losses subtracted with the initial loan amount, to calculate the expected return of the loan:

$$r^e = \sum_{j=1}^{\eta} \left((1 - PD_{x,t}) \frac{ds_j^{L^d}}{(1 + i_{b,t}^{IBL})^j} - PD_{x,t} \frac{L_j^d (1 - \delta_x)}{(1 + i_{b,t}^{IBL})^j} \right) - L^d \quad (22)$$

where $ds_j^{L^d} = L^d \frac{1}{\eta} + L_j^d i_{b,t}^L$ representing the debt service at time j and $L_j^d = L^d \frac{\eta-j+1}{\eta}$ is the remaining loan value at time j . The debt service and the potential defaulted loan amount are discounted using the interbank rate $i_{b,t}^{IBL}$ (Section 3.4.3) as a proxy for financing costs. Unlike in JMAB 1.0, where the hazard rate decreases over time, here it remains constant.

2.6.2 Probability of Default of Firms

Banks compute the probability of default for firms using a logistic function that accounts for the deviation of a firm's operating cash flow from the debt service of the requested loan:

$$PD_{x,t} = \frac{1}{1 + \exp\left(\frac{OCF_{x,t-1} - \zeta_x ds_{t+1}^{L^d}}{ds_{t+1}^{L^d}}\right)} \quad (23)$$

where ζ_x is the risk aversion parameter of banks towards firms, and $ds_{t+1}^{L^d} = (i_{b,t}^L + \frac{1}{\eta}) L^d$ is the first debt service payment of a hypothetical loan L^d .

Caiani et al. (2016) define operating cash flow as after-tax profits minus capital amortization costs, minus changes in inventories, and minus principal repayments. Fig. 7 illustrates the logistic function rearranged to the debt service coverage ratio $DSCR = OCF_{x,t}/ds_{t+1}^{L^d}$ using the calibrated values of Caiani et al. (2016) for consumption firms, $\zeta_c = 3.219798917$. The initial probability of default is then defined as $PD_{c,0} = 25.0231/(25.0231 + \exp(DSCR))$.

There are five issues with this mechanism. The first issue is the miscalibration of the risk aversion parameters in the steady state. These were calibrated with a probability of default of 0.01, but this value is too high compared to the loan interest rate. A probability of default of 0.01, with only a 0.0075 interest margin (or 0.0025 if financing costs are considered), cannot compensate for the expected loss in the loan approval decision. A loan of 100 would generate 0.75 in interest earnings but suffer an expected loss of 1 per period if no collateral is pledged. Capital firms without collateral are unable to secure loans under these conditions, and

consumption firms can only obtain loans because banks do not factor in financing costs, as discussed earlier. This contributes to the credit gap shown in Fig. 1 (f).

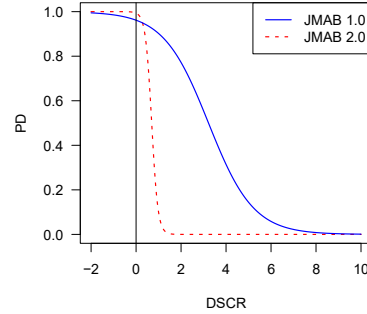


Fig. 7 Probability of default function in JMAB 1.0 and 2.0

There is a second issue with this miscalibration which can be seen in the shallow logistic function in Fig. 7. The initial probability of default of 0.01 has a corresponding DSCR of 7.8. However, minimal deviations from the steady state cash flows lead to implausible default rates: a firm with a DSCR of 3.8 has a 50 percent probability of default, while a DSCR of 1 results in a 90 percent probability of default. Consequently, firms that can cover their debt service more than once with their cash flows are still denied the full loan amount.

Third, the calculation of the debt service is inaccurate. In the calculation of the deviation of the cash flow from the debt service $(OCF_{x,t-1} - \zeta_x ds_{t+1}^{L^d})/ds_{t+1}^{L^d}$ the debit services of 21 periods in total are subtracted from the firms cash flow. In $OCF_{x,t-1}$ the debt service from loans $L_{x,t-2...t-21}$ are subtracted while $ds_{t+1}^{L^d}$ subtracts the debt service of the hypothetical loan on top of that. However, in the next period the oldest loan with the age of 21-periods ($L_{x,t-21}$) has been paid off and the firm would only pay debt services for 20 loans in total (loans from the past 19 periods and the new hypothetical loan). This miscalculation reduces the operating cash flow and makes the debt service deviate more from it. The impact on the model is limited, though, because the risk aversion parameter is calibrated with the extra debt service. Additionally, the calculation inaccurately takes into account the full debt service of the most recent loan twice. The cash flow $OCF_{x,t-1}$ already includes the first debt service payment of the most recent loan $L_{x,t-2}$, which includes the principal and interest on the full initial loan amount (20/20). Caiani et al. (2016) mistakenly assume that in the next period, the firm pays the initial debt service for both the old loan $L_{x,t-2}$ and a new hypothetical loan L^d , even the old loan aged one more period and only requires a fraction (19/20) of the debt service.

Fourth, capital expenditure (CAPEX) is not included in the cash flow of consumption firms. A large portion of a consumption firm's cash flow is used for maintenance CAPEX, which is essential for generating revenue. Excluding CAPEX results in an inaccurate depiction of the firm's financial position. In fact, when maintenance CAPEX is deducted from the cash flows of consumption firms in the steady state of Caiani et al. (2016), the cash flows become negative, so that it only covers interest payments. This places firms in a speculative financial position, according to the Minskian classification of financial positions, described by Caiani et al. (2016). According to this classification, firms can be in three financial positions: hedge (cash flow is positive and covers debt service), speculative (cash flow is negative but covers interest), and Ponzi (cash flow is negative and covers neither interest nor principal). It is unclear why Caiani et al. (2016) places firms in a speculative position in the steady state.

Fifth, the model's definition of "operating cash flow" may lead to confusion. Typically, operating cash flow refers to cash flows generated by a company's revenue-producing activities. Caiani et al. (2016) deduct principal repayments from operating cash flow, but principal payments are a financing activity, as stated in paragraph 17(d) of IAS 7. Therefore, their definition of operating cash flow provides no clear information about the actual operating cash flow of the firm.

To address these issues, I propose using a traditional DSCR approach, where a firm's expected cash flow is divided by the total debt service, consisting of the future debt services of both existing and newly granted loans. The probability of default of a capital firm is calculated as:

$$PD_{k,t} = \frac{1}{1 + \exp\left(\zeta \frac{EBIT_{k,t}^{e^{DES}}}{ds_{k,t+1}^{tot}} - 5\right)} \quad (24)$$

where ζ is the bank's risk aversion parameter towards firms and $EBIT_{k,t}^{e^{DES}}$ is the double-exponential smoothed expectation of earnings before interest and taxes, $EBIT_{k,t}$, defined as pre-tax profits plus interest payments:

$$EBIT_{k,t} = \Pi_{k,t} + \sum_{j=t-\eta}^{t-1} i_{k,j}^L L_{k,j} \frac{\eta - [(t-1) - j]}{\eta} \quad (25)$$

The probability of default of consumption firms is calculated similarly with the difference that $EMC_{c,t}^{e^{DES}}$ is used. This term represents the double exponential smoothed expectation of $EMC_{c,t}$, defined as EBITDA (earnings before interest, taxes, depreciation and amortization)

minus CAPEX. This adds interest payments and capital amortization to pre-tax profits and subtracts CAPEX to provide a more realistic representation of the financial situation of the firm:

$$EMC_{c,t} = \Pi_{c,t} + \sum_{j=t-\eta}^{t-1} i_{c,j}^L L_{c,j} \frac{\eta - [(t-1) - j]}{\eta} + \sum_{k \in K_{c,t-1}} (k^k p^k) \frac{1}{\kappa} - I_{c,t}^d \quad (26)$$

The total debt service is defined as the sum of the debt services of all existing loans in the next period and the first debt service of the demanded loan:

$$ds_{x,t+1}^{L^{tot}} = \sum_{j=t-\eta+1}^{t-1} \left(L_{x,j} \frac{1}{\eta} + i_j^L L_{x,j} \frac{\eta - 1 - [(t-1) - j]}{\eta} \right) + \left(i_{b,t}^L + \frac{1}{\eta} \right) L^d \quad (27)$$

This ensures that each period's debt service is only factored in once. To avoid the second-mentioned issue, the function is made steeper by adjusting the risk aversion parameter in the calibration so that a DSCR of 1 corresponds to a 10 percent probability of default. The function is also shifted to the right of the x-axis by subtracting 5, so that a DSCR of 0 converges towards a PD of 1. Otherwise, the PD for a DSCR of 0 would be 0.5. The final function with this calibrated risk aversion parameter is shown in Fig. 7.

2.6.3 Deposit Interest Rate

In JMAB 1.0 banks adjust their interest rates based on their liquidity ratio LR_{bt} compared to the target liquidity ratio LR_{bt}^T , which is defined in JMAB 1.0 as the average liquidity ratio of all banks in the previous period for simplification. If a bank's liquidity ratio is above the target, it raises its interest rate. If the ratio is below the target, the bank lowers its interest rate:

$$i_{b,t}^D = \begin{cases} \bar{i}_{b,t-1}^D - FN & \text{if } LR_{b,t} \geq LR_b^T \\ \bar{i}_{b,t-1}^D + FN & \text{otherwise} \end{cases} \quad (28)$$

where $\bar{i}_{b,t-1}^D$ is the average deposit interest rate of all banks in the previous period.

There are two issues with this mechanism. One is the usage of the average liquidity ratio as the reference variable. After the interactions in the deposit market the liquidity of banks tends to accumulate between a few who offer the highest interest rates. Fig. 8 (a) shows that the number of banks with liquidity ratios above or equal to the average ranges between 3 and 4 most of the time (With 10 banks in total). This causes the majority of banks to raise their interest rate so that they converge towards the rate on advances. This is depicted in Fig. 8 (b) with the different bank interest rates. JMAB 1.0, however, was calibrated as a floor regime with a structural

liquidity surplus, where banks cover all their minimum reserve requirements with reserves issued through bond purchases by the central bank (Keister, 2012). In this situation banks are in no need of extra liquidity and are incentivized to repel customers by setting their deposit interest rate towards the interest rate of reserves, which is 0 in JMAB 1.0. Otherwise, banks incur losses or make less profit since the rate on reserves is lower than the rate on deposits. In JMAB 1.0 banks can only offset these losses because the interest rate on loans is steadily increasing, which is an issue on its own and is explained in the next subsection. Overall, the use of the average liquidity ratio as a target is an oversimplification that lacks economic rationale from the perspective of banks in the model and leads to the opposite of real-world bank behavior.

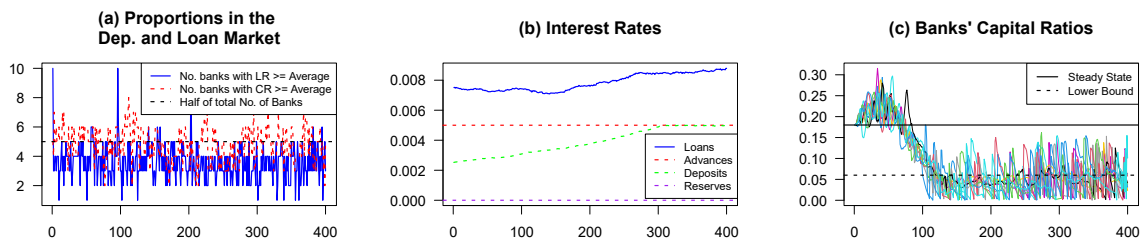


Fig. 8 Bank-specific variables in a single run in JMAB 1.0. In (b) lines are averages. In (c) each colored line represents one bank

A second issue concerns the incorrect calculation of the upper bound of the deposit interest rate. While JMAB 1.0 treats the advances rate as the upper bound for the deposit rate, it neglects the costs of maintaining the minimum liquidity requirement and the costs of reserves created via bond purchases from the central bank. Banks typically need to hold reserves proportional to their deposits to meet liquidity requirements. These reserves can incur interest costs if acquired through central bank loans. If a bank offers deposit rates as high as the advances rate, its deposit-taking activity becomes unprofitable, as it must also make interest payments to the central bank. The same applies to reserves that yield interest lower than the deposit rate.

JMAB 2.0 uses a more sophisticated mechanism that enables banks to adapt to different monetary policy regimes and be profitable. This mechanism is a revised version of the one proposed by Schasfoort et al. (2017).⁶ Additionally, JMAB 2.0 introduces an interbank market

⁶ A revision was necessary because the mechanism proposed by Schasfoort et al. (2017) does not clearly incorporate the central bank's policy rate, preventing deposit rates from accurately following that rate. In the model, deposit rates continue to increase until period 200 despite the presence of a floor system and the interest rate on reserves set at zero. The mechanism also employs three different aspects—(1) liquidity, without accounting for advances or interbank loans; (2) a funding rate; and (3) profits from loans—whose roles are not entirely clear.

where banks can lend out excess reserves at the interbank rate $i_{b,t}^{IBL}$ to reduce costs from unremunerated reserves. This market is described in Section 3.4.3. To determine its deposit interest rate, a bank considers its liquidity, opportunity costs, and the profit from reserves. A bank will aim to attract customers (by increasing the deposit rate) when it has a liquidity deficit (excess reserves are zero or negative), deposit funding is cheaper than interbank market funding (the current deposit rate is lower than or equal to the upper bound), and the profit on reserves exceeds the cost of deposits. Conversely, a bank will seek to repel customers (by lowering the deposit rate) when it holds excess reserves, alternate funding is cheaper than deposits, or no profits are earned from reserves. The liquidity deficit aspect is covered by χ^{LD} , the opportunity cost aspect by χ^{OC} and the profit on reserves aspect by χ^{PR} :

$$\chi^{LD} = \begin{cases} 1 & \text{if } ER_{b,t} \leq 0 \\ -1 & \text{otherwise} \end{cases} \quad (29)$$

$$\chi^{OC} = \begin{cases} 1 & \text{if } i_{b,t-1}^D \leq i_{b,t}^{DUB} \\ -1 & \text{otherwise} \end{cases} \quad (30)$$

$$\chi^{PR} = \begin{cases} 1 & \text{if } i_{b,t-1}^D \leq i_{cb,t}^R \\ -1 & \text{otherwise} \end{cases} \quad (31)$$

Thereby banks determine their excess reserves as follows:

$$ER_{b,t} = R_{b,t-1} - A_{b,t-1} + IBL_{b,t-1} - IBB_{b,t-1} - D_{b,t-1}LR_b^T \quad (32)$$

where LR_b^T is the exogenously set target liquidity ratio.

The deposit upper bound $i_{b,t}^{DUB}$ represents the maximum rate the bank is willing to pay before deposit funding becomes more expensive than funding through the interbank market. This upper bound considers the cost of minimum reserves, as banks must pay for central bank advances to maintain minimum reserves. Additionally, it accounts for the cost of excess reserves. If excess reserves earn a lower interest rate than the interbank rate, the bank incurs losses. Therefore, the upper bound is defined as:

$$\begin{aligned} i_{b,t}^{DUB} = i_{b,t}^{IBL} - \max\{LR_b^T - \max\{\overline{NLR}_{b,t}, 0\}, 0\}(i_{cb,t}^A - i_{cb,t}^R) \\ - \max\{\overline{NLR}_{b,t}, 0\}(i_{b,t}^{IBL} - i_{cb,t}^R) \end{aligned} \quad (33)$$

The cost of minimum reserves is determined by the first subtrahend, where the portion (relative to deposits) of minimum reserves financed with advances is multiplied by the spread between the advances rate and reserves rate. The second subtrahend accounts for the cost of excess reserves. The proportion of excess reserves is multiplied by the spread between the interbank

rate and the central bank reserves rate. The interbank rate is used here as a proxy for the funding cost of excess reserves. $\overline{NLR}_{b,t}$ is the average net liquidity ratio of all banks, defined as:

$$\overline{NLR}_{b,t} = \frac{\sum_{bSize} (R_{b,t-1} - A_{b,t-1})}{\sum_{bSize} D_{b,t}} \quad (34)$$

Based on these values, an adaptive heuristic is applied. If the sum of the values is greater than 0, the bank raises its rate above the previous average deposit interest rate. Otherwise, the rate is decreased below the average:

$$i_{b,t}^D = \begin{cases} \min\{\bar{i}_{b,t-1}^D + \alpha_b^D FN, i_{b,t}^{DUB}\} & \text{if } \chi^{LD} + \chi^{OC} + \chi^{RP} > 0 \\ \max\{\bar{i}_{b,t-1}^D - \alpha_b^D FN, 0\} & \text{otherwise} \end{cases} \quad (35)$$

2.6.4 Loan Interest Rate

In JMAB 1.0 banks are assumed to have a preferred capital structure. They are aiming to achieve a specific capital ratio, defined as the average capital ratio of all banks in the previous period. To attain this goal, banks adjust their interest rate on loans. If the capital ratio is below the target the loan rate is increased which makes loans less attractive and shrinks the loan stock so that the capital ratio is more in line with the target. If the capital ratio is above the target the rate is decreased, which makes loans more attractive and potentially decreases the capital ratio. In doing so, banks consider a minimum capital ratio of 0.06. There is one main issue and two potential issues with this mechanism. The main one is an error in the implementation of the capital ratio's lower bound. As the capital ratios in Fig. 8 (c) demonstrate, the lower bound is actually 0 instead of 0.06 as stated, which leads banks to lower their capital ratio to 0 and go bankrupt more frequently. One potential issue is the steadily increasing loan interest rate, as Fig. 8 (b) shows. This trend leads to a deviation of profits of banks and borrowers from the steady state, which may be undesired. The reason for this is the market structure. As depicted in Fig. 8 (a), the number of banks with capital ratios above the average is more balanced than in the deposit market. Still over the whole 400 periods the minority of banks have capital ratios above average, so that the majority increase their loan rates as consequence. The second potential issue is the absence of a linkage between the loan interest rate and the rate on central bank advances. As result, the loan interest rate could fall below the rate on advances, causing losses for the bank, without any counter measure.

JMAB 2.0 implements a behavior that is more in line with the pecking order theory. Thereby banks adjust their capital ratio to match their target with their dividend policy and retained earnings, which is described in Section 3.4.2. This allows banks to set their loan interest rates

based on the loan demand and independently of capital ratios. A bank sets its loan rate as a non-negative markup $mu_{b,t}$ over the interbank loan rate as a reference rate:

$$i_{b,t}^L = i_{b,t}^{IBL} + mu_{b,t} \quad (36)$$

This way banks consider the cost of their loans. The markup is adjusted using an adaptive heuristic, similar to the one used for firms' real sales expectations. Instead of real sales, a bank relies on the real new loans granted in the previous period $\hat{l}_{b,t-1} = \hat{L}_{b,t-1}/\pi_{t-1}$ and its expectation $\hat{l}_{b,t}^{eRB}$. If real new loans from the previous period exceed expectations, the bank increases its markup and expectation. Otherwise, both are decreased:

$$mu_{b,t} = \begin{cases} \overline{mu}_{b,t-1} + \alpha_b^{mu} LN & \text{if } \hat{l}_{b,t-1} > \hat{l}_{b,t-1}^{eRB}, \\ \overline{mu}_{b,t-1} - \alpha_b^{mu} LN & \text{if } \hat{l}_{b,t-1} < \hat{l}_{b,t-1}^{eRB} \end{cases} \quad (37)$$

$$\hat{l}_{b,t}^{eRB} = \begin{cases} \hat{l}_{b,t-1}^{eRB} + \alpha_b^{\hat{l}} LN & \text{if } \hat{l}_{b,t-1} > \hat{l}_{b,t-1}^{eRB}, \\ \hat{l}_{b,t-1}^{eRB} - \alpha_b^{\hat{l}} LN & \text{if } \hat{l}_{b,t-1} < \hat{l}_{b,t-1}^{eRB} \end{cases} \quad (38)$$

where $\overline{mu}_{b,t-1}$ is the average markup of all banks in the previous period. With this mechanism the markup stays at a relatively stable level.

2.6.5 Demand for Bonds

The demand for bonds of a bank b_{Db} in JMAB 1.0 depends on its excess reserves:

$$b_{b,t}^D = \max\{R_{b,t} - D_{b,t}LR_b^T, 0\} \quad (39)$$

There are two issues with this mechanism. First, the implemented mechanism does not consider the actual excess reserves of a bank at the end of the period, instead it uses the amount of reserves in the middle of the period after the government paid off its bonds, where the paid off bonds temporarily increased the amount of reserves. Furthermore, it is not entirely clear why excess reserves are used, as they are not a suitable measure of how many bonds a bank can purchase. Banks technically need reserves to buy bonds. However, when considering only the start/end of each period, reserves play no role since after the bond purchase by banks they will be spent by the government on wages and dole for households so that they flow back to banks. This can be demonstrated with the following example involving two banks (Bank A and Bank B).

Bank A and Bank B both start with 100 loans and 100 deposits each (200 loans and deposits in total). After interactions in the deposit market, 75 percent of total deposits flow to Bank B and 25 percent to Bank A, resulting in 50 deposits for Bank A and 150 for Bank B. While Bank A

has a reserve deficit of 50, Bank B has a reserve surplus of 50. It is assumed that Bank A's deficit is balanced out by central bank loans at the end of the period, just as in the model. If Bank B buys 50 government bonds, 50 reserves are transferred to the government, and Bank B receives 50 bonds. The government then spends its reserves on wages and dole to households, who have accounts either with Bank A or Bank B, increasing the reserves and deposits of the banks. Due to the earlier interactions in the deposit market, 75 percent of reserves (37.5) flow back to Bank B and 25 percent (12.5) to Bank A. Bank B ends up with 187.5 deposits and 37.5 excess reserves, while Bank A has 62.5 deposits and a reserve deficit of 37.5.

This government bond purchase does not change the total amount of reserves in the banking system, but it does affect the distribution of reserves among banks and the total amount of deposits. If minimum reserve requirements are considered, the banking system may only need extra reserves for the additional deposits. In an ex-post view, government bonds are financed on the balance sheet by deposits or central bank loans if there are not enough deposits. In JMAB 1.0, the central bank grants banks unlimited central bank loans. Therefore, each bank can theoretically buy unlimited amounts of bonds, regardless of whether they are financed through deposits or central bank loans. However, financing bonds with deposits instead of central bank loans might be more profitable, as deposits are usually cheaper than central bank funding. In JMAB 2.0, banks consider their deposit amounts when buying government bonds. The portion of newly issued bonds that a bank buys is determined by two factors: first, the bank's deposit amount relative to the total non-bank money supply, since this portion can be financed by deposits. Second, the relation between the non-bank money supply other than bank deposits and the total non-bank money supply divided by the number of banks. This ensures that the portion of bonds that cannot be financed through deposits is distributed equally among all banks, accounting for the possibility of money other than deposits, such as cash, in the economy:

$$b_{b,t}^d = b_{g,t}^s \left(\frac{D_{b,t-1}}{M_{nonbs,t-1}} + \frac{\left(1 - \frac{D_{nonbs,t-1}}{M_{nonbs,t-1}}\right)}{size_B} \right) \quad (40)$$

where $D_{nonbs,t-1}$ and $M_{nonbs,t-1}$ are deposits and the money supply of all non-banks. Note that this way banks buy all bonds leading to a corridor system for the central bank. If a floor system is simulated the bond demand of banks needs to be reduced.

2.7 Additional Issues

There are additional issues with the model concerning bankruptcy handling and the implementation of various mechanisms.

Due to the pricing mechanism described previously, many firms price themselves out of the market and go bankrupt. The bankruptcy mechanism distributes the firm's liquid assets to creditors and symbolically sells the firm's capital to households to raise additional funds. However, the firm remains stuck in this bankruptcy situation because it retains its non-competitive markup and its capital stock, which may exceed the capacity required after the bankruptcy. This leads to massive losses due to capital amortization, causing the firm to go bankrupt again after a short period. In JMAB 2.0, the capital value is therefore reduced, and the firm's markup is set to an average level. Furthermore, in JMAB 1.0, the bail-in mechanism that handles bank bankruptcies is inaccurately modeled. In JMAB 1.0, bankrupt banks undergo a bail-in process in which depositors pay off the bank's negative net wealth and recapitalize the bank. The recapitalization should convert deposits into shares of the bank, so that depositors become owners with increased dividend claims. However, in JMAB 1.0, all households receive dividends proportionally to their net wealth, and the depositors' dividend claims do not increase. While JMAB 2.0 still does not implement the bail-in mechanism accurately, it allows all households to recapitalize the bank (after depositors have paid off the negative net wealth), aligning the mechanism with the model's dividend policy.

There is also an error in the implementation of the market for bank loans. The strategy whereby firms choose the cheapest lender does not function properly. During the process, the algorithm checks whether the previous lending bank provides more than 0 loans, but the loan stock identifier is not set, so firms always choose a new supplier. Beyond that there are errors in the implementation of the order of agent activities—namely, the timing of bank interest payments—, the implementation of the wage determination of households, and in the household's consumption of dividends. All of these issues will be explained in Section 3 at their corresponding JMAB 2.0 mechanisms.

3 Rest of JMAB 2.0

In this section, the rest of the model is described, including the order of agent activities and the remaining mechanisms of firms, households, banks, the government, and the central bank.

3.1 Order of Agent Activities

The order of agent activities must ensure that each agent has the necessary information and assets at the right time within one period to perform its activities. To make JMAB 2.0 function properly, a few adjustments need to be made compared to JMAB 1.0. Since JMAB 2.0 does not use wage expectations in firms' calculations, wage determination and interactions in the labor market occur before all other interactions of firms and households. This allows firms to consider the wages of the current period and households to consider the current consumption goods prices. Additionally, in JMAB 2.0, firms pay wages before households purchase goods. Otherwise, households may not have enough deposits if the propensity to consume out of income is set at a realistic level. In JMAB 2.0, interest payments also take place before households consume, ensuring that interest paid on deposits from the previous period is part of the current income and consumption. In JMAB 1.0, deposit interest payments occurred after households had consumed, causing a lag in interest payments that contradicts the steady state calculation (Eq. (A.24) in Caiani et al. (2016) calibration and (90) in the JMAB 2.0 calibration). Therefore, the order of agent activities in JMAB 2.0 is as follows:

1. Expectations and production planning: All agents formulate their expectations. Firms plan their desired production based on expectations.
2. Deposit and reserve interest payments: Banks and the central bank pay interest on deposits and reserves.
3. Central bank policy: The central bank sets the rate on advances and reserves.
4. Interbank interest rate: Banks determine the interest rate on interbank loans.
5. Loan and deposit interest rates: Banks set their interest rates on deposits and loans.
6. Labor demand, labor supply, and labor market interaction: Firms determine their labor demand while households determine their wage. Firms select households in the labor market.
7. Price determination: Consumption and capital goods firms set their prices on consumption and capital goods.
8. Capital market brochure: Consumption firms choose their supplier in the capital market to receive a price for their credit demand planning.
9. Investment demand: Consumption firms determine their desired investment in capital goods.

10. Loan supply, loan demand and loan market interaction: Banks determine their maximum supply of loans and firms determine their demand for loans. Firms choose their loan-supplying bank, and banks provide credit after assessing creditworthiness.
11. Production: Firms produce consumption and capital goods.
12. Wages and dole: Firms pay wages to their employees. The government pays wages to public servants and dole to unemployed households.
13. Consumption demand and market interaction: Households determine their demand for consumption goods, select the supplying firm and purchase goods.
14. Capital market interaction: Consumption firms purchase capital goods from their previously chosen supplier.
15. Interest and principal payments on loans, advances, interbank loans, and bonds: Firms make interest and principal payments on their loans. Banks make interest and principal payments on advances and interbank loans. The government pays interest on its bonds and repays them.
16. Taxes: Firms, banks, and households make tax payments.
17. Dividends: Firms and banks pay dividends.
18. Deposit demand and market interaction: Firms and households determine their demand for deposits (if cash is also available), choose their deposit supplier and transfer their deposits to that bank.
19. Bankruptcy handling: Illiquid firms and banks with negative net wealth undergo a bankruptcy process and are recapitalized.
20. Bond interest, supply, demand, and market interaction: The government sets the interest rate and supply of bonds and issues them. Banks determine their demand for bonds and purchase them. The central bank may also buy bonds.
21. Interbank credit supply, demand, and market interaction: Banks determine their supply and demand for interbank credit. Borrowing banks select their supplier, and lending banks grant credit.
22. Reserve demand and market interaction: Banks determine their demand for reserves. The central bank grants advances to banks.

3.2 *Firms*

This subsection contains the rest of the firm's mechanisms, including the production planning, the labor demand, profits, and dividends.

3.2.1 Production Planning

Every firm x computes its desired output $y_{x,t}^d$ based on the firms' sales expectations s_{xt}^e , the current inventories inv_{xt} and the target inventories-to-sales ratio v :

$$y_{x,t}^d = s_{x,t}^e(1 + v) - inv_{x,t} \quad (41)$$

3.2.2 Labor Demand

Capital firms produce their output using only labor. Their demand for labor is determined by the desired output and labor productivity μ_N :

$$N_{k,t}^d = y_{k,t}^d / \mu_N \quad (42)$$

The labor productivity is assumed to be constant and exogenously given. Labor demand by consumption firms is:

$$N_{c,t}^d = cu_{c,t}^d \frac{k_{c,t}}{l_k} \quad (43)$$

where $k_{c,t}$ is the real stock of capital, l_k is the constant capital-labor ratio, and $cu_{c,t}^d$ is the rate of capacity utilization that is necessary to produce $y_{c,t}^d$ defined as:

$$cu_{c,t}^d = \min \left\{ 1, \frac{y_{c,t}^d}{k_{c,t} \mu_K} \right\} \quad (44)$$

where μ_K is capital productivity, which is fixed and determined exogenously.

3.2.3 Firm's Profits and Dividends

The pre-tax profit of a consumption firm is defined by considering revenues from sales, interest received, the nominal variation of inventories (priced in unit costs), wages, interest paid on loans, and capital amortization:

$$\begin{aligned} \Pi_{c,t} = & s_{c,t} p_{c,t} + i_{b,t-1}^D D_{c,t-1} + (inv_{c,t} uc_{c,t} - inv_{c,t-1} uc_{c,t-1}) \\ & - \sum_{n \in N_{c,t}} W_{n,t} - \sum_{j=t-\eta}^{t-1} i_{c,j}^L L_{c,j} \frac{\eta - [(t-1) - j]}{\eta} - \sum_{k \in K_{c,t-1}} (k^k p^k) \frac{1}{\kappa} \end{aligned} \quad (45)$$

where $i_{b,t-1}^D$ is the interest rate on deposits from the previous period $D_{c,t-1}$. Pre-tax profits of capital firms are defined similarly, except that there is no capital amortization. Based on pre-tax profits the dividends can be determined as follows:

$$Div_{x,t} = \rho_x (1 - \tau_x) \max\{0, \Pi_{x,t}\} \quad (46)$$

where τ_x is the firm's tax rate and ρ_x is its dividend payout ratio which are both fixed and exogenously given.

3.2.4 Loan demand

To ensure sufficient liquid assets for their operations, consumption firms take out loans. It is assumed that firms do not issue new shares, relying instead on retained profits and bank loans. The loan demand of a consumption firm is determined by its investment, expected dividends, wages, principal payments, minus the expected operating cash flow and deposits:

$$L_{c,t}^d = \max \left\{ I_{c,t}^d + Div_{c,t}^e + \sigma \sum_{n \in N_{c,t}} W_{n,t} + \sum_{j=t-\eta}^{t-1} L_{c,j} \frac{1}{\eta} - OCF_{c,t}^e - D_{c,t}, 0 \right\} \quad (47)$$

where $Div_{c,t}^e = \rho_x(1 - \tau_x)\Pi_{x,t}^e$ are the expected dividend disbursements and σ is the ratio of expected wage disbursements, which is set to a value greater than zero so that firms maintain a liquidity buffer. Expected profits $\Pi_{x,t}^e$ are calculated analogously to Eq. (45), with the exception that revenue and change in inventories are calculated using expected sales $s_{c,t}^{eRB}$ instead of actual sales $s_{x,t}$. Expected operating cash flow is calculated as:

$$OCF_{x,t}^e = s_{x,t}^{eRB} p_{x,t} + i_{x,t-1}^D D_{x,t-1} - \sum_{n \in N_{c,t}} W_{n,t} - i_{x,t-1}^L L_{x,t-1} - T_{x,t}^e \quad (48)$$

where expected taxes are defined as $T_{x,t}^e = \tau_x \Pi_{x,t}^e$. The loan demand for capital firms is determined similarly, except that investment in capital goods is excluded.

3.3 Households

This subsection contains the wage and consumption mechanisms of households.

3.3.1 Wage Determination

A household determines its desired wage based on an adaptive heuristic. If the household has been unemployed for more than four periods, it decreases its wage demanded. Otherwise, the household increases it:

$$W_{h,t}^d = \begin{cases} W_{h,t-1}^d (1 + LN) & \text{if } \sum_{n=1}^4 \varepsilon_{h,t-n} > 0 \\ W_{h,t-1}^d (1 - LN) & \text{else} \end{cases} \quad (49)$$

where $\varepsilon_{h,t} = 1$ if h is employed in t , and 0 otherwise. Unemployed households receive a share θ of the average wage as dole.

There is also a turnover ratio ϑ , which describes the portion of the workforce in consumption firms, capital firms, and the government that is fired and replaced each period by random households from the unemployed population, which includes the fired workers.

In JMAB 1.0 the wage determination for households is implemented incorrectly. Instead of using the employment variable $\varepsilon_{h,t}$ JMAB 1.0 uses the unemployment variable $u_{h,t}$ that is 1 if the household is unemployed and 0 if employed. However, the implementation uses the opposite definitions, with 0 for unemployed and 1 for employed, therefore the same value as JMAB 2.0. Consequently, the wage determination in JMAB 1.0 behaves conversely as described in the paper.

3.3.2 Consumption

A household's consumption is determined by fixed propensities to consume out of net income pc_h^{NI} and net wealth pc_h^{NW} . Real consumption demand can be derived by dividing net consumption by the current price:

$$c_{h,t}^d = \frac{pc_h^{NI} NI_{h,t} + pc_h^{NW} (NW_{h,t-1} - Div_{h,t-1})}{p_{h,t}} \quad (50)$$

where $NI_{h,t}$ is the net income defined as $W_{h,t} + i_{h,t-1} i_{h,t-1}^D D_{h,t-1} + Div_{h,t-1}$, $NW_{h,t-1}$ is the previous net wealth, and $p_{h,t}$ is the current price for consumption goods. Dividends are paid at the end of each period and are consumed in the next period. In JMAB 1.0 these dividends are consumed twice: as part of income and past net wealth. With that consumption out of income and consumption out of net wealth are not clearly separated. To separate both and prevent dividends from being consumed twice they are excluded from previous net wealth in JMAB 2.0.

3.4 Banks

This subsection contains the rest of the bank's mechanisms including the loan supply, dividends, interbank market and the demand for reserves.

3.4.1 Loan Supply

The loan supply of a bank is constrained by its expected capital adequacy ratio and its target. The capital adequacy ratio is defined as the ratio of net wealth to risky assets $CAR_{b,t} = NW_{b,t}/L_{b,t}$ while the target capital adequacy ratio CAR_b^T is exogenously given. Loans are considered risky, whereas bonds and interbank credit are considered risk-free. The maximum

loan supply is determined by the expected net wealth divided by the target capital adequacy ratio, minus current loans plus the principal payments:

$$L_{b,t}^s = \frac{NW_{b,t-1} + \Pi_{b,t}^e}{CAR_b^T} - L_{b,t-1} + \sum_{j=t-\eta}^{t-1} L_{b,j} \frac{1}{\eta} \quad (51)$$

where $\Pi_{b,t}^e$ represents expected after-tax profits, calculated by subtracting the interest costs of all liabilities from the interest revenue of all assets and applying the tax rate.

3.4.2 Bank's Dividends

Banks maintain a variable dividend payout ratio and behave according to the pecking order theory (Myers, 1984) so that they finance their required capital for their loan business with internal funds. Thus, dividends depend on their capital adequacy ratio and its regulatory target. A bank compares its past net worth $NW_{b,t-1}$ with its target net worth, defined as $NW_{b,t}^T = CAR_b^T L_{b,t}$. If past net worth is lower than the target, the bank only pays dividends if profits exceed the missing capital gap. If past net worth is higher than the target, the bank pays out its full profit as dividends, plus a portion λ of the excess capital to gradually reduce it:

$$\begin{aligned} Div_{b,t} &= \begin{cases} \max\{0, (1 - \tau_b)\Pi_{b,t}\} + (NW_{b,t-1} - NW_{b,t}^T)\lambda & \text{if } NW_{b,t-1} \geq NW_{b,t}^T, \\ \max\{0, \max\{0, (1 - \tau_b)\Pi_{b,t}\} + (NW_{b,t-1} - NW_{b,t}^T)\} & \text{otherwise} \end{cases} \end{aligned} \quad (52)$$

3.4.3 Interbank Market

In JMAB 1.0 banks cannot lend out their excess reserves, which reduces their profits if the interest rate on reserves is below the interest rate on deposits. For that reason, JMAB 2.0 implements an interbank market where mutual reserve obligations resulting from customers shifting between banks in the deposit market can be balanced out with interbank loans. A bank's supply of interbank loans is determined by its excess reserves, as described in Section 2.6.3:

$$IBL_{b,t}^s = ER_{b,t} \quad (53)$$

The demand for reserves is determined analogously:

$$IBL_{b,t}^d = \min\{0, ER_{b,t}\}(-1) \quad (54)$$

I assume perfect competition and information in the interbank market. Therefore, the interbank interest rate is based on a linear function describing the ratio of total net reserves to required reserves:

$$i_{b,t}^{IBL} = i_{cb,t}^A - (i_{cb,t}^A - i_{cb,t}^R) \min \left\{ \frac{\sum_{bSize} (R_{b,t-1} - A_{b,t-1})}{LR_b^T \sum_{bSize} D_b}, 1 \right\} \quad (55)$$

Banks are always willing to lend if they have excess liquidity, as this is more profitable than holding unremunerated reserves at the central bank and interbank loans are considered risk-free. Banks also prefer interbank loans over central bank loans to satisfy their liquidity demand since empirical data suggest there is a stigma associated with borrowing from the central bank, even if interbank loans are more expensive (Furfine, 2001).

3.4.4 Demand and Supply of Reserves

If the demand for reserves cannot be satisfied through the interbank market, banks apply for advances from the central bank. The demand for reserves of a bank is determined by the target liquidity ratio multiplied by its current deposits minus its reserves:

$$R_{b,t}^d = \max\{LR_b^T D_{b,t} - R_{b,t}, 0\} \quad (56)$$

Banks can borrow from the central bank without collateral, and the central bank is always willing to lend as the lender of last resort.

3.5 Government

The government employs households and pays unemployment benefits to unemployed households. Additionally, it has a reserve account at the central bank and handles all transactions through this account. The government's deficit is financed through the issuance of bonds and is determined by taxes, wages for government employees, dole, and interest payments on bonds. The quantity of newly issued bonds per period is defined as:

$$\bar{p}^b \Delta b_t = T_t + \Pi_{cb,t} - \sum_{n \in N_{g,t}} W_n - U_t d_t - i_{g,t-1}^B \bar{p}^b b_{t-1} \quad (57)$$

where T_t is the sum of $T_{H,t} + T_{C,t} + T_{K,t} + T_{B,t}$, d_t are the unemployment benefits defined as $\theta \bar{W}_h$, U_t is the number of unemployed households, $i_{g,t}^B$ the interest rate on bonds, $\bar{p}^b$ is the fixed price of bonds, and $N_{g,t}$ is the collection of public workers. The interest rate on bonds follows the rate on interbank loans, so that bonds remain attractive to their holders:

$$i_{g,t}^B = i_{b,t}^{IBL} \quad (58)$$

3.6 Central bank

The central bank lends at the rate on advances and buys government bonds. In JMAB 1.0, the interest rate on central bank advances is fixed. However, to demonstrate that the bank mechanisms work properly and follow the policy rate, the central bank adjusts its interest rate on advances in JMAB 2.0 by following a Taylor rule with inflation targeting and an unemployment gap:

$$i_{cb,t}^A = \pi_{t-1} + i^{nat} + (\pi_{t-1} - \pi_{cb}^T) + (u_{t-1} - u_{cb,t}^{eSES}) \quad (59)$$

where π_t is the inflation rate on consumption goods, π_{cb}^T is the exogenously given inflation target, and i^{nat} is the exogenously given natural rate of interest. The expected unemployment rate $u_{cb,t}^{eSES}$ is an approximation of the natural rate of unemployment (NROU) and is based on simple exponentially smoothed past unemployment rates. SES is employed in this case since there is no trend in the data.

The profit of the central bank is transferred to the government and is derived from interest on government bonds plus interest on central bank advances minus interest on reserves:

$$\Pi_{cb,t} = i_{g,t-1}^B B_{cb,t-1} + i_{cb,t-1}^A A_{cb,t-1} - i_{cb,t-1}^R R_{cb,t-1} \quad (60)$$

The central bank buys government bonds that have not been purchased by banks:

$$b_{cb,t}^d = b_{g,t}^s - b_{b,t}^d \quad (61)$$

In this paper, banks buy all bonds, so this only becomes relevant if there should be excess reserves in the system or a floor system be simulated.

4 Calibration

The calibration of the model follows the original one by Caiani et al. (2016) which consists of six steps: First, an aggregated stock-flow model of the model is derived, with one consumption firm, one capital firm, one bank, the government and the central bank. Second, the model is constrained to a real stationary state with a nominal growth rate g_{SS} . Third, the model is solved numerically. Exogenous variables are set with consideration of real-world values. This creates the initial (steady state) values for all stocks, flows and endogenous variables. Fourth, the aggregate values are distributed across all agents uniformly. Fifth, the original amount, outstanding values and age of durable stocks such as loans and capital goods are determined. Thereby it is assumed that firms obtained a loan and capital goods in every past period with the same real amount. Sixth, the agent's previous suppliers are set, ensuring that each supplier

has the same number of customers in the steady state. Households and consumption firms get a supplier assigned for consumption and capital goods as well as a supplier for deposits. Firms get a previous loan supplying banks assigned. This way agents are completely homogenous in the steady state and differences only emerge because of stochastic processes. In JMAB 1.0, however, there are issues with the choice of the exogenous variable values and the aggregated model of step two contains several typesetting errors in the paper, which needed to be fixed. In Appendix C the aggregated model is described correctly. Table 2 in Appendix D contains the model parameters for JMAB 2.0. “pre-SS” parameters are those which were exogenously set to calibrate and influence the steady state, while “ss-given” parameters were derived from that steady state calibration. “free” parameters were exogenously set independently of the steady state. Table 3 in Appendix D also contains the aggregated stocks of the sectors, showing that JMAB 2.0 has consistent stocks. The distribution of the aggregated stocks to the single agents will not be described in detail here since this is already described in Appendix A of Caiani et al. (2016).

5 Results

The model was run 100 times with a Monte Carlo simulation for 1200 periods. Below the macro data, correlations and micro data for the simulation are presented. Robustness checks as applied to JMAB 1.0 are left out since the main goal of this research is the model to create plausible outputs.

5.1 Macro Data

The average values from all Monte Carlo simulation runs in JMAB 2.0 for various macroeconomic variables are shown in Fig. 9, alongside the results of JMAB 1.0 for comparison. As in Caiani et al. (2016), the data was smoothed with a Hodrick-Prescott (HP) filter and the “burn-in” phase from periods 1 to 200 is not removed, allowing for a deeper understanding of the model’s behavior. According to Caiani et al. (2016), this approach is useful for three reasons: first, it helps distinguish which model dynamics stem from the initial steady state and which are inherent to the model itself. Second, extreme fluctuations in the early periods can provide insights into the mechanisms causing them. Third, it may reveal path dependencies between the transition phase and the model’s long-run outcomes. JMAB 1.0 undergoes three distinct phases, as shown in the plots: (1) self-sustained growth, (2) trend inversion and great recession, and (3) recovery and convergence to a quasi-steady state. While Caiani et al. (2016) identify path dependencies between these phases, they do not sufficiently

explain the causes of the extreme fluctuations and deviations during the transition phase or assess to what extent these are tolerable. They only argue that the symmetric conditions of the agents in the steady state cause the initial dynamic. But this does not explain the cause of the credit gap in period 1 and the large deviation of capital goods and consumption goods from the steady state in the long run.

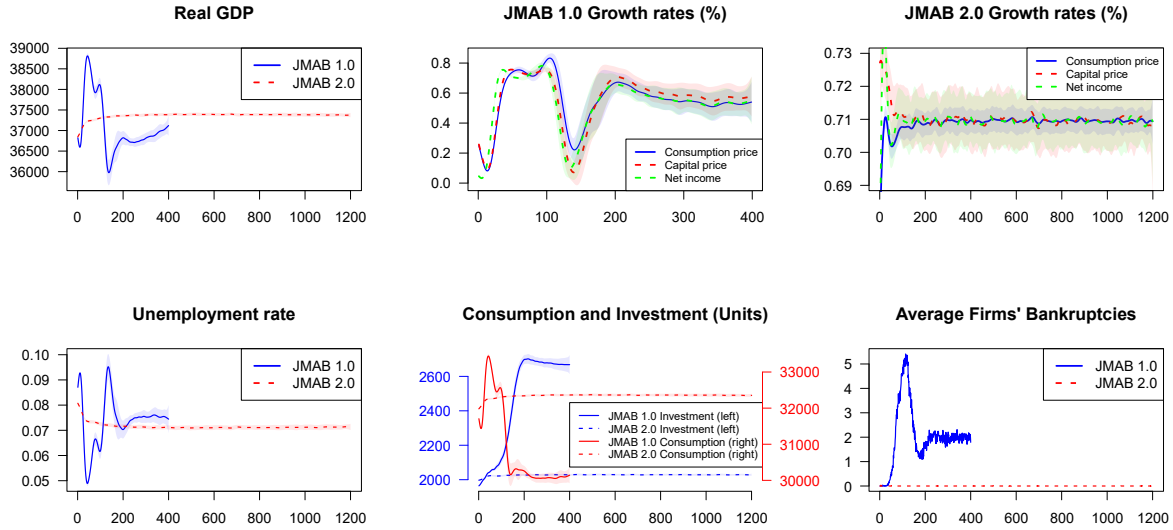


Fig. 9 Comparison of macroeconomic variables between JMAB 1.0 and 2.0. Solid and dotted lines are averages of all simulation runs, while shaded areas are standard deviations

In contrast, JMAB 2.0 exhibits only two phases: a brief period of self-sustained growth followed by direct convergence to the quasi-steady state. A clear path dependency exists between this quasi-steady state and the growth observed during the transition phase. The GDP increase from periods 1 to 200 can be attributed to the model's behavior, particularly the household wage mechanism. Although the model is calibrated with a nominal growth rate of 0.0075, household wages grow slightly slower at approximately 0.0071, as shown in Fig. 9 as the net income growth rate. This discrepancy occurs because unemployed households lower their wage demands, reducing aggregate wage growth. Without this deviation, the model would align with the calibrated steady state from the start. Besides JMAB 2.0 operates smoothly and maintains the steady state for 1,200 periods and longer due to the improved expectation and markup mechanisms of firms. It was also tested for extended runtimes and found to crash after approximately 4,000 rounds. This is expected, as nominal values eventually grow too large for the program's data types to store. The model would run longer without the nominal growth. Furthermore, JMAB 2.0 is more stable during the burn-in phase, as it is not affected by the consumption and wage shocks that impacted JMAB 1.0 due to the unsuitable expectation

method for consumption prices and wages. Additionally, large fluctuations in investment units are eliminated due to the revised investment mechanism, and firm bankruptcies are avoided because of the pricing mechanism that accounts for competitors' prices.

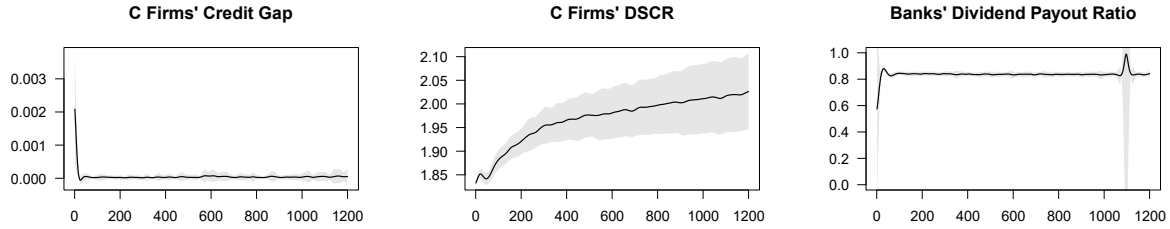


Fig. 10 Firm and bank-specific variables in JMAB 2.0. Solid and dotted lines are averages of all simulation runs, while shaded areas are standard deviations

Furthermore, firms in JMAB 2.0 almost always receive their full requested loan amounts as the credit gap of consumption firms in Fig. 10 suggests due to the reworked loan approval decision and the probability of default of firm. The DSCR of consumption firms in Fig. 10 ranges between 2.2 and 2.4, implying an average probability of default close to zero, according to the revised probability of default function in Section 2.6.2.

Fig. 11 also compares the markups in both models. While markups in JMAB 1.0 increase steadily, they remain at the calibrated levels in JMAB 2.0 due to the revised markup-setting mechanisms.

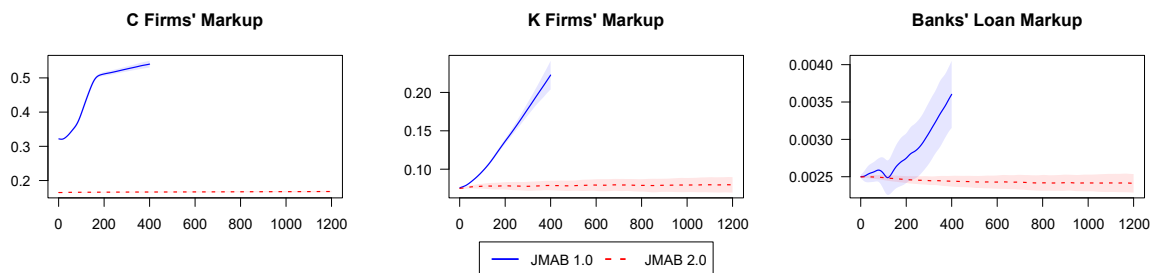


Fig. 11 Comparison of markups in JMAB 1.0 and 2.0. Solid and dotted lines are averages of all simulation runs, while shaded areas are standard deviations

The interest rates for advances, loans, deposits, and reserves in a single run in JMAB 2.0 are depicted in Fig. 12 (a). As shown, the rate on advances is volatile and is adjusted by the central bank in response to inflation and unemployment targets. As expected, banks in the corridor system keep the deposit interest rate close to the advances rate, unlike in JMAB 1.0, where a floor system incorrectly produces this result. The distance between the deposit and advances rates is determined by the revised upper bound, which accounts for the cost of minimum reserve

requirements and reserves. Additionally, the bank's dividend payout ratio is endogenous in JMAB 2.0 but remains roughly at the same level, as suggested by Fig. 10. There is only one hike at period 1097 caused by one Monte Carlo run where banks made almost no profit but paid out their excess capital as dividends. As result of the new dividend payout strategy that pays out excess capital the capital adequacy ratio stays strictly at the target level of 0.08, as can be seen in Fig. 12 (b).

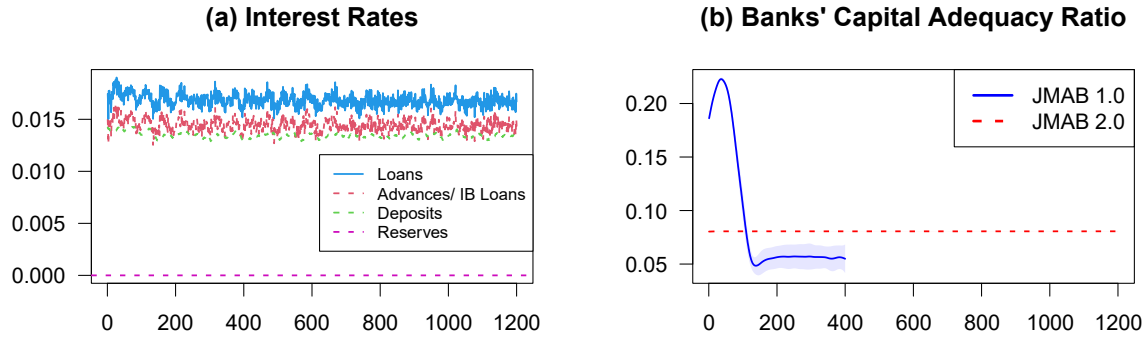


Fig. 12 Interest rates in JMAB 2.0 and banks' capital adequacy ratio in both models. (a) shows the values of a single run. In (b) solid and dotted lines are averages of all simulation runs, while shaded areas are standard deviations

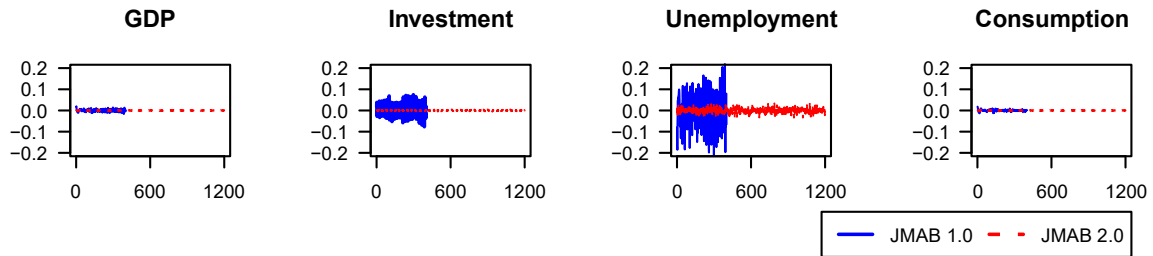


Fig. 13 Cyclical components of the HP-filtered time series of several macro variables in JMAB 1.0 and 2.0

Fig. 13 illustrates the cyclical components of the HP-filtered time series of several macro variables in JMAB 1.0 and 2.0. While the relative volatilities between the variables in JMAB 2.0 are comparable to JMAB 1.0, the absolute values are much higher in JMAB 1.0 despite the stochastic variables being within the same range in both models.

5.2 Correlations in Macro Data

This section shows correlations in the model's data and compares them to correlations in a real time series.⁷ Fig. 14 (a) displays the autocorrelations of the variables real GDP, unemployment, real investment, and real consumption for JMAB 1.0, JMAB 2.0 and a real time series.

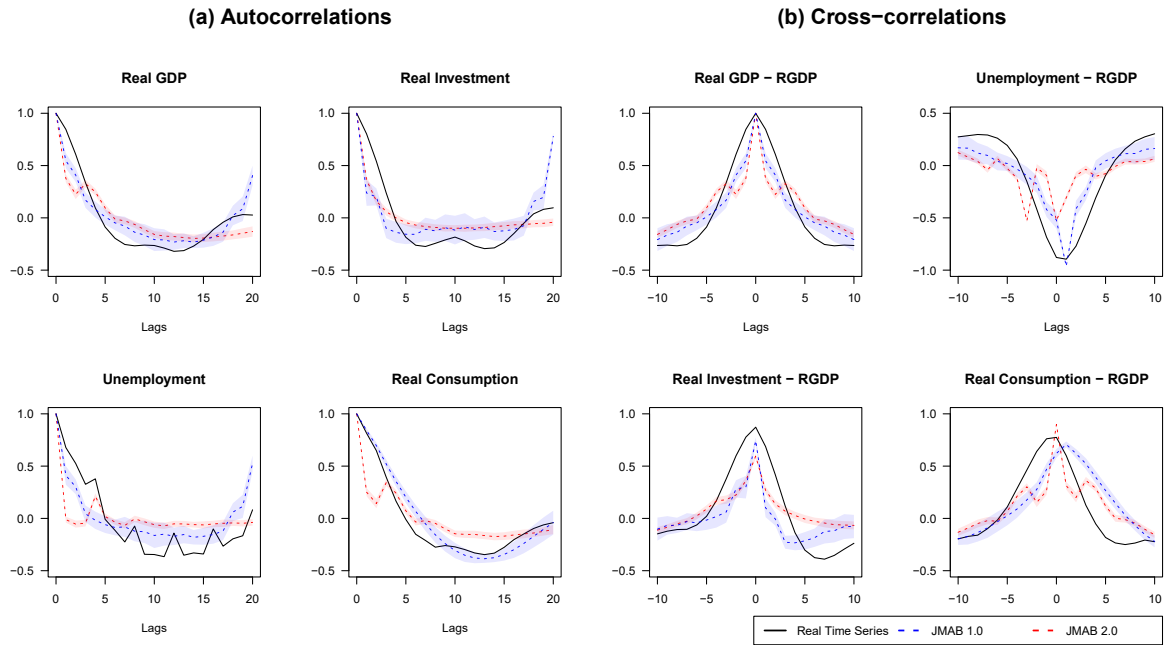


Fig. 14 Autocorrelations and cross-correlation of variables in JMAB 1.0, 2.0 and the real time series. Solid and dotted lines represent correlations based on averages of all simulation runs, while shaded areas are standard deviations

Overall, JMAB 2.0 aligns well with empirical data but is not as smooth as JMAB 1.0, as prices and wages are not smoothed. The small spikes observed can be attributed to the countercyclical nature of monetary policy under the Taylor rule. Additionally, standard deviations are lower compared to JMAB 1.0, as investment is less volatile. In JMAB 1.0, real investment and unemployment deviate significantly from real-world series at the 20th lag. Caiani et al. (2016) explain this by pointing to the capital duration of 20 periods and the resulting cyclical component. However, this explanation is only partially valid, as JMAB 2.0 does not exhibit the same deviation despite using the same capital duration. Instead, the difference arises because JMAB 1.0 directly factors residual capacity and worn-out capital into investment demand in a one-to-one ratio, whereas JMAB 2.0 considers worn-out capital only indirectly, keeping

⁷ The real time series used is the same as the one used by Caiani et al. (2016): Quarterly data of the US from the Federal Reserve Economic Data (FRED) including not seasonally adjusted unemployment from 1955-01-01 to 2013-10-01 (FRED code: LRUN64TTUSQ156N) and investment, consumption and GDP from 1947-01-01 to 2013-10-01 (FRED codes: PCECC96, GPDIC96, and GDPC1).

investment per period relatively stable. Fig. 14 (b) illustrates the cross-correlation of the variables real GDP, unemployment, real investment, and real consumption with real GDP for JMAB 1.0, JMAB 2.0 and a real time series. As in JMAB 1.0, real GDP, real investment, and real consumption are procyclical, while unemployment is countercyclical. Fig. 15 presents the cross-correlations of the variables firms' markups, prices, and leverage with real GDP in JMAB 1.0 and 2.0.

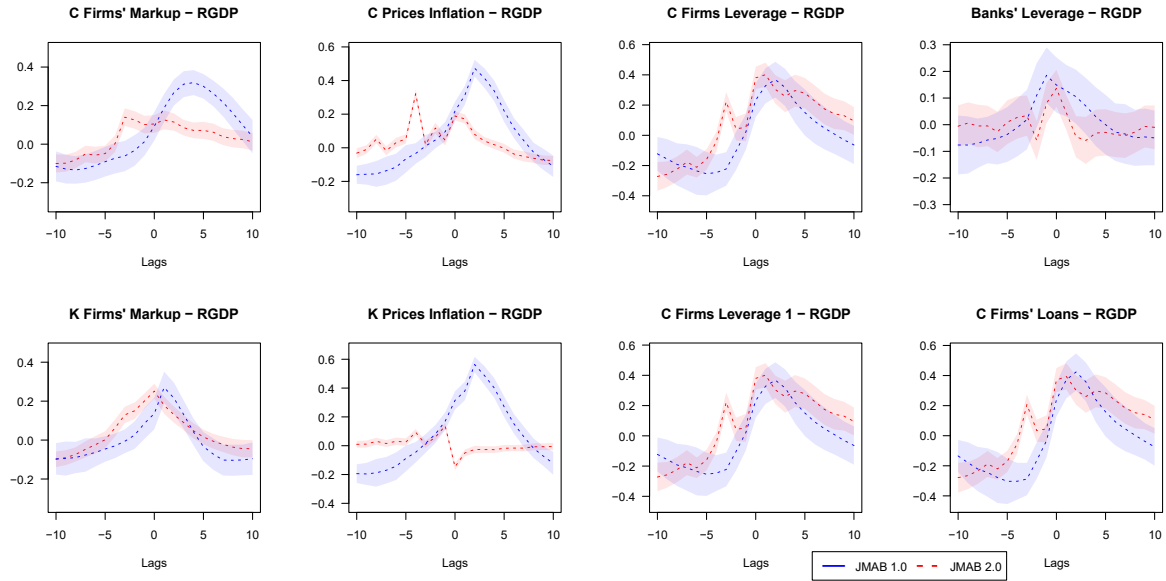


Fig. 15 Cross-correlations between variables and real GDP in JMAB 1.0 and 2.0. Shaded areas are standard deviations. In the upper plots leverage is defined as loans divided by net wealth, while in the bottom plot it is defined as total assets divided by loans

The markups in JMAB 2.0 are procyclical, aligning with more recent empirical research. For example, Nekarda and Ramey (2020) found that markups are generally procyclical or acyclical, challenging previous research that suggested countercyclical markups. In the model, this can be explained by the markup mechanism, which increases markups as a result of higher sales and GDP. Caiani et al. (2016) identified countercyclical markups in JMAB 1.0; however, this is due to an error in the markup calculation. Instead of using the actual markups of firms they calculated the markup based on expected unit labor cost but used the actual wage instead of the expected wage, as described in their price mechanism. The corrected JMAB 1.0 plots in Fig. 15 use the actual markup data and show procyclicality as well. Inflation should also be procyclical, which is evident in consumption prices since they are composed of markups and costs, both of which are procyclical. Inflation for capital goods is procyclical until lag 1 and countercyclical afterward. This occurs because, as GDP increases, the leverage of capital firms decreases, reducing interest costs and thereby causing deflation in capital goods prices.

Furthermore, the leverage of consumption firms is procyclical, similar to JMAB 1.0, with a noticeable bump caused by the Taylor rule.

5.3 Micro Data

This section presents the differences in micro data between JMAB 1.0 and 2.0. Fig. 16 (a) and (b) illustrate the persistence of market shares for 20 consumption firms and 20 capital firms in JMAB 1.0, and for 20 consumption firms and 4 capital firms in JMAB 2.0.⁸

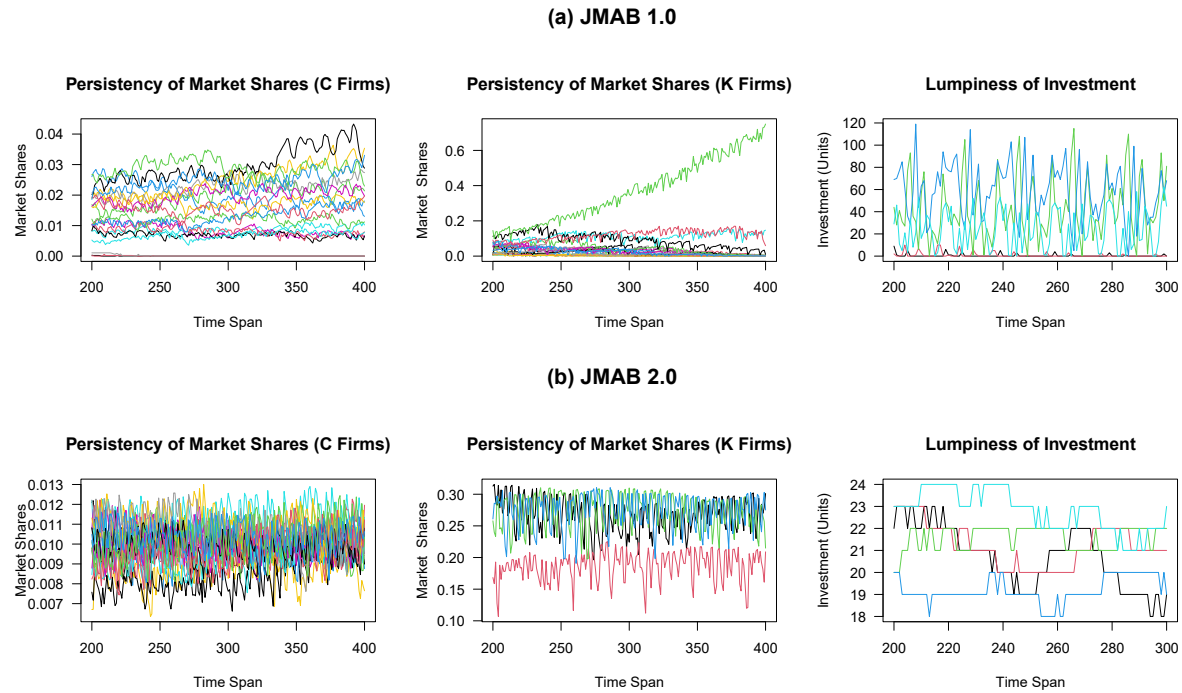


Fig. 16 Market share persistency and investment of firms in a single run in JMAB 1.0 (a) and 2.0 (b). Each line represents a firm from a randomly selected sample

As expected, JMAB 2.0 does not reproduce the stylized fact of heterogeneous market shares of firms, as incorporating the average markup into the pricing mechanism leads to a more homogeneous distribution of market shares. In JMAB 1.0, the market shares of consumption firms range from 0 to 0.04, whereas in JMAB 2.0, the variance is significantly smaller, ranging from 0.006 to 0.013. The same pattern applies to capital firms. In JMAB 1.0, market shares vary between 0 and 0.6 across 20 firms, while in JMAB 2.0, the range is more stable, fluctuating between 0.10 and 0.3 across four firms. Additionally, as Fig. 16 (a) and (b) shows, individual firm investment is far less volatile in JMAB 2.0 due to the revised investment function. Investment values range only between 18 and 24, whereas in JMAB 1.0, they fluctuate between

⁸ The reason why there are only four capital firms in JMAB 2.0 is explained in Appendix C.

0 and 120. As a result, no lumpiness can be observed. Fig. 17 displays the distributions of firm sizes, bank credit allocation, and bank credit degree (the number of firms a bank has loan relationships with). Since JMAB 2.0 includes fewer capital firms and banks, an additional scaled distribution is provided to align the number of firms and banks with those in JMAB 1.0, ensuring comparability. As expected, the size distributions of consumption and capital firms in JMAB 2.0 follow a Gaussian distribution, in contrast to the lognormal fat-tailed distribution observed in JMAB 1.0. The same pattern holds for bank credit and bank credit degree.

Fig. 20 in Appendix E also contains samples for all expectation mechanisms of JMAB 2.0 including the expectations and actual values of firms, banks, and the central bank. All figures show no systematic under- or overestimation of the variables.

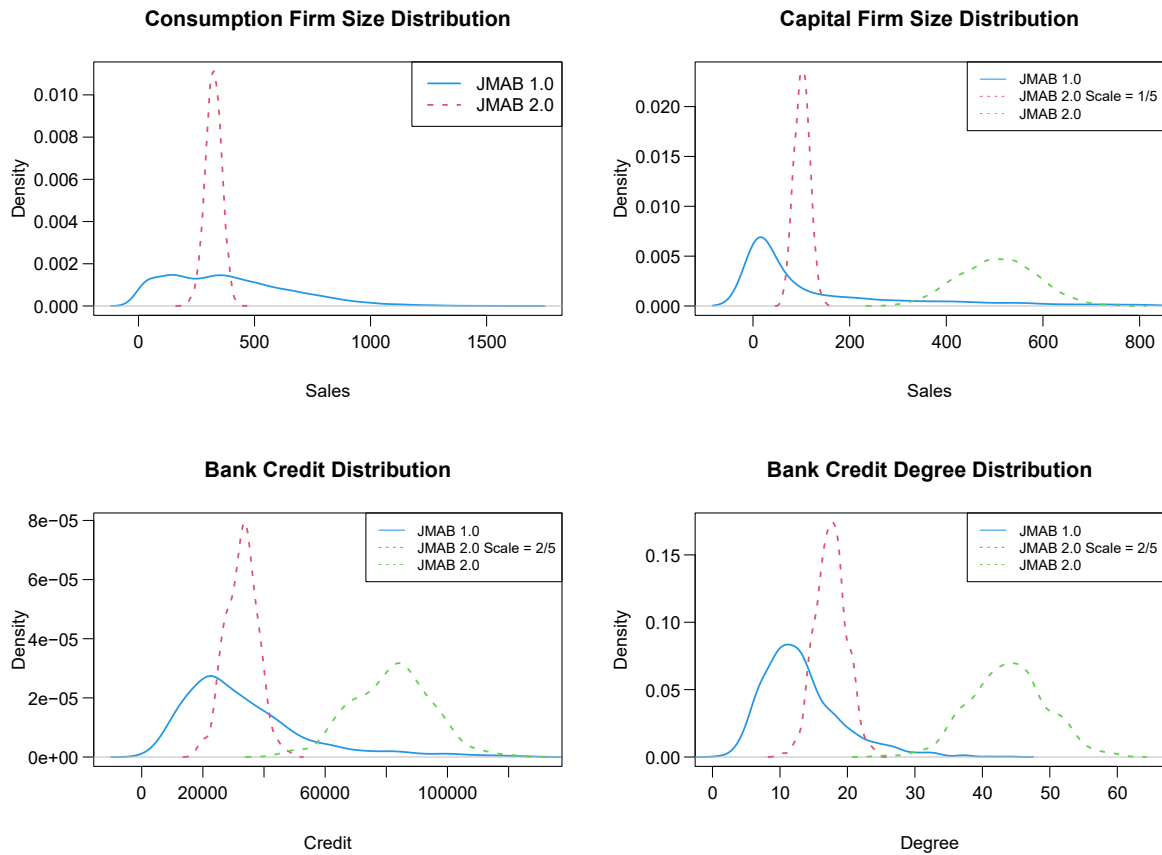


Fig. 17 Distribution of firm-specific and bank-specific variables in JMAB 1.0 and 2.0

6 Discussion

This section first discusses the suitability of JMAB 1.0 and 2.0 as economic benchmark models and then evaluates the validation methods proposed by Caiani et al. (2016). Thereby, a set of standards is proposed to improve the publication and validation of future ABMs. Lastly, the models are examined from a technical perspective as modeling software.

The first objective of Caiani et al. (2016) in developing JMAB 1.0 was to create a simple, general, and flexible benchmark macroeconomic AB-SFC model for policy analysis, particularly in the field of banking regulation. As demonstrated in this paper, this goal was only partly met. On the one hand, it replicates a large set of stylized facts and was one of the first models, that introduced endogenous money creation to more accurately represent the stocks and flows of banks and thereby enhance the realism of the model's banking system. On the other hand, it generates implausible outputs for various key variables, especially for those of banks, and does not clearly converge to a long-term steady state, which limits its potential use as a general benchmark model and undermines the realism of its banking system. It has been shown that these issues arise from misspecifications in agent mechanisms. This applies to the deposit interest rate, the expected return on loans, the bond demand of banks, the investment of firms in excess capacity, and the expectations for wages and prices. Other mechanisms, such as the expectation for sales and the investment behavior with feedback-loops, are not fully compatible with the model's internal structure. In its basic form, the model can therefore only be applied without restrictions in future studies where these issues do not affect the variables of interest. Otherwise, it may produce misleading results. Also, follow-up studies suggest that there are issues with mechanisms in the original model. For instance, Schasfoort et al. (2017) reworked the credit and deposit mechanisms to investigate monetary policy transmission, while Caiani et al. (2019) revised the pricing mechanism to extend the model's runtime from 400 to 1,000 periods. Schasfoort et al. (2017), however, did not resolve the issue of deposit interest rates not adjusting to the policy rate and therefore concluded that the monetary policy pass-through to deposit and loan rates is uncertain or insignificant, contrary to empirical findings. In contrast, JMAB 2.0 can be considered as a completer and more robust benchmark model. It produces plausible outputs for all variables, reaches a steady state in the long-term, and exhibits only minor deviations from the calibrated steady state, all of which can be fully explained. On the macro level, it roughly replicates the same stylized facts as JMAB 1.0. On the micro level, it does not replicate the same stylized facts as JMAB 1.0. However, this was intentional and is not problematic, as those stylized facts in JMAB 1.0 were not clearly based on their real-world causes. Nevertheless, agent mechanisms related to firms, such as pricing and investment, are modeled more realistically in JMAB 2.0, as the average price and NPV are incorporated. For banks, JMAB 2.0 newly replicates the stylized fact, that deposit and loan interest rates follow the central bank's policy rate. It is thus the first descendant in the family of JMAB models to reproduce this fact. Overall, with its feature-rich banking sector, JMAB 2.0 also sets itself apart

from other major macroeconomic ABMs, such as the EURACE models, the Keynes meets Schumpeter models, and the CATS models.

The second objective of Caiani et al. (2016) was to establish a coherent framework for designing, calibrating, analyzing, and validating AB-SFC models. With regard to analysis and validation, this objective is achieved only with reservations. In their analysis, Caiani et al. (2016) explain all the extreme fluctuations and deviations from the steady state by the symmetric starting conditions of agents, but do not clearly identify which mechanisms drive specific deviations or assess to what extent the extreme deviations are tolerable. As a result, several issues in the calibration and agent mechanisms remain undetected. Moreover, their proposed validation methods—stock-flow consistency and empirical—exhibits limitations, which prevents the validation of the model to its full extend. Stock-flow consistency alone does not prevent implausible results, and empirical validation is subject to various restrictions. First, it is prone to spurious correlations, which the analysis presented in this paper suggests was the case with the heterogeneous market shares and lumpy investment patterns of firms, where the model created empirical facts without the causal relationships found in the real-world. Second, the macro-results of the model were validated with cross-correlations, but cross-correlations in empirical data could be ambiguous, depending on the statistical method used, and therefore may not always provide a reliable basis for validation. The cross-correlation validation on the model's markup-GDP relationship, for example, showed alignment with empirical data, yet it failed to reveal that the markup was incorrectly calculated and, in fact, aligns with empirical data in the opposite direction. Third, the empirical validation was performed too restrictively, since several crucial variables on the macro-level, for which clear empirical evidence can be found, were excluded from validation. This applies to the steadily increasing markup levels, the persistently rising deposit interest rates, the capital ratios of banks frequently approaching zero, the systematically underestimated expectations of households and firms, and the increasing volatility of investment.

The blind spots in the proposed analysis and validation methods highlight the need for more basic standards for the publication and validation of ABMs in order to improve plausibility, comprehensibility, and reproducibility of results, that go beyond mere fit to empirical data. The validation of agent-based models has been an ongoing topic for the last two decades and several proposals have been made on how validation could be performed in order to better match empirical data (Assenza et al., 2015; Barde & van der Hoog, 2017; Fagiolo et al., 2019; Windrum et al., 2007). However, the existing literature does not explicitly address publication

practices, and journals generally do not provide specific guidelines in this regard. Building on the shortcomings identified in the JMAB model and broader literature, the following principles are proposed as basic standards:

1. Publication of all data on key variables produced by the model: Authors should publish all data on key variables as a plausibility check. This is a necessity to prove that the described mechanisms of a model work properly and enables reviewers and readers to easily identify implausible results and limitations of the model.
2. Explanation of deviations from steady state: Any significant deviations from the steady state should be analyzed and explained. Large deviations may indicate shortcomings or errors in the model or calibration. Furthermore, the predictivity of a model may be negatively affected if the initial steady state is calibrated with empirical data but the model's outcomes deviate strongly from it. With the agent-based methodology, it is generally possible to trace deviations in greater detail since the effects of single mechanisms can be studied by only activating these mechanisms while keeping other mechanisms disabled and their variables constant.
3. Justification of modelling decisions: Authors should provide comprehensible reasons why agents behaviors are modelled in a certain way. This would prevent implementing implausible behaviors right from the start. Valid justifications could include economic rationality, empirical support, simplicity, or compatibility with the overall model structure. Simplified or compatible mechanisms should be economically rational from the perspective of the individual agent. Firms and banks, for example, should operate in a profit-oriented or loss-reducing manner.
4. Demonstration of causal relationships for empirically sound results: Authors should explain the mechanisms driving their empirically sound results and explain how the causal relationships in the model align with the causal relationships behind the real-world phenomena. If this is not the case, empirically looking results of a model might be only a model-specific output and no replication of real-world phenomena. This issue has been highlighted in previous studies, and several sophisticated methods have been proposed to address it. However, for basic validation, it may be sufficient to demonstrate that agents in the model base their behavior on the same key factors as microeconomic surveys suggest being the most important ones.

5. Public release of the model's code: In general authors should make their model's underlying code publicly available, so that results can be easily reproduced. Caiani et al. (2016) made their code publicly available, but not every ABM author follows this practice.

Implementing these basic standards, in combination with stock-flow consistency and empirical validation, would improve the quality of agent-based research. Without rigorous publication and validation standards, the peer-review process loses credibility, and peer-reviewed papers become indistinguishable from non-reviewed research.

Besides their economic implications, JMAB 1.0 and JMAB 2.0 can also be evaluated as software artifacts from a software engineering perspective. Caiani et al. (2016) intended to create a simple and flexible model that could be easily employed, adapted, and modified. However, these software engineering aspects were not explicitly considered in the validation process, and no metrics were provided to assess the model's simplicity, usability, or adaptability relative to other models. With over 60,000 lines of code, it can be argued that JMAB 1.0 is rather complex. Additionally, its long runtime further complicates usability. While JMAB 2.0 is not necessarily superior as modeling software, it does introduce improvements: it executes simulations much faster, includes a simpler way to add reports to simplify customization, and provides a script for calibrating the aggregated model. Further improvements are beyond the scope of this paper and fall within the domain of software engineering research.

7 Conclusion

This paper identified the main issues with the agent-based stock-flow model JMAB developed by Caiani et al. (2016) and proposes an updated version that addresses these. Despite being able to replicate a large set of stylized facts, there are various shortcomings in the model, which limit its applicability as a general benchmark model and policy analysis tool. The model was originally intended to be used in the field of banking regulation, but it generates implausible outputs for several key variables of banks and other agents. Furthermore, it does not clearly converge to a long-term steady state. These issues arise because some of the agent mechanisms are misspecified or are not fully compatible with the model's internal structure. Furthermore, the validation methods proposed by Caiani et al. (2016)—namely, empirical validation and logical validation through stock-flow consistency—exhibits limitations in detecting these issues. Several key variables in the banking sector are left out from validation and some of the

highlighted stylized facts in the validation on the micro level appear to be caused by model-specific mechanisms, rather than by their real-world counterparts, implying spurious correlations. This paper has presented solutions to all these issues, resulting in the development of JMAB 2.0. The revised model generates more plausible and less volatile outputs, particularly for the banking sector, and therefore provides a more robust foundation for use as a general benchmark model and policy analysis tool. Additionally, this paper proposes a set of basic standards for the publication and validation of future economic agent-based models. These standards include: (1) the publication of all data on key variables produced by the model, (2) explanation for deviations from the steady state, (3) justification of modelling decisions, (4) demonstrations of causal relationships, and (5) the public release of the model's underlying code.

This research also opens up several avenues for future study. From an economic perspective, JMAB 2.0 can be further extended by incorporating more realistic agent behaviors to better match micro level stylized facts, such as the fat-tailed distribution of firms. From a software engineering perspective, the primary challenge is improving usability and reducing complexity. With over 60,000 lines of code, the model's complexity needs to be reduced to enhance accessibility and ease of use. The model's usability could be evaluated through experimental testing, where different user groups—such as students and researchers—are required to use multiple models, including JMAB 2.0, to solve a basic economic problem. Such an experiment could reveal JMAB 2.0's strengths and weaknesses compared to other agent-based models and DSGE models.

References

- Assenza, T., Gatti, D. D., & Grazzini, J. (2015). Emergent dynamics of a macroeconomic agent based model with capital and credit. *Journal of Economic Dynamics and Control*, 50, 5–28. <https://doi.org/10.1016/J.JEDC.2014.07.001>
- Barde, S., & van der Hoog, S. (2017). An empirical validation protocol for large-scale agent-based models. *Working Papers in Economics and Management 04-2017*, Bielefeld University. <https://doi.org/10.4119/unibi/2912187>
- Bhaduri, A., & Marglin, S. (1990). Unemployment and the real wage: The economic basis for contesting political ideologies. *Cambridge Journal of Economics*, 14(4), 375–393. <https://doi.org/10.1093/OXFORDJOURNALS.CJE.A035141>
- Caballero, R. J., Engel, E. M. R. A., Haltiwanger, J. C., Woodford, M., & Hall, R. E. (1995). Plant-Level Adjustment and Aggregate Investment Dynamics. *Brookings Papers on Economic Activity*, 1995(2), 1. <https://doi.org/10.2307/2534611>
- Caiani, A., Godin, A., Caverzasi, E., Gallegati, M., Kinsella, S., & Stiglitz, J. E. (2016). Agent based-stock flow consistent macroeconomics: Towards a benchmark model. *Journal of Economic Dynamics and Control*, 69, 375–408. <https://doi.org/10.1016/j.jedc.2016.06.001>

- Caiani, A., Russo, A., & Gallegati, M. (2019). Does inequality hamper innovation and growth? An AB-SFC analysis. *Journal of Evolutionary Economics*, 29(1), 177–228. <https://doi.org/10.1007/S00191-018-0554-8>
- Caiani, A., Russo, A., & Gallegati, M. (2020). Are higher wages good for business? An assessment under alternative innovation and investment scenarios. *Macroeconomic Dynamics*, 24(1), 191–230. <https://doi.org/10.1017/S1365100518000299>
- Dawid, H., & Gatti, D. D. (2018). Agent-Based Macroeconomics. *Handbook of Computational Economics*, 4, 63–156. <https://doi.org/10.1016/bs.hescom.2018.02.006>
- Dawid, H., Gemkow, S., Harting, P., van der Hoog, S., & Neugart, M. (2012). The Eurace@Unibi Model: An Agent-Based Macroeconomic Model for Economic Policy Analysis. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.2408969>
- Dosi, G., Fagiolo, G., & Roventini, A. (2010). Schumpeter meeting Keynes: A policy-friendly model of endogenous growth and business cycles. *Journal of Economic Dynamics and Control*, 34(9), 1748–1767. <https://doi.org/10.1016/j.jedc.2010.06.018>
- Dosi, G., Napoletano, M., Roventini, A., & Treibich, T. (2017). Micro and macro policies in the Keynes+Schumpeter evolutionary models. *Journal of Evolutionary Economics*, 27(1), 63–90. <https://doi.org/10.1007/S00191-016-0466-4>
- Dosi, G., & Roventini, A. (2019). More is different.. and complex! the case for agent-based macroeconomics. *Journal of Evolutionary Economics*, 29(1), 1–37. <https://doi.org/10.1007/S00191-019-00609-Y>
- Dutt, A. K. (1984). Stagnation, income distribution and monopoly power. *Cambridge Journal of Economics*, 8(1), 25–40. <https://doi.org/10.1093/OXFORDJOURNALS.CJE.A035533>
- Fabiani, S., Druant, M., Hernando, I., Kwapił, C., Landau, B., Loupias, C., Martins, F., Mathä, T., Sabbatini, R., Stahl, H., & Stokman, A. (2006). What Firms' Surveys Tell Us about Price-Setting Behavior in the Euro Area. *International Journal of Central Banking*, 2(3).
- Fagiolo, G., Guerini, M., Lamperti, F., Moneta, A., & Roventini, A. (2019). Validation of Agent-Based Models in Economics and Finance. In C. Beisbart & N. J. Saam (Eds.), *Computer Simulation Validation: Fundamental Concepts, Methodological Frameworks, and Philosophical Perspectives* (pp. 763–787). Springer International Publishing. https://doi.org/10.1007/978-3-319-70766-2_31
- Fierro, L. E., Caiani, A., & Russo, A. (2022). Automation, Job Polarisation, and Structural Change. *Journal of Economic Behavior & Organization*, 200, 499–535. <https://doi.org/10.1016/J.JEBO.2022.05.025>
- Furfine, C. (2001). The reluctance to borrow from the Fed. *Economics Letters*, 72(2), 209–213. [https://doi.org/10.1016/S0165-1765\(01\)00419-0](https://doi.org/10.1016/S0165-1765(01)00419-0)
- Gatti, D. D., Desiderio, S., Gaffeo, E., Cirillo, P., & Gallegati, M. (2011). Macroeconomics from the bottom-up. In *New Economic Windows* (Vol. 11). Springer. <https://doi.org/10.1007/978-88-470-1971-3>
- Gatti, D. D., Di Guilmi, C., Gaffeo, E., Giulioni, G., Gallegati, M., & Palestrini, A. (2005). A new approach to business fluctuations: heterogeneous interacting agents, scaling laws and financial fragility. *Journal of Economic Behavior & Organization*, 56(4), 489–512. <https://doi.org/10.1016/J.JEBO.2003.10.012>
- Godley, W., & Lavoie, M. (2007). *Monetary economics: an integrated approach to credit, money, income, production and wealth*. Palgrave Macmillan.
- Graham, J. R., & Harvey, C. R. (2001). The theory and practice of corporate finance: evidence from the field. *Journal of Financial Economics*, 60(2–3), 187–243. [https://doi.org/10.1016/S0304-405X\(01\)00044-7](https://doi.org/10.1016/S0304-405X(01)00044-7)
- Heckbert, S., Baynes, T., & Reeson, A. (2010). Agent-based modeling in ecological economics. *Annals of the New York Academy of Sciences*, 1185(1), 39–53. <https://doi.org/10.1111/J.1749-6632.2009.05286.X>
- Hottman, C. J., Redding, S. J., & Weinstein, D. E. (2016). Quantifying the Sources of Firm Heterogeneity. *The Quarterly Journal of Economics*, 131(3), 1291–1364. <https://doi.org/10.1093/QJE/QJW012>
- Keister, T. (2012, April 4). *Corridors and Floors in Monetary Policy*. Liberty Street Economics. Retrieved November 26, 2024, from <https://libertystreeteconomics.newyorkfed.org/2012/04/corridors-and-floors-in-monetary-policy/>
- Kremer, E. (2021). Contingent Convertible Bonds and Macroeconomic Stability in a Stock-Flow Consistent Agent-Based Model. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.3929224>

- Myers, S. C. (1984). The Capital Structure Puzzle. *The Journal of Finance*, 39(3), 574–592. <https://doi.org/10.1111/J.1540-6261.1984.TB03646.X>
- Nekarda, C. J., & Ramey, V. A. (2020). The Cyclical Behavior of the Price-Cost Markup. *Journal of Money, Credit and Banking*, 52(S2), 319–353. <https://doi.org/10.1111/JMCB.12755>
- Nikiforos, M., & Zezza, G. (2017). Stock-flow Consistent Macroeconomic Models: a Survey. *Journal of Economic Surveys*, 31(5), 1204–1239. <https://doi.org/10.1111/JOES.12221>
- Reissl, S. (2021). Heterogeneous expectations, forecasting behaviour and policy experiments in a hybrid Agent-based Stock-flow-consistent model. *Journal of Evolutionary Economics*, 31(1), 251–299. <https://doi.org/10.1007/S00191-020-00683-7>
- Richiardi, M. G. (2017). The future of agent-based modeling. *Eastern Economic Journal*, 43(2), 271–287. <https://doi.org/10.1057/S41302-016-0075-9>
- Rowthorn, B. (1981). Demand, real wages and economic growth. In *Studi Economici* (Vol. 1, Number 18). Thames Polytechnics.
- Schasfoort, J., Godin, A., Bezemer, Di., Caiani, A., & Kinsella, S. (2017). Monetary Policy Transmission in a Macroeconomic Agent-Based Model. *SOM Research Reports*, 17010-GEM, 1–48. <https://doi.org/10.1142/S0219525918500030>
- Turrell, A. (2016). Agent-based models: understanding the economy from the bottom up. *Bank of England Quarterly Bulletin*, 56(4), 173–188.
- U.S. Bureau of Economic Analysis. (2024, November 20). *Personal Saving Rate [PSAVERT]*, retrieved from FRED, Federal Reserve Bank of St. Louis. <https://fred.stlouisfed.org/series/PSAVERT>
- van der Hoog, S., & Dawid, H. (2019). Bubbles, Crashes, And The Financial Cycle: The Impact Of Banking Regulation On Deep Recessions. *Macroeconomic Dynamics*, 23(3), 1205–1246. <https://doi.org/https://doi.org/10.1017/S1365100517000219>
- Windrum, P., Fagiolo, G., & Moneta, A. (2007). Empirical Validation of Agent-Based Models: Alternatives and Prospects. *Journal of Artificial Societies and Social Simulation*, 10(2), 8. <https://www.jasss.org/10/2/8.html>

8 Statements and Declarations

Funding

The author declares that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests

The author has no relevant financial or non-financial interests to disclose.

Data availability statement

The source code of the JMAB 2.0 model and all necessary steps required to generate the presented data are available at the following URL: <https://github.com/simonhess/benchmark2>.

The source code used to generate the data concerning the JMAB model is available at the following URL: <https://github.com/S120/benchmark>.

The source code of the simplified version of the JMAB model and all necessary steps required to generate the presented data are available at the following URL: https://github.com/simonhess/benchmark2_supp_data.

9 Appendix A

Table 1 List of issues with JMAB 1.0

No.	Issue name	Description	Related page/ equation in orig. paper
Model related			
1	Real sales expectation	Simple exponential smoothing leads to steadily increasing markups.	383, Eq. 3.1; 384, Eq. 3.7
2	Wage and price expectation	Simple exponential smoothing unsuitable for forming expectations for wages and prices, as these variables exhibit persistent upward trends.	383, Eq. 3.1; 384, Eq. 3.6; 388, Eq. 3.16
3	Firm's investment	Feedback-loop creates exponentially increasing volatility in investment.	384, Eq. 3.9
4	Firm's investment	Target profit rate makes firms unreasonably increase their investment to reduce their profits.	384, Eq. 3.9
5	Loan approval decision	Funding costs for the loan are missing.	386
6	Typesetting error payoff tree	In the loan payoff tree, no collateral is considered in the first left branch.	387
7	Probability of default of firms	Consideration of paid off loans in the debt service.	386, Eq. 3.13
8	Probability of default of firms	Maintenance CAPEX not included in the cashflow calculation of consumption firms.	386, Eq. 3.13
9	Deposit interest rate	Upper bound is calculated incorrectly.	387, Eq. 3.14
10	Deposit interest rate	Interest rates incorrectly increasing in a floor system.	387, Eq. 3.14
11	Bond demand	Excess reserves not a suitable indicator of how many bonds a bank should buy.	387
12	Bankruptcy handling of firms	Firms keep their capital stock and markup in the bankruptcy which makes them go bankrupt again.	387
13	Order of agent activities	Deposit interest payments affect households only in the next period contradictory to calibration where they affect them in the current period.	383
14	Household consumption	Dividends are consumed twice: as part of net income and past net wealth.	388, Eq. 3.16
Calibration related			
15	Probability of default of firms	Value is set too high relative to the loan interest rate.	404, Eq. A.49
16	Bond interest rate	Calibration of the bond interest rate does not consider the policy rate of the central bank.	406
17	Deposit interest rate	Calibration of the deposit interest rate does not consider the policy rate of the central bank.	406
18	Typesetting error	Deviation of loans of C firms: Change in inventories is multiplied instead of added.	402, Eq. A.22
19	Typesetting error	Nominal capital of C firms: Wrong exponent.	401, Eq. A.14
20	Typesetting error	Nominal income of households: Dole is subtracted instead of added.	402, Eq. A.24
21	Typesetting error	Unemployment rate: Number of employees are incorrectly in the denominator.	403, Eq. A.39
Implementation related			
22	Loan interest rate	No lower bound for capital ratio is set as described in the model.	386, Eq. 3.12
23	Loan approval decision	Wrong calculation of expected loss of the first period of the loan.	387
24	Probability of firms switching their loan supplier	Firms ignore the probability and always switch their supplier.	382
25	Wage determination	Values for the unemployment variable are reversed.	387, Eq. 3.15

No.	Issue name	Description	Related page/ equation in orig. paper
Validation related			
26	Spurious correlation in the stylized fact of heterogenous market shares of firms	The heterogenous market shares of firms in the model are caused by the exclusion of competitor's price in the pricing mechanism, whereas empirical studies suggest different underlying causes.	395-396
27	Spurious correlation in the stylized fact of lumpy investments	The lumpiness of investment in the model is caused by model-specific factors rather than by its real-world cause, fixed adjustment costs.	396-397
28	Error in cross correlation calculation	Calculation of markup uses the actual wage instead of the expectation.	394

10 Appendix B

This appendix compares the different quantity-price mechanisms of firms found in the agent-based literature with JMAB 1.0 and 2.0. These mechanisms incorporate the price of competitors and typically work as follows: firms either update their expectations or their markup/price—never both simultaneously. Firms compare their actual sales with their expectations, as in JMAB 1.0. In addition, they compare their own price or markup with the average across all firms to avoid pricing themselves out of the market. According to Dawid and Gatti (2018) the most general form looks as follows:

$$s_{x,t}^e = \begin{cases} s_{x,t-1}^e(1 + FN) & \text{if } \frac{inv_{x,t-1}}{s_{x,t-1}} < v^m \text{ and } mu_{x,t-1} > \overline{mu}_{x,t-1} \\ s_{x,t-1}^e(1 - FN) & \text{if } \frac{inv_{x,t-1}}{s_{x,t-1}} > v^M \text{ and } mu_{x,t-1} < \overline{mu}_{x,t-1} \end{cases} \quad (62)$$

Firms increase their expected sales if their inventory-to-sales ratio is below the minimum threshold v^m and the markup is above the average markup. Analogously, firms decrease their expected sales if their inventory ratio is above the maximum threshold v^M and the markup is below the average markup. For this simulation the minimum threshold is set to 0.05, the maximum threshold to 0.15. Firms increase their markup if their inventory-to-sales ratio is below the minimum threshold and the markup is below the average markup. Firms decrease their markup if their inventory-to-sales ratio is above the maximum threshold and the markup is below the average markup:

$$mu_{x,t} = \begin{cases} mu_{x,t-1}(1 + FN) & \text{if } \frac{inv_{x,t-1}}{s_{x,t-1}} < v^m \text{ and } mu_{x,t-1} < \overline{mu}_{x,t-1} \\ mu_{x,t-1}(1 - FN) & \text{if } \frac{inv_{x,t-1}}{s_{x,t-1}} > v^M \text{ and } mu_{x,t-1} > \overline{mu}_{x,t-1} \end{cases} \quad (63)$$

Assenza et al. (2015) propose a similar mechanism that is based on simple exponential smoothing. Furthermore, it does not use thresholds, which has almost no impact though. Expected sales are adjusted with exponential smoothing only if sales are greater than expected and the markup is above the average or sales are lower than expected and the markup is below the average:

$$s_{x,t}^e = \begin{cases} s_{x,t-1}^e + \beta(s_{x,t-1} - s_{x,t-1}^e) & \text{if } s_{x,t-1} > s_{x,t-1}^e \text{ and } mu_{x,t-1} > \overline{mu}_{x,t-1} \\ s_{x,t-1}^e + \beta(s_{x,t-1} - s_{x,t-1}^e) & \text{if } s_{x,t-1} < s_{x,t-1}^e \text{ and } mu_{x,t-1} < \overline{mu}_{x,t-1} \end{cases} \quad (64)$$

The smoothing parameter β is set to 0.9, following the configuration in Assenza et al. (2015). Firms increase their markup if sales are greater than expected and the markup is below the average. Firms decrease their markup if sales are lower than expected and the markup is above the average of all firms:

$$mu_{x,t} = \begin{cases} mu_{x,t-1}(1 + FN) & \text{if } s_{x,t-1} > s_{x,t-1}^e \text{ and } mu_{x,t-1} < \overline{mu}_{x,t-1} \\ mu_{x,t-1}(1 - FN) & \text{if } s_{x,t-1} < s_{x,t-1}^e \text{ and } mu_{x,t-1} > \overline{mu}_{x,t-1} \end{cases} \quad (65)$$

By default, neither Dawid and Gatti (2018) nor Assenza et al. (2015) apply a switching probability PS in their models. Therefore, both mechanisms are simulated with and without a switching probability. Both mechanisms are compared to JMAB 1.0 and JMAB 2.0 in Fig. 18 and Fig. 19. While Fig. 18 depicts the average markup of all firms in each mechanism, Fig. 19 shows sales and expectations of 10 firms for each mechanism.

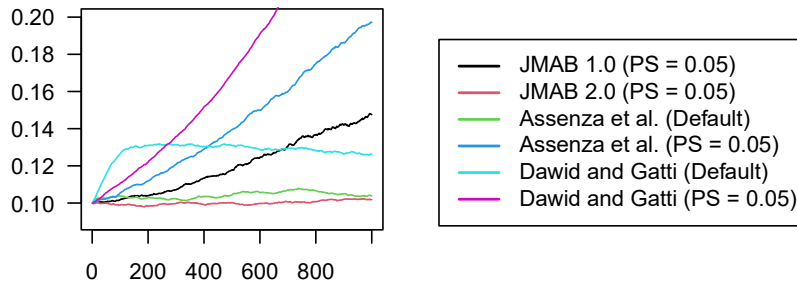


Fig. 18 Average markup of consumption firms of different price-quantity mechanisms. All data was created by the simplified JMAB 1.0 model

The default versions of the mechanisms by Assenza et al. (2015) and Dawid and Gatti (2018) without the switching probability show more spikes in sales but maintain relatively homogeneous firm sales and keep the markup on the same level. However, their expectations always rise to 400, a level above the steady state of 320, within the first 200 periods. On the other hand, the mechanisms with the switching probability of 0.05 can keep the sales and expectations on the same level but their markups are steadily increasing, as Fig. 18 shows. The

JMAB 1.0 mechanism, in comparison, achieves neither a stable level of markups nor homogenous sales. Finally, the JMAB 2.0 mechanism is the only one that provides homogenous firm sales with stable markups without systemically increasing expectations at the beginning. Note that, for the comparison, the JMAB 2.0 mechanism uses a folded normal distribution of JMAB 1.0 instead of a lognormal distribution.

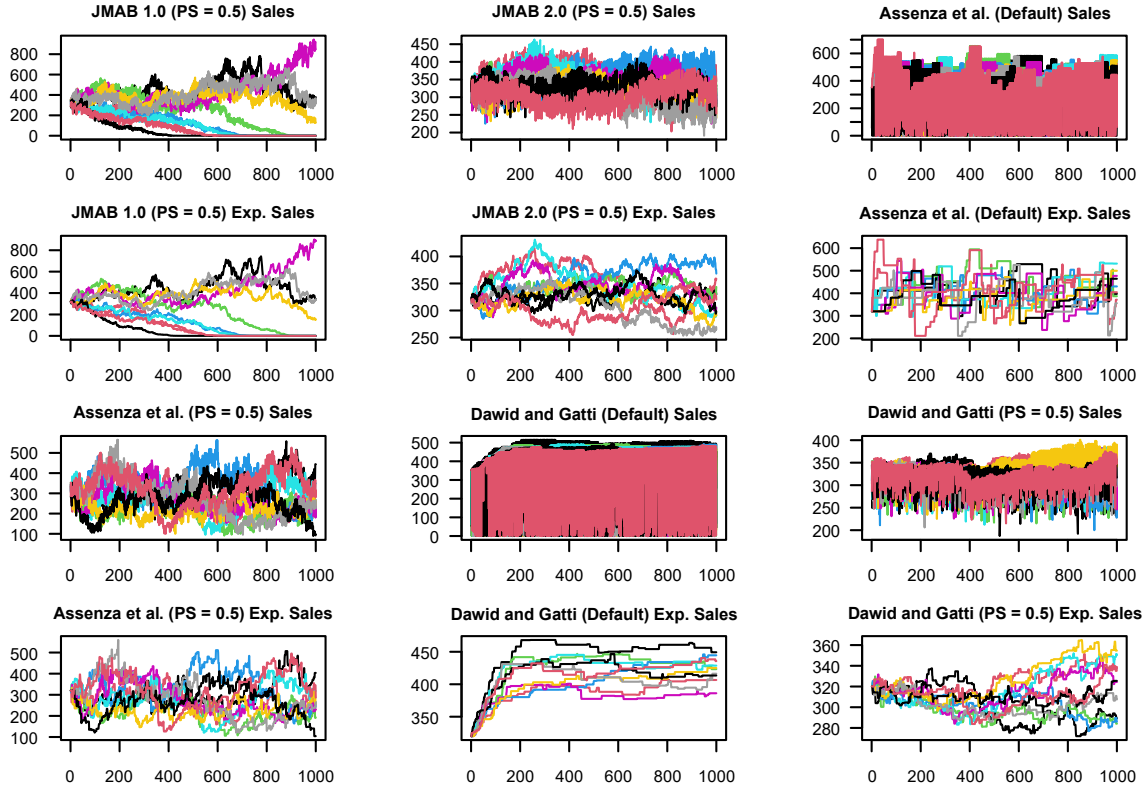


Fig. 19 Consumption firm's real sales and expectations of different price-quantity mechanisms. Each line represents one consumption firm from one run in the model. All data was created by the simplified JMAB 1.0 model

11 Appendix C

This appendix contains the part of the calibration containing the construction of the aggregated model and the setting of the exogenous parameters. In the following the corrected aggregated model used to calculate the steady state values is described with four blocks describing the interest rates (Eq. (66) - (69)), capital firm (Eq. (70) - (79)), consumption firm (Eq. (80) - (90)), household, bank and the government (Eq. (91) - (111)). Unknown dependent variables are bold in the equations while known exogenously set ones are not.

There are two logical errors in the calibration of the interest rates in the steady state in JMAB 1.0. The calibrated values for the deposit interest rate and the bond interest rate are both not

aligned with the central bank's policy rate. The deposit interest rate is set to 0.0025, but this value is not aligned with the deposit mechanism of JMAB 1.0, where the deposit rate (incorrectly) converges towards the central bank's policy rate of 0.005 in a floor system. The deposit rate starting at 0.0025 implies that the central bank implemented a policy rate hike (from 0.0025 to 0.005) in the steady state and banks reaching the steady state policy rate of 0.005 on their deposits only after a while. The interest rate on bonds is set to 0.0025 as well. This causes banks to incur excess losses from their bond business when the deposit interest rate converges towards 0.005 since banks pay 0.005 on their liabilities while only receiving 0.0025 on their bonds. To make the calibration of interest rates for JMAB 2.0 more comprehensible this paper contains an extra block for it. In JMAB 2.0 the initial value for the deposit interest rate is set to the deposit interest rate upper bound (Eq. (67)), so that there is no deviation between the initial deposit interest rate and the long-term deposit interest rate. Furthermore, the interest rate on bonds in JMAB 2.0 is set to the interest rate on interbank loans (Eq. (69)), so that banks neither make profits nor incur losses from their bond business. In addition, the calibration of interest rate of JMAB 2.0 include the interest rate on interbank loans (Eq. (66)) and the interest rate on bank loans (Eq. (68)).

$$i^{IBL} = i^A - (i^A - i^R)NLR_b \quad (66)$$

$$i^D = i^{IBL} - \max(LR_b^T - \max(NLR_b, 0), 0)(i^A - i^R) - \max(NLR_b, 0)(i^{IBL} - i^R) \quad (67)$$

$$i^L = mu_b + i^{IBL} \quad (68)$$

$$i^B = i^{IBL} \quad (69)$$

The equations describing the aggregated capital firms (Eq. (70) - (79)) contain no errors in JMAB 1.0, so they are just adopted for JMAB 2.0 with one small adjustment: The unit costs now include the interest on loans (Eq. (72)).

$$N_k = \frac{y_k}{\mu_N} \quad (70)$$

$$uc_k = \frac{W}{\mu_N} + \frac{i^L L_k}{(g_{SS} + 1)y_k} \quad (71)$$

$$p_k = (mu_k + 1)uc_k \quad (72)$$

$$D_k = W\sigma N_k \quad (73)$$

$$y_k = \frac{k}{\kappa} \quad (74)$$

$$inv_k = v y_k \quad (75)$$

$$\Pi_k = \frac{g_{SS}}{g_{SS} + 1} inv_k uc_k + y_k p_k + \frac{i^D D_k}{g_{SS} + 1} - W N_k - \frac{i^L L_k}{g_{SS} + 1} \quad (76)$$

$$T_k = \tau_k \Pi_k \quad (77)$$

$$Div_k = \rho_k (\Pi_k (1 - \tau_k)) \quad (78)$$

$$\frac{g_{SS}}{g_{SS} + 1} L_k = \frac{g_{SS}}{g_{SS} + 1} inv_k uc_k + \frac{g_{SS}}{g_{SS} + 1} D_k - (\Pi_k - Div_k - T_k) \quad (79)$$

The equations for the consumption firm in JMAB 1.0 contain two typesetting errors. One is in the deviation of loans where the change in inventories is multiplied instead of added. This was corrected in Eq. (90). The second one is in the calculation of the nominal capital which included CL as exponent instead of $\kappa - j$. This was corrected in Eq. (82). Furthermore, in line with JMAB 2.0 interest on loans is included in the unit cost (Eq. (81)) and the price is calculated based on unit cost instead of variable cost (Eq. (83)).

$$N_c = \frac{y_c}{l_K \mu_K} \quad (80)$$

$$uc_c = \frac{N_c W + \frac{L_c i^L}{g_{SS} + 1} + \frac{k p_k}{\kappa^2} \sum_{j=1}^{\kappa} \frac{1}{(g_{SS} + 1)^j}}{y_c} \quad (81)$$

$$K_c = \frac{k p_k}{\kappa^2} \sum_{j=1}^{\kappa} \frac{j}{(g_{SS} + 1)^{\kappa-j}} \quad (82)$$

$$p_c = (m u_c + 1) uc_c \quad (83)$$

$$D_c = \sigma N_c W \quad (84)$$

$$y_c = c u_c^T k \mu_K \quad (85)$$

$$inv_c = y_c v \quad (86)$$

$$\begin{aligned} \Pi_c = y_c p_c + \frac{g_{SS}}{g_{SS} + 1} inv_c uc_c + \frac{D_c i^D}{g_{SS} + 1} - N_c W - \frac{L_c i^L}{g_{SS} + 1} \\ - \frac{k p_k}{\kappa^2} \sum_{j=1}^{\kappa} \frac{1}{(g_{SS} + 1)^j} \end{aligned} \quad (87)$$

$$T_c = \tau_c \Pi_c \quad (88)$$

$$Div_c = \rho_c (\Pi_c (1 - \tau_c)) \quad (89)$$

$$\begin{aligned} \frac{g_{SS}}{g_{SS} + 1} L_c = & y_k p_k + \frac{g_{SS}}{g_{SS} + 1} inv_c uc_c + \frac{g_{SS}}{g_{SS} + 1} D_c - (\Pi_c - T_c - Div_c) \\ & - \frac{k p_k}{\kappa^2} \sum_{j=1}^{\kappa} \frac{1}{(g_{SS} + 1)^j} \end{aligned} \quad (90)$$

The equations for the household, the bank, and the government in JMAB 1.0 contain two typesetting errors. In the original equation of the nominal income dole is subtracted instead of added which was corrected in Eq. (93). Additionally, the equation of the unemployment rate in JMAB 1.0 is incorrect since it contains the number of employees in the denominator instead of the number of households which was corrected in Eq. (92).

Apart from that JMAB 2.0 newly implements the share of bonds which are held by the central bank ψ . This share is defined in Eq. (108) as all deposits multiplied with the net liquidity ratio divided by all government bonds and is used to calculate the bonds of the central bank in Eq. (107). Furthermore, the equation of bank's net wealth (Eq. (106)) was adjusted so that it incorporates the capital adequacy ratio. In Eq. (95) households' real consumption now also excludes previous dividend payments from previous net wealth so that they are not considered twice (in current net income and previous net wealth). Dividends are already subtracted from the derivation of net wealth in Eq. (98), but these relate to dividends received two periods ago if applied to net wealth from one period ago.

$$N_{tot} = N_c + N_g + N_k \quad (91)$$

$$u = 1 - \frac{N_{tot}}{size_{\phi_H}} \quad (92)$$

$$NI_h = \left(WN_{tot} + \frac{D_h i^D}{g_{SS} + 1} + \frac{Div_b + Div_c + Div_k}{g_{SS} + 1} \right) (1 - \tau_h) + \theta W (size_{\phi_H} - N_{tot}) \quad (93)$$

$$T_h = \left(WN_{tot} + \frac{D_h i^D}{g_{SS} + 1} + \frac{Div_b + Div_c + Div_k}{g_{SS} + 1} \right) \tau_h \quad (94)$$

$$c_h = p c_h^{NI} \frac{NI_h}{p_c} - p c_h^{NW} \frac{NW_h - (Div_b + Div_c + Div_k)}{p_c (g_{SS} + 1)} \quad (95)$$

$$c_h = y_c \quad (96)$$

$$C_h = p_c c_h \quad (97)$$

$$\frac{g_{SS}}{g_{SS} + 1} NW_h = NI_h - C_h - \frac{Div_b + Div_c + Div_k}{g_{SS} + 1} + (Div_b + Div_c + Div_k) \quad (98)$$

$$NW_h = D_h \quad (99)$$

$$\Pi_b = \frac{(L_c + L_k)i^L}{g_{SS} + 1} + \frac{B_b i^B}{g_{SS} + 1} + \frac{R_b i^R}{g_{SS} + 1} - \frac{(D_c + D_h + D_k)i^D}{g_{SS} + 1} - \frac{A_b i^A}{g_{SS} + 1} \quad (100)$$

$$T_b = \Pi_b \tau_b \quad (101)$$

$$Div_b = \rho_b (\Pi_b (1 - \tau_b)) \quad (102)$$

$$A_b = (D_c + D_h + D_k)LR_b^T - B_{cb} \quad (103)$$

$$R_b = A_b + B_{cb} \quad (104)$$

$$NW_b = L_c + L_k + B_b + R_b - D_c - D_h - D_k - A_b \quad (105)$$

$$NW_b = (L_c + L_k)CAR_b^T \quad (106)$$

$$B_{cb} = \psi B_g \quad (107)$$

$$\psi = \frac{(D_c + D_h + D_k)NLR_b}{B_g} \quad (108)$$

$$\Pi_{cb} = \frac{A_b i^A}{g_{SS} + 1} + \frac{B_{cb} i^B}{g_{SS} + 1} - \frac{R_b i^R}{g_{SS} + 1} \quad (109)$$

$$\frac{g_{SS}}{g_{SS} + 1} B_g = N_g W + \theta W (size_{\phi_H} - N_{tot}) + \frac{B_g i^B}{g_{SS} + 1} - (T_b + T_c + T_h + T_k) - \Pi_{cb} \quad (110)$$

The system contains 45 equations and 46 unknown variables which is numerically solvable. There is also another equation containing the risk aversion which is independent of the previous equations:

$$\zeta = \log \left(\frac{1}{PD} - 1 \right) + 5 \quad (111)$$

Some exogenous variables have been adjusted in comparison to JMAB 1.0. The propensity to consume out of income has been adjusted to 0.9 which is in line with empirical data (U.S. Bureau of Economic Analysis, 2024). The interest rate on advances is set to 0.0015 which corresponds to the Taylor Rule with 0.0075 nominal growth rate and an exogenously given natural rate of interest of 0.0075. The target capital adequacy ratio of banks is set to 0.08 according to Basel III regulation. Furthermore, the number of banks and capital firms has been reduced from 10 and 20, respectively, to 4 each. This ensures that every bank and capital firm is affected by the switching behavior of their customers. A switching probability of 0.05 in the respective markets would only translate to 10 consumption firms changing their supplier so that not every single one of the 20 capital firms or 20 banks in JMAB 1.0 would be affected. With only 4 capital firms and banks every single agent will be affected. In the original

calibration there are also some variables which use the same symbol such as unemployment rate and capacity utilization. This was corrected by using distinct symbols.

12 Appendix D

Table 3 Model parameters

Symbol	Info	Description	Value
g_{SS}	pre-SS	Nominal rate of growth in the SS	0.0075
$size_{\phi_H}$	pre-SS	Number of households	8000
$size_{\phi_C}$	pre-SS	Number of consumption firms	100
$size_{\phi_K}$	pre-SS	Number of capital firms	4
$size_{\phi_B}$	pre-SS	Number of banks	4
N_g	SS-given	Number of public servants (constant)	1360
$N_{c,0}$	pre-SS	Consumption firms' initial workers	5000
$N_{k,0}$	pre-SS	Capital firms' initial workers	1000
u_0	pre-SS	Initial unemployment	0.08
$\xi^k = \xi^c$	free	Number of potential partners on C and K goods markets	5
$\xi^d = \xi^l$	free	Number of potential partners on deposit and credit markets	4
ξ^n	free	Number of potential partners on labor market (for each vacant job)	10
$PS^k = PS^c = PS^d = PS^l$	free	Probability to switch K good supplier, C good supplier, deposit demander and loan supplier	0.05
$(\mu_{LN}, \sigma_{LN}^2)$	free	Log-normal Distribution parameters	(0,0.0094)
μ_K	pre-SS	Productivity of Capital	1
μ_N	SS-given	Productivity of labor in K sector	2
l_K	SS-given	Capital/labor ratio	6.4
ν	pre-SS	Firms' target inventories to sales ratio	0.1
ϑ	free	Labor turnover ratio	0.05
$mu_{c,0}$	pre-SS	Initial mark-up on NUC for C firms	0.165
$mu_{k,0}$	pre-SS	Initial mark-up on ULC for K firms	0.075
$\tau_k = \tau_c = \tau_b = \tau_h$	pre-SS	Profit and Income tax rates	0.18
η	pre-SS	Loans duration	20
κ	pre-SS	Capital goods duration	20
cu_c^T	pre-SS	Target capacity utilization	0.8
σ	pre-SS	Firms' precautionary deposits as share of wage cost	1.25
$\rho_k = \rho_c$	pre-SS	Firms' profits' share distributed as dividends	0.9
ι	free	Haircut on defaulted firms' capital value	0.5
$mu_{b,0}$	pre-SS	Initial mark-up for banks	0.0025
λ	free	Banks' decay parameter for excess capital	0.25

CAR_b^T	pre-SS	Banks' target capital adequacy ratio	0.08
LR_b^T	pre-SS	Banks' target liquidity ratio	0.05
$NLR_{b,0}$	pre-SS	Banks' initial net liquidity ratio	0
ζ	SS-given	Banks' risk aversion towards C and K firms	7.1972
$\rho_{b,0}$	SS-given	Banks' initial profit share distributed as dividends	0.80224
$i_{b,0}^{IBL}$	SS-given	Initial interest rate on interbank loans	0.015
$i_{b,0}^L$	SS-given	Initial interest rate on loans	0.0175
$i_{b,0}^D$	SS-given	Initial interest rate on deposits	0.01425
$i_{g,0}^b$	SS-given	Initial interest rate on bonds	0.015
$i_{cb,0}^A$	pre-SS	Initial interest rate on CB advances	0.015
$i_{cb,0}^R$	pre-SS	Initial interest rate on CB reserves	0
π_{cb}^T	pre-SS	Inflation target of the central bank	0.0075
i^{nat}	pre-SS	Natural rate of interest	0.0075
$W_{h,0}$	pre-SS	Initial wages	5
θ	SS-given	Ratio of dole to average wage	0.47164
pc_h^{NI}	pre-SS	Propensity to consume out of net income	0.9
pc_h^{NW}	pre-SS	Propensity to consume out of net wealth	0.1
p^b	pre-SS	Bonds price	1
ψ	SS-given	Central bank's share of bond holdings	0
α_c^s	free	Adaptive parameters for C firm sales expectation	320
α_k^s	free	Adaptive parameters for K firm sales expectation	500
$\alpha_k^{mu} = \alpha_c^{mu}$	free	Adaptive parameter for firm markup	0.1
α_c^i	free	Adaptive parameter for C firm investment	20
α_b^D	free	Adaptive parameter for banks deposit interest rate	0.01
α_b^{mu}	free	Adaptive parameter for banks markup for loans	0.001
$\beta^{lvl} = \beta^{trd} = \beta^{SES}$	free	Smoothing parameter for level, trend, and simple exponential smoothing	0.05

Table 4 Aggregated balance sheet in the steady state

	Households	C Firms	K Firms	Banks	Gov	Central bank	Total
Deposits	+37993.42	+31250	+6250	-75493.42	0	0	0
Loans	0	-27929.76	-1584.29	+29514.06	0	0	0
C Goods	0	+3048.65	0	0	0	0	+3048.65
K Goods	0	+ 54160.05	+502.75	0	0	0	+54662.80
Bonds	0	0	0	+48340.49	-48340.49	0	0
Reserves	0	0	0	+3774.67	0	-3774.67	0
Advances	0	0	0	-3774.67	0	+3774.67	0
Net Wealth	+37993.42	+60528.94	+5168.46	+2361.12	-48340.49	0	+57711.45

13 Appendix E

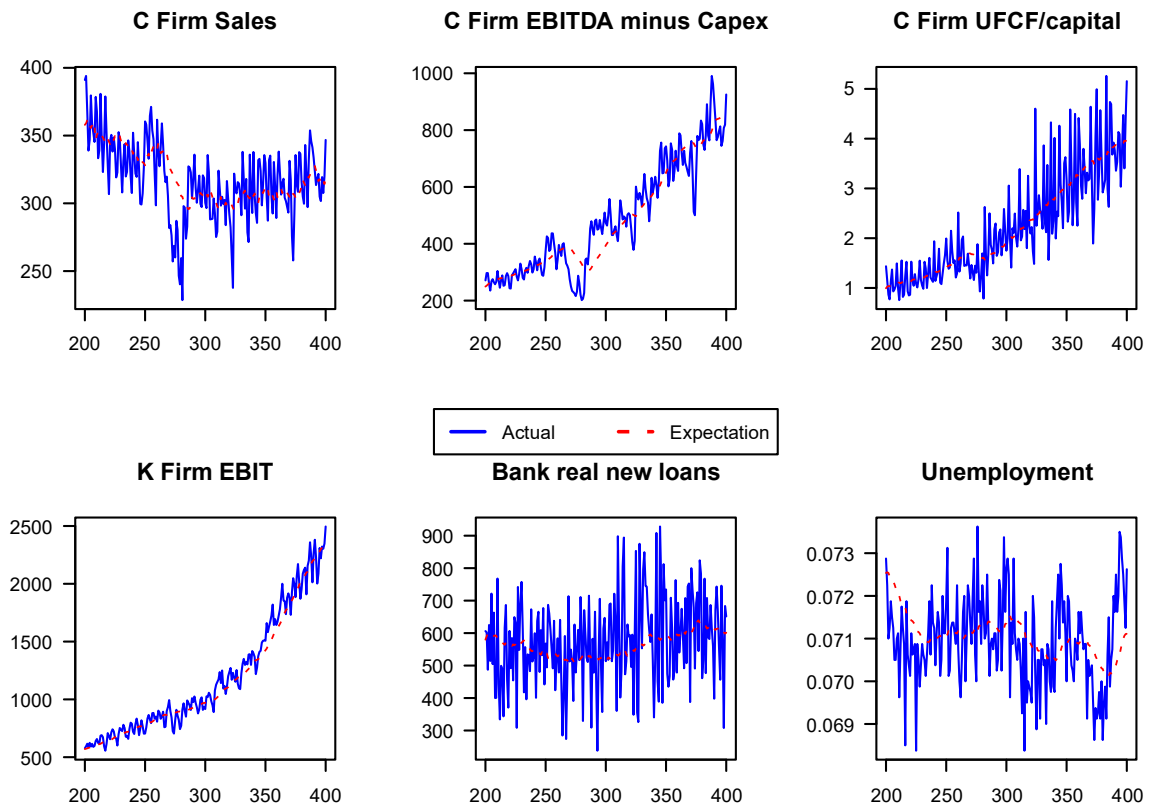


Fig. 20 Sample actual and expected values of multiple variables in JMAB 2.0 for one randomly selected agent per variable. Actual unemployment relates to households while the expectation is formed by the central bank