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REGULAR ARTICLE

# Rationality, inequality, and the output gap: evidence from a disaggregated Keynesian cross diagram

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## Abstract

This paper examines the conditions under which a representative agent (RA) model can accurately approximate the output of a multi-agent model that assumes many interacting agents. The study compares the widely used Keynesian cross diagram, which employs a representative agent, to an extended model that explicitly considers multiple interacting households and firms. The extended model reduces to the original RA model when there is one agent of each type. The findings suggest that the RA Keynesian cross diagram model does not accurately approximate the extended multi-agent model when: (1) the network structure of the economy is asymmetric (e.g., firms have different sizes), or (2) the rationality of agents is too low. Additionally, when income inequality is considered by introducing capitalists, the RA model is no longer a good approximation, even if agents are rational. However, fiscal policies that redistribute income can improve the accuracy of the RA model's predictions. In general, features that increase the overall rationality of the economy and decrease heterogeneity tend to improve the performance of the RA approximation.

**Keywords** Macroeconomics · Rationality · Inequality · Representative agent · Agent-based models · Networks

**JEL Classification** E00 · E12 · C63

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*All happy families are alike; each unhappy family is unhappy in its own way.*
*Leo Tolstoy*

## 1 Introduction

If a society could be accurately represented by a single typical family, great authors like Tolstoy would not have produced their celebrated works. The richness and depth of literary content depends on the existence of a multitude of diverse families, and without accounting for this diversity, it would be impossible to create compelling literature. In essence, there is no interesting literary dynamics related to the representative family.

A similar question can be posed in economics: Is it possible to create "compelling economics" by relying on the assumption of a representative agent? The aim of this paper is to provide some new elements to outline a possible answer. The problem could be reformulated in the following, more precise, terms: Can we measure the error that we make, in predicting aggregate outcomes, by approximating a multiplicity of agents (that is what is given in the real world) with the hypothesis of a representative agent?

I use the term "multiplicity," which indicates the property of being multiple, instead of the more commonly used "heterogeneity," which indicates the property of being diverse, because it is more general and more relevant to the paper. Multiplicity can exist without heterogeneity, but the reverse is not true. For example, hydrogen atoms or perfect gas molecules possess multiplicity but not heterogeneity. In the case of human beings, which can be considered as the elementary particle in economics, multiplicity can be distinguished by heterogeneity only in the abstract,[1] as two identical human beings do not exist. Atoms and molecules, even if identical in the internal structure, can still undergo heterogeneous interactions, determined by the network configuration, which can lead to different aggregate outcomes. In a similar way, humans can be identical (in the abstract) and still generate different outcomes because of their diverse interactions.

Commenting the work of economists that employ agent-based models, Blanchard (2018) states: "*If their view of the world is correct, and network interactions are of the essence, they may well be right. But they have not provided an alternative core from which to start*." In response to Blanchard's inquiry, this paper explores the consequences of substituting a single representative agent (RA) with a network of multiple agents (MA) on the equilibrium solution of the Keynesian cross diagram, which is a widely used macroeconomic model and forms a fundamental part of introductory economics courses. The selection of the Keynesian cross diagram for this study is driven by several factors: (1) the model's well-established nature; (2) its simplicity; and (3) its stable equilibrium, which allows for an easily accessible benchmark to measure deviations from the representative agent case. With respect to these motivations, our work should therefore be read as the description of

[1] I emphasize this because the models presented in the paper are abstract, allowing therefore the distinction of the two properties.

"mechanical" effect stemming from the process of disaggregation of an extremely simplified model, rather than as an attempt to provide a theoretical contribution to Keynesian economics.

This paper offers two main innovative contributions to the existing literature. The first result shows that the mere presence of multiple agents can lead to significant deviations from the representative agent equilibrium, even if the agents are initially homogeneous, i.e., characterized by the same parameters. It turns out that these deviations depend on two key factors: (1) the symmetry of the network, which represents the complexity of economic interactions, and (2) the rationality of the agents. When the network is symmetric enough, the RA equilibrium is a good approximation of the multiple agents equilibrium. When the network is asymmetric, implying more complex interaction between agents, the RA equilibrium becomes a very poor approximation, unless a high degree of rationality of the agents is assumed. Asymmetry, if not counterbalanced by rationality, generates income—and thus wealth—inequality, causing an output loss with respect to the RA prediction, which coincides with a potential output level where no coordination failures exist. In other words, the representative agent model accurately describes a complex economy only under the assumption that individuals are rational enough to fully comprehend and resolve its complexity.

The second main finding of this study reveals that when firms' profits are paid to a limited number of households, referred to as "capitalists," the aggregate equilibrium output of the economy decreases significantly below the predictions of the RA equilibrium output. This outcome arises from the demand-driven nature of the Keynesian cross diagram, in combination with the assumption of heterogeneous (capitalist or non-capitalist) interacting agents. Non-capitalist households, having lower total incomes, often cannot achieve their desired levels of consumption and must draw down wealth to meet expenses. When wealth is depleted, consumption by these households declines without being offset by demand from higher-income households who accumulate excess savings. This accumulation of savings leads to a decrease in aggregate demand and production. In this case, higher rationality of households cannot improve output (and thus the predictive power of the RA model) because inequality does not arise from a coordination problem but from a structural mechanism related to income distribution. Policies that redistribute the excess savings of capitalists to low-income households tend to decrease inequality and improve aggregate output.

It is worth noting that the key results of the paper stem from the presence of multiple interacting agents and not from their heterogeneity in parameters or initial endowments. Each agent (e.g., household) is described by an individual dynamic balance sheet, which changes according to its interactions with other agents (e.g., firms). The position of initially identical agents in the network leads to endogenous heterogeneity through direct interactions and rationing processes. For this reason, representative agent models, even those incorporating some degree of heterogeneity, would be unable to generate the same outcomes.

## 2 Literature discussion

Anderson (1972) claims that "*the more the elementary particle physicists tell us about the nature of the fundamental laws the less relevance they seem to have to the very real problems of the rest of science*" and that "*the behavior of large and complex aggregates of elementary particles is not to be understood in terms of a simple extrapolation of the properties of a few particles*." Adjusting these considerations to economics, one faces at least two additional complications: (1) there are no fundamental laws for the elementary particle in economics (i.e., humans), (2) these elementary particles are able to adapt their behavior to changes in the symmetry of the system. This last characteristic has often been considered as the essential attribute of the human being,[2] and has been usually called "rationality," also by economists. The rationality hypothesis [see, e.g., Arrow (1991)] implies that agents are intelligent enough to smooth out the complexity given by the network structure, and that, therefore, economists do not have to care too much about it. About rationality in economics, see for instance (Becker 1962) for a seminal introduction of the topic, Russell and Thaler (1985) for a study of the implications of irrationality, Conlisk (1996) for an interesting review on incorporating bounded rationality in economic models, and all the pioneering work of Herbert Simon in this field, e.g., Simon (1955).

In fact, the "representative agent" and the "rationality" hypotheses often coexist in general equilibrium models,[3] and Arrow Kenneth (1986) talks of the two as "auxiliary assumptions." A representative agent can actually represent a multiplicity of humans only if they are rational enough to take always the best decisions. The question about the limitations of the representative agent description has been addressed by several authors, as Clower and Leijonhufvud (1975); Leijonhufvud (1993); Kirman (1992, 2010), or Hartley James (1996) for an historical perspective. The main story is that the RA assumption is not a costless simplification, as it often leads to conclusions which are misleading and even wrong. Kirman (1992) notes how in textbook models, "*without any precise results on the relation between the properties of individual and aggregate demand behavior, the easiest way to proceed was simply to assume that the whole economy behaved as one individual*," concluding that "*all basic production and consumption can be subsumed under the activity of one amoeba-like individual who owns the one firm and consumes what it produces*." This study follows Kirman's advice, trying to revive the individuals stuck together into the glutinous amoeba of a textbook aggregate model, giving them back their multiplicity.

There are examples in the literature extending RA models, like Arifovic and Yıldızoğlu (2019) who start from a setting inspired by Kydland and Prescott (1977) to show the effects of introducing class of agents with different mental approaches, or papers that study the deviations from rational-expectations equilibrium outcomes

[2] According to a classical philosophical perspective, initiated by Aristotle (e.g., Nicomachean Ethics I.13) and accepted by scholasticism, Kant, and many other scholars, the essence of human beings consists in "rationality," making them different from all other animals.

[3] For example, DSGE models traditionally treated a society of utility-maximizers as if it consisted of a single "representative" individual (see, e.g., Christiano et al. (2005) and Smets and Wouters (2003)).

in the case of agents with adaptive behavior (see (Arifovic 2000) for a review). Asano et al. (2021) develop an extended version of the Ramsey model where the dynamics of households is embedded in a social network and inequality arises. Several works have explored how to compare agent-based models with representative agent models, also seeking intermediate solutions. Assenza and Delli Gatti (2013) embed an agent based model in an optimizing IS-LM framework, while Lengnick (2013) and Guerini et al. (2018) present agent-based models that can be compared to a DSGE counterpart. The latter concludes that in the centralized scenario the economy comes back to the full-employment equilibrium, thus exhibiting a dynamics consistent with standard DSGE models. However, in a fully decentralized regime, the economy fluctuates around a underemployment equilibrium. Unlike (Guerini et al. 2018), who report results limited to a complete network, this article examines how the results change as the underlying structure of network interactions varies. Di Domenico (2023) presents a multi-agent extension of the Sraffian supermultiplier model, developed by Serrano (1995), showing the effect of multiplicity in firms. While the current study concentrates on the short-term effects of different rationality endowments, Di Domenico (2023) analyzes the long-term implications of multiplicity on the degree of capacity utilization. In general, the main innovation of the current paper with respect to the cited literature is that results are simply driven by mechanical balance sheet interactions between agents, emerging from the mere introduction of a network, and not from different behavioral characterizations or heterogeneity. In addition, the model's structure is simple enough to facilitate a clear reconstruction of causal relationships, and to demonstrate how the results vary based on agents' degrees of rationality and network's symmetry.

Rationality in the paper is defined as the capacity of the agent to understand and adapt to the irregularity of the network, which reflects the complexity of market interactions. RA macroeconomic models do not need to define this type of rationality,[4] because their network structure is extremely simplified, and agents do not face any relevant choice related to their direct interactions. The trade-off between complexity and rationality may be interpreted through the lens of Gode and Sunder (1993), who present markets as partial substitutes for individual rationality. They demonstrate that allocative efficiency largely derives from market structure, independent of traders' motivation, intelligence, or learning. In the current paper, the concept of allocative efficiency can be defined as the state in which individuals are able to allocate their consumption over firms in order to maximize the total output. Like in Gode and Sunder (1993), the level of individual rationality and the structure of the market (here played by the network) both contribute to determine the "allocative efficiency," and for some particular network structures, a modest level of rationality may be sufficient to get close to the optimal allocation.

Arrow Kenneth (1986) states that "*the homogeneity assumption seems especially dangerous...*," as "*...it takes attention away from a very important aspect of the economy, namely, the effects of the distribution of income and of other individual characteristics on the working of the economy*." This paper examines the impact of

[4] Alternatively, we could claim that they implicitly assume the highest degree of rationality, able to discern even the most complex network structure.

the "homogeneity assumption" on aggregated output, or more precisely, the influence of the even stronger representative agent assumption. Describing the economy as consisting of a multiplicity of agents leads necessarily to endogenous heterogeneity, which, as Arrow predicted, affects the functioning of the economy, its distributional properties, and its aggregate outcomes.

From a methodological point of view, this work is based on an agent-based model that extends the Keynesian cross diagram, including an explicit network structure. LeBaron and Tesfatsion (2008) argue that the agent-based computational economics (ACE) methodological approach provides macroeconomists "with a tremendous flexibility to tailor the breadth and depth" of the agents in their models. In recent times, several macroeconomic studies, based on the ACE methodology, flourished in the literature,[5] proposing an alternative paradigm to the so-called New Consensus Macroeconomics. However, the dialogue between the two approaches has been largely unsatisfactory thus far,[6] due in part to the difficulty of comparing two perspectives that have very different starting points. In this regard, the current paper allows a direct comparison of the Keynesian cross diagram with its multi-agent extension, thereby enabling an understanding of the circumstances under which the two models differ and the value added of the multi-agent version in different scenarios. As noted by Rahmandad and Sterman (2008) in the field of contagious disease diffusion, a comparison of agent-based and differential equations models should guide the choice of models for policy analysis. In future works, the "disaggregation" methodology proposed in this paper may be extended to other workhorse macroeconomic models in the literature.

This paper is structured as follows. Section 3 presents both the core RA model and its MA extension. Section 4 presents and discusses results. In particular, section 4.1 analyzes the effects of symmetry and rationality, while Sect. 4.3 introduces capitalists in the economy. The conclusions provide a critical synthesis of the paper, along with basic policy implications and potential future developments.

## 3 The models

This section describes the "disaggregation" process that transforms the standard Keynesian cross diagram into an extended multi-agent model, incorporating multiple interacting agents. The baseline dynamic version of the Keynesian cross diagram, or core model, is outlined in Sect. 3.1. Section 3.2 incorporates heterogeneity into household consumption functions as an intermediate step before accounting for explicit interaction between agents. Section 3.3 presents the complete multi-agent model, which reduces to the core model when only one household and one firm exist, thereby serving as a generalized version of the Keynesian cross diagram.

[5] A non-exhaustive list of macroeconomic agent-based models (ABMs): (Domenico et al. 2005; Dosi et al. 2010; Cincotti et al. 2010; Dawid et al. 2014; Russo et al. 2015; Petrović et al. 2020). Dawid and Delli Gatti (2018) provide a survey on this topic.

[6] Richiardi (2017) proposes a general reflection on the present and the future of agent-based modelling, while Fagiolo and Roventini (2017) provide a critical comparison between the ABM and the DSGE approaches (the comparison is written by ABM advocates, but I am not aware of any similar work written by DSGE researchers).

### 3.1 The core

The so-called Keynesian cross diagram constitutes the dominant paradigm in basic macroeconomics textbooks. The model assumes that the aggregate demand of consumption goods can be described as the sum of a constant component $c_0$, and another one proportional to income: $c_1 Y$. When production is lower than the aggregate demand, the excess demand drives it toward the equilibrium level, through the depletion of inventories. When production is higher than demand, the excess supply generates an accumulation of inventories and a consequent decrease in production toward the equilibrium level. The typical representation of the aggregate demand function is: $Z = C + G + I + NX$.[7] To the scope of this paper, it suffices to focus on consumption, which is the only endogenous component of demand in the basic Keynesian cross diagram.[8]

When production $Y$ is equal to aggregate demand $Z$, which coincides to consumption $C$ in our simplified model, the economy is in equilibrium and the corresponding output can be defined as: $Y^* = \frac{c_0}{1-c_1}$. If $Y_0$ is the initial level of income, the dynamic version of the model becomes:

$$\begin{cases} Y(t+1) = c_0 + c_1 Y(t) \\ Y(0) = Y_0 \end{cases} \tag{1}$$

In the spirit of the Keynesian cross diagram, firms adapt production to demand. In particular, firms produce at time $t+1$ an amount of goods equal to the demand they faced at time $t$. The globally stable solution of system (1) is

$$Y(t) = \left( Y_0 - \frac{c_0}{1 - c_1} \right) c_1^t + \frac{c_0}{1 - c_1}, \tag{2}$$

converging asymptotically to $Y^* = \frac{c_0}{1-c_1}$, which is the autonomous spending ($c_0$ in this case) multiplied by the Keynesian multiplier.

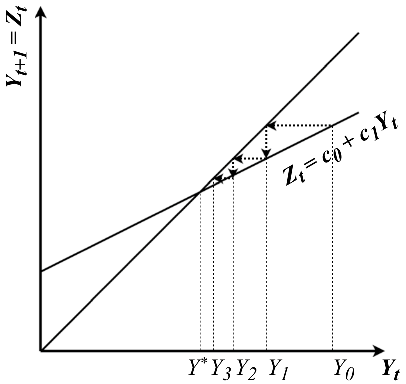
This simple dynamic model represents explicitly the convergence process toward the equilibrium of the static Keynesian cross diagram, as shown in Fig. 1a, where the case of initial excess supply, $Y_0 > Z(Y_0)$, is presented. Firms accumulate inventories, decrease production to $Y_1$, still lower than $Z(Y_1)$, thus leading to a further reduction of production, until the final equilibrium $Y^*$ is asymptotically reached.

Figure 1b shows the simple topology of the aggregated model, that we can think as one representative household that provides labor to a representative firm, receiving income, and consumes it according to its linear consumption function. The topology of the model will be further examined in Sect. 3.3.

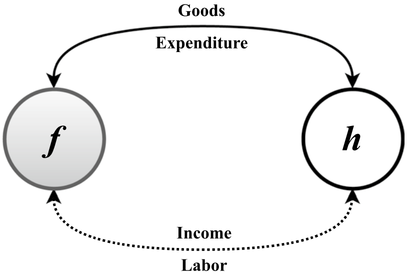
One of the main assumptions of this short-run model is that the price level is constant, determining de facto a correspondence between real and nominal variables.

[7] $C = c_0 + c_1 Y$ is consumption, $G$ public spending, $I$ investments, $NX$ net exports.

[8] I am not interested here in the economic relevance of the components of aggregate demand but only in their functional role. Thus, I do not distinguish between the different exogenous components, which are eventually reduced to $c_0$.




(a) Dynamics.




(b) Topology

**Fig. 1** The Keynesian cross diagram

All the models presented in the paper preserve this feature of constant price and therefore a substantial equivalence between real and nominal variables. Henceforth, I will conventionally call the model described in Eq. (1) as the Representative Agent model, or simply the RA model.

## 3.2 Statistical heterogeneity

The purpose of this section is to highlight the contrast between two types of heterogeneity in economic modeling: statistical heterogeneity, which involves economic agents possessing diverse characteristics, and network heterogeneity, which involves agents distributed in a particular topology and interacting directly based on their connection structure.

Even without introducing an explicit topology in the model, it can be shown that the presence of statistical heterogeneity weakens the "predictive power" of the representative agent core model. In other words, the equilibrium income $Y^* = \frac{c_0}{1-c_1}$ is no more valid if propensity to consume is heterogeneous. Let's assume that $\boldsymbol{c_1}$ and $\boldsymbol{c_0}$ are vectors containing the propensity to consume and autonomous consumption, respectively, of the $N$ households in the economy. Coherently with (1), the law of motion of output is $Y(t+1) = \sum_h^N \left[c_{0\,h}(t) + c_{1\,h}(t)y_h(t)\right]$, where $y_h(t)$ is the income of household $h$ at time $t$, or the $h^{\text{th}}$ element of the vector of income $\boldsymbol{y}\,(t)$. It can be simply written as $Y(t+1) = C(t) = \sum_h^N c_{0\,h}(t) + \sum_h^N c_{1\,h}(t)y_h(t)$, where $C(t)$ is aggregate consumption. To stick to the original Keynesian cross diagram, let's drop the time dependence of the parameters.

The first term of the equation, the aggregate autonomous consumption $\sum_h^N c_{0h} = c_0$, can be described by the average autonomous consumption across households ($\bar{\mathbf{c}}_\mathbf{0}$), multiplied by $N$, i.e, $c_0 = \bar{\mathbf{c}}_\mathbf{0}N$. However, in the second term there is an interaction between income and propensity to consume. The average propensity to consume (or the representative one) is no more able to describe the aggregate consumption function. In particular, $C(t) = c_0 + \sum_h^N c_{1h} y_h(t)$, or $C(t) = c_0 + \mathbf{c}_1^\top \cdot \mathbf{y}(t)$, where $\mathbf{c}_1^\top$ is the transpose of $\mathbf{c}_1$.

Considering that the covariance between $\mathbf{c}_1$ and $\mathbf{y}(t)$ can be written as $\sigma\left(\mathbf{c}_1, \mathbf{y}(t)\right) = \frac{1}{N}\mathbf{c}_1^\top \cdot \mathbf{y}(t) - \bar{\mathbf{c}}_1 \bar{\mathbf{y}}(t)$, which becomes $\sigma\left(\mathbf{c}_1, \mathbf{y}(t)\right) = \frac{1}{N}\mathbf{c}_1^\top \cdot \mathbf{y}(t) - \bar{\mathbf{c}}_1 \frac{Y_t}{N}$, then the aggregate consumption of the economy can be expressed as $C(t) = \bar{\mathbf{c}}_0 N + \bar{\mathbf{c}}_1 Y_t + N\sigma\left(\mathbf{c}_1, \mathbf{y}(t)\right)$, and the dynamics of the model becomes:

$$\begin{cases} Y(t+1) = c_0 + c_1 Y(t) + N\sigma\left(\mathbf{c}_1, \mathbf{y}(t)\right) \\ Y(0) = Y_0 \end{cases} \tag{3}$$

The first two terms are the ones used in the representative agent (RA) model, described in Eq. (1), but the third term depends on agents' heterogeneity. If the propensity to consume of households is negatively correlated with their income ($\sigma\left(\mathbf{c}_1, \mathbf{y}(t)\right) < 0$), then the RA consumption function is overestimating the correct one. If it is positively correlated with income ($\sigma\left(\mathbf{c}_1, \mathbf{y}(t)\right) > 0$), then the RA consumption function of Eq. (1) is underestimating the correct one. Only if the propensity to consume is scarcely correlated with income ($\sigma\left(\mathbf{c}_1, \mathbf{y}(t)\right) \sim 0$), then the RA consumption function is close to the correct one. If we assume that the covariance is bounded, i.e., $\forall t,\ \sigma\left(\mathbf{c}_1, \mathbf{y}(t)\right) \in [-\sigma_m, \sigma_M]$, then the equilibrium output will be in the range: $Y^* \in \left[\frac{c_0 - N\sigma_m}{1-c_1}, \frac{c_0 + N\sigma_M}{1-c_1}\right]$, and the interaction between propensity to consume and income could be interpreted as a sequence of shocks to aggregate demand, which determine the final equilibrium output within that range. It is worth noting that, according to the Consumer Expenditure Surveys,[9] propensity to consume is lower for higher quantiles of income, implying an overestimation of output by the RA model. Jappelli and Pistaferri (2014) confirm these findings for the Italian Survey of Household Income and Wealth.

### 3.3 The topology

The simple topology of Fig. 1b shows a representative household that consumes from a representative firm that, in turn, transfers its revenues back to the household. In this section, the RA will be replaced by a multiplicity of households $h$ and firms $f$, belonging to some given sets $H$ and $F$, respectively. The economy will be then composed by $|H|$ households and $|F|$ firms, where the vertical bars denote the cardinality of the sets. In order to provide some symmetry to the models, the total number of households will be generally considered as a multiple of the total number of companies, i.e., $|H| = \alpha |F|$.

As "each unhappy family is unhappy in its own way," introducing a plurality of agents opens up many potential configurations of the model, in terms of individual attributes, topology of the network and interaction patterns. Therefore, several choices must be made regarding the specific characteristics of each agent (heterogeneity definition) and the way they interact (network definition). The number of parameters will then depend on the degree of heterogeneity and on the complexity

[9] The Consumer Expenditure Surveys program provides data on expenditures, income, and demographic characteristics of consumers in the United States: https://www.bls.gov/cex/home.htm.

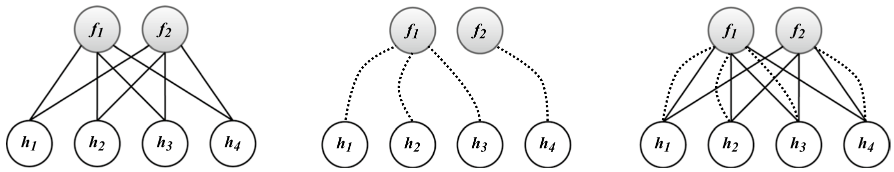



**Fig. 2** An example of the topology of the model with 4 households and 2 firms. The continuous lines represent consumption links, while the dotted lines are job links

of interactions. The rationale for designing the model has been to stick as much as possible to the original Keynesian cross diagram, in order to be able to compare the aggregated and the "disaggregated" models in a meaningful way, assessing the net effect of the introduction of a multiplicity of agents, embedded in some given topology, on the model outcomes. To minimize the complexity of the agent-based model, no heterogeneity in the parameters of the households has been introduced.

The topology of the model can be represented as a dynamic, bipartite graph $G(V, E)$, where there is no direct interaction among agents of the same category. The vertex set $V$ can be partitioned into two subsets $H$ and $F$, households and firms, and every edge $e \in E$ has one end in $H$ and one end in $F$. Such a partition $(H, F)$ is called a bipartition of the graph $G$, while $H$ and $F$ are its parts. Also the edge set $E$ can be partitioned into two subsets $E_{\mathrm{C}}$ and $E_{\mathrm{J}}$, representing consumption and job links, respectively. An incidence function $\psi$ associates with each edge of $G$ a pair of vertices of $H$ and $F$. In particular, if $e_{\mathrm{C}} \in E_{\mathrm{C}}$ is an edge, $\psi(e_{\mathrm{C}}) = (h,f)$, with $h \in H$ and $f \in F$, shows the existence of a consumption link between household $h$ and firm $f$. In a similar way, if $e_J \in E_J$, $\psi(e_J) = (h,f)$ shows that household $h$ is working in firm $f$.

Figure 2 presents an example of a bipartite graph with 4 households and two firms. Each household works in one firm, receiving its revenues as income, and consumes from all firms.

In the computational experiments, the number of households $|H|$ and firms $|F|$ is kept constant. Also $|E_{\mathrm{J}}|$ and $\psi(e_{\mathrm{J}})$ do not change over time, meaning that a firm has always the same number of employees. The only dynamics in the topology of the graph regards $|E_{\mathrm{C}}|$ and $\psi(e_{\mathrm{C}})$, which can vary over time. As it will be shown in Sect. 3.5, households can modify their consumption links according to different levels of rationality, from a zero-intelligence scenario to more rational behaviors. For instance, if a household happens to be rationed by a firm, it will generally cut the consumption link with that firm, looking for another one with higher availability of products. In more formal terms, the dynamics in the topology of the model from time $t$ to $t+1$ can be described as $G(t+1) = G(t) \cup E^{+}_{\mathrm{C}}(t) \setminus E^{-}_{\mathrm{C}}(t)$, where $E^{+}_{\mathrm{C}}(t)$ and $E^{-}_{\mathrm{C}}(t)$ are the subsets of edges which are added or cut in time $t$, respectively.

### 3.4 Balance sheets

Households and firms have dynamic interactions that are directly derived from the Keynesian cross diagram of Eq. (1). Firms distribute revenues, in form of income, to

**Table 1** Agents' balance sheets

| Household $h$ | | Firm $f$ | |
|---|---|---|---|
| **Assets** | **Liabilities** | **Assets** | **Liabilities** |
| $w_h$: wealth | $e_h$: equity | $s_f$: inventory | $e_f$: equity |

households, who spend it to buy firms' products. These two payments, from firms to households and from households to firms, flow through job links and consumption links, respectively, according to the topology of the model. These flows determine the law of motion of the balance sheet items of the agents,[10] which are presented in Table 1.

Household's wealth is augmented by income and depleted by consumption: $w_\mathrm{h}(t+1) = w_\mathrm{h}(t) + y_\mathrm{h}(t) - c_\mathrm{h}(t)$. At the same time, wealth constitutes a budget constraint for consumption,[11] as no debt instrument is designed in the model. Therefore, net worth $e_h$ is the only liability in household's balance sheet.

In a similar way, firm's inventory $s_f(t)$ is augmented by production and depleted by sales[12]: $s_\mathrm{f}(t+1) = s_\mathrm{f}(t) + y_\mathrm{f}(t) - r_\mathrm{f}(t)$. Inventories act as a buffer for firms, which allow them to sell more goods than their current production, i.e., at time $t$ firm $f$ can sell a maximum amount of goods equal to $s_\mathrm{f}(t) + y_\mathrm{f}(t)$. Households can be rationed if a firm runs out of stocks. Firms cannot take loans either, and their equity is always positive and equal to inventories. The gap between production and sales represents the deviation from the equilibrium of the economy, both at the micro level, where $\delta_f(t) = y_f(t) - r_f(t)$ is the accumulation of inventories of firm $f$, and at the macro level, where $\Delta(t) = Y(t) - R(t)$ is the aggregate excess supply.

### 3.5 Behavior and rationality

In the core model presented in Sect. 3.1, the dynamics of the economy is determined by excess demand. When there is a shortage of demand, the representative firm responds by reducing production, leading to an accumulation of inventories. Conversely, when there is excess demand, the firm increases production, depleting inventories. The representative consumer, which generates the aggregate demand, behaves according to: $Z(t) = c_0 + c_1 Y(t)$.

When considering multiple agents, I apply the same behavioral rule, but account for each household's local budget constraint. As a result, the demand for goods of each of the $|H|$ households in the economy at time $t$ is given by:

$$z_\mathrm{h}(t) = \min\left[c_{0\mathrm{h}} + c_{1\mathrm{h}} y_\mathrm{h}(t), w_\mathrm{h}(t)\right], \tag{4}$$

10 see (Teglio et al. 2010) for more details on the balance sheet approach in agent based models.

11 see Sect. 3.5 for details.

12 Sales are equal to revenues, and they are indicated by $r_\mathrm{f}$.

**Table 2** Households' behavioral schemes

| Households rationality[a] | N of links[b] | Consumption links dynamics[c] $e_{Ch}(t+1)=e_{Ch}(t)\cup e^{+}_{Ch}(t)\backslash e^{-}_{Ch}(t)$ |
|---|---|---|
| Ø intelligence (random links) | $\frac{\lvert F\rvert}{2}$ | $e^{-}_{Ch}(t)=\mathcal{R}_{h}[\psi^{-1}(h,F_{h}(t),t)]$ |
| | | $e^{+}_{Ch}(t)=\mathcal{R}_{h}[\psi^{-1}(h,\overline{F_{h}(t)},t)]$ |
| Ø intelligence (fixed links) | $\frac{\lvert F\rvert}{2}$ | $e^{-}_{Ch}(t)=\emptyset$ |
| | | $e^{+}_{Ch}(t)=\emptyset$ |
| Bounded rational | $\frac{\lvert F\rvert}{2}$ | $e^{-}_{Ch}(t)=\psi^{-1}(h,F_{h}(t),t)\mid\delta(h,f\in F_{h}(t),t)>0$ |
| | | $e^{+}_{Ch}(t)=\mathcal{R}_{h}[\psi^{-1}(h,\overline{F_{h}(t)},t)]$ |
| Semi rational | $\frac{\lvert F\rvert}{2}$ | $e^{-}_{Ch}(t)=\psi^{-1}(h,F_{h}(t),t)\mid\delta(h,f\in F_{h}(t),t)>0$ |
| | | $e^{+}_{Ch}(t)=\begin{cases}\mathcal{R}_{h}[\psi^{-1}(h,\overline{F_{h}(t)},t)] \iff \exists f\in F_{h}(t)\mid\delta(h,f,t)>0\\ \emptyset \iff \nexists f\in F_{h}(t)\mid\delta(h,f,t)>0\end{cases}$ |

[a]The definitions are purely qualitative and are intended solely to label household behaviors

[b] This is the number of initial consumption links used in the simulations presented in this paper. Our results are robust to variations in this number. For example, if bounded rational agents have fewer initial links (i.e., $|F|/4$) or if zero intelligent agents have more initial links, the conclusions of the paper remain valid. Initially, each household randomly assigns its consumption links to $|F|/2$ different firms

[c]Here $e_{Ch}(t)$ is the set of consumption links (edges) of household $h$ at time $t$; $e^{-}_{Ch}(t)$ and $e^{+}_{Ch}(t)$ are the sets of lost links and new links at time $t$, respectively; $\mathcal{R}_{h}[A]$ is a function that returns one random element from the set $A$ according to a uniform distribution; $F_{h}(t)$ is the subset of firms connected to household $h$ at time $t$; $\psi^{-1}$ is an inverse incidence function that, given an household $h$ and a subset of firms $F_{x}$, returns all the potential edges between $h$ and each member of $F_{x}$; $\overline{F_{h}(t)}$ is the complement of subset $F_{h}(t)$, corresponding to the firms that are not connected to $h$; $\delta(h,f,t)$ is the excess demand of household $h$ with respect to firm $f$ at time $t$

where[13] $\sum_{h=1}^{|H|} c_{0h}=c_{0}$, $\frac{1}{|H|}\sum_{h=1}^{|H|} c_{1h}=c_{1}$, $\sum_{h=1}^{|H|} y_{h}(t)=Y(t)$, and $w_{h}(t)$ is the total wealth of household $h$ at time $t$. Equation 4 shows that household $h$ cannot consume more than its total wealth.

Household $h$, given its consumption link set $e_{Ch}$, purchases desired consumption goods according to Eq. (4), with equal shares from all connected firms. Each household can change the allocation of its consumption budget among existing firms by modifying the set $e_{Ch}$. For instance, if household $h$ is rationed by firm $f_1$, it can remove the consumption link with firm $f_1$ from the set $e_{Ch}$ and establish a new connection with another firm $f_2$. This decision regarding consumption allocation is influenced by the level of rationality of the household, as defined in Table 2, and occurs over the production period (i.e., every time $t$). This paper studies the impact of different levels of household's rationality on the equilibrium output of the economy. The first two levels of rationality, called "zero-intelligence," refer to households never changing their consumption links set, or doing it randomly. In both cases the rationality of households is "zero" because they do not adapt to any economic input, or information. "Bounded rational" households stop purchasing from a firm if they have been rationed by it, randomly choosing

[13] As explained in section 3, $c_{0h}$ and $c_{1h}$ are assumed equal across households in all the presented scenarios.

a new firm to connect with, thus maintaining a constant number of links. In the "semi-rational" case, households behave similarly, but they only establish connections with new firms if they are unable to consume their total desired amount $z_{\mathrm{h}}(t)$. In other words, if a household can satisfy its desired consumption from its current set of firms, it may permanently reduce the number of firms from which it purchases. Table 2 presents the four rationality endowments with respect to the dynamics of consumption links in a more formal way. The network is initialized with a given amount of consumption links per household, which are iteratively and randomly assigned to non-connected firms according to a uniform distribution. Concerning job links, they are one per household, as I assume that each household can be employed by just one company.

It is worth noting that the concept of households' rationality in this paper is not arbitrary, but rather it derives naturally from the disaggregation process. When there is only one firm and one household in the economy, it does not make sense to speak of the allocation of consumption across firms. However, when multiple households and firms exist, it becomes necessary to define the behavior of each household and, consequently, to define its rationality. Therefore, the introduction of this specific concept of rationality is not an optional feature of the model, but rather a necessary step.

In line with the Keynesian cross diagram, firm $f$ plans a production equal to past demand, which is the sum of customers' demands, i.e., households connected to the firm through a consumption link $e_{\mathrm{Cf}}(t)$. Therefore, if $H_{\mathrm{Cf}}(t)$ is the set of customers of firm $f$ at time $t$, defined as $H_{\mathrm{Cf}}(t) = \{h \mid h \in \psi(e_{\mathrm{Cf}}(t))\}$, the demand faced by firm $f$ is

$$z_{\mathrm{f}}(t) = \sum_{\mathrm{h} \in H_{\mathrm{Cf}}(t)} z_{\mathrm{h}}(t). \tag{5}$$

However, production can be also constrained by the set of available workers, which can be defined as $H_{\mathrm{Jf}} = \{h \mid h \in \psi(e_{\mathrm{Jf}})\}$.[14] In this regard, I posit that labor productivity, denoted by $\beta_h$, is both homogeneous and constant across households. Each household is capable of producing the RA equilibrium output when employed for a standard working hour,

$$\beta_{\mathrm{h}} = \beta = \frac{1}{|H|} \cdot \frac{c_0}{1 - c_1}, \forall h \in H. \tag{6}$$

To enable firms to meet temporary spikes in demand for goods, which is consistent with the demand-driven approach of the Keynesian cross diagram, households can work overtime. The parameter *extra* determines the maximum percentage of additional time, beyond the standard working hour, that households can work. This percentage is typically regulated by laws governing the maximum working hours. Therefore, if firm $f$ employs enough workers, it produces an amount of goods equal to its past demand:

[14] I drop the time dependence here, as the employees of a firm do not change in time.

$$y_f(t+1) = \min\left[z_f(t), \beta \cdot (1 + \text{extra}) \cdot |H_{Jf}|\right]. \tag{7}$$

Equation 7 simply states that a single firm's output adjusts to the total demand for its goods, provided that there is sufficient flexibility in terms of labor supply. The MA model, like its original RA version, does not incorporate a mechanism for adjusting prices but rather assumes that demand can generally be met by the available labor force.

The revenues, or sales, $r_f(t)$ of firm $f$ are finally distributed as income to a subset of the households, which corresponds to the workers $H_{Jf}$ of the firm.[15] It is important to note that the model does not distinguish between labor and capital income, but rather focuses on the circular flow of income, similar to the original Keynesian cross.

$$\sum_{h \in H_{Jf}} y_h(t+1) = r_f(t), \tag{8}$$

For the sake of simplicity and realism, equation 8 conjectures that a household receives income only from one firm, as $\forall f \neq k$, $H_{Jf} \cap H_{Jk} = \emptyset$, with $f, k = 1, 2 \ldots |F|$.

In general, I assume that revenues are distributed to the workers of the firm in equal parts, i.e., $y_h(t+1) = r_f(t)/|H_{Jf}|$, $\forall h \in H_{Jf}$. In some cases, this assumption will be relaxed, allowing for the unequal distribution of firm's revenues, which will be associated with the presence of shareholders in a profit-making company (see Sect. 4.3).

The parameters of the model used for Monte carlo simulations are the following: autonomous consumption $c_{0h} = 0.01$, propensity to consume $c_{1h} = 0.6$, maximum percentage of extra hours worked $extra = 0.1$, number of households $N = 100$, number of firms $F = 10$.

## 4 Results and discussion

This section presents a comparison between the representative agent (RA) model and the multi-agent (MA) model. I assume the MA version reflects the "true" structure of the economy, while the RA model approximates it by ignoring the multiplicity of economic agents. The accuracy of this approximation depends on some economic characteristics, such as agent attributes and network connections. I define an approximation error that measures how closely the RA model replicates outcomes of the MA model. I then study the conditions under which this error is small, implying the RA model provides a good approximation, versus when the error is large, implying the RA model performs poorly.

Considering the MA version as the "true" model reflects the simple observation that in the real world, no representative agent exists. RA models are not intended

[15] Revenues may flow to capital holders as income, including shareholders who work for another firm. However, this scenario is not modeled in the current framework.

to study problems involving direct interactions or coordination among economic agents, but rather examine aggregate macroeconomic phenomena (see Kirman 1992 for discussion). However, since economic agents exist and interact in reality, neglecting this fact leads to inaccuracies. This paper aims to measure this loss of accuracy, which is a critical question, as Blanchard (2018) clearly notes.

The MA model can be viewed as a generalization of the RA model, collapsing to the Keynesian cross when there is a single household and firm (i.e., $|H| = |F| = 1$). Using the RA configuration may be a functional simplification in some cases, but too imprecise in others. Thus, it is valuable to investigate the trade-off between the MA model's realism and intricacy, versus the RA model's simplicity. The MA approach entails more complex modeling choices and less control over results. In contrast, the RA model risks inaccurate outcomes. To measure this inaccuracy in different scenarios, I compute the deviation of RA output from the MA model's asymptotic behavior.

We can interpret the RA equilibrium as the best possible outcome, absent frictions from agent multiplicity (see Eq. 6). The deviation of MA output from RA output then reflects the output reduction cost of having many interacting agents who are not always able to coordinate optimally.

The paper presents the main results as propositions with informal proofs. This organization arranges the section for clarity, emphasizing key findings and improving readability. The explanations of results are generally based on observations from simulation outcomes rather than strict formal proofs, which are difficult to apply in this context. The aim is to provide a conceptual discussion with insight rather than demonstrate mathematical theorems.

**Definition 1** The representative agent equivalent, or RA equivalent, of a given multi-agent model $G(V, E)$ where household $h$ is characterized by $c_{0\text{h}}$ and $c_{1\text{h}}$, and firm $f$ produces an initial output $Y_{0\text{f}}$, is defined as in Eq. (1) with $c_0 = \sum_{h=1}^{|H|} c_{0h}$ (the sum of all individual autonomous consumptions), $c_1 = \frac{1}{|H|} \sum_{h=1}^{|H|} c_{1\text{h}}$ (the average of individual propensities to consume) and $Y_0 = \sum_{f=1}^{|F|} Y_{0f}$ (the sum of the initial production of each firm). Moreover, the solution $Y_{\text{RA}}(t)$ of the RA equivalent model, obtained in Eq. (2), is called the RA solution and the limit of this solution for $t \to \infty$, or simply $Y_{\text{RA}}(\infty)$, is called the RA equilibrium.

It is worth noting that $Y_{\text{RA}}(\infty) = \frac{c_0}{1-c_1}$. Moreover, if we assume that $c_{0\text{h}}$ and $c_{1\text{h}}$ are homogeneous over households,[16] the two parameters of households can be obtained as $c_0 = |H| \cdot c_{0\text{h}}$, and $c_1 = c_{1\text{h}}$.

**Definition 2** The quasi-equilibrium of a multi-agent model $Y_{\text{MA}}(\mathcal{T})$, or simply $Y_{\text{MA}}$, is defined as the average value, computed over the time span $\mathcal{T}$, of the aggregate output trajectory when it becomes stationary.

[16] This is the standard assumption in the paper, implying the presence of multiplicity but not of heterogeneity.

Since the asymptotic behaviour of the MA model output might not be (and in general is not) a fixed point,[17] $Y_{\mathrm{MA}}$ provides an approximate measure of the level of output. By stationarity in $\mathcal{T}$ we just mean the absence of a stochastic trend. This is controlled by testing for the absence of a unit root via an augmented Dickey-Fuller test.

**Definition 3** Being $Y_{\mathrm{RA}}(\infty)$ the RA equilibrium, and $Y_{\mathrm{MA}}$ the quasi-equilibrium of a multi-agent model, the "deviation from the RA equilibrium" is defined as:

$$\Delta_Y = \frac{|Y_{\mathrm{MA}} - Y_{\mathrm{RA}}(\infty)|}{Y_{\mathrm{RA}}(\infty)} \,. \tag{9}$$

I will refer to the quantity $\Delta_Y$ also as the "prediction error of the RA model," as the "true" value to predict is $Y_{\mathrm{MA}}$.[18]

The output trajectories of the multi-agent models are obtained by running computer simulation. In the next sections I analyze results, focusing on the dependence of the prediction error $\Delta_Y$ on the different configurations of the multi-agent model. In particular, I will examine the effect of households' rationality and network asymmetries in the following section, and the effect of inequality in the subsequent one.

### 4.1 Symmetry versus rationality

The representative agent model shown in Eq. (1) can be thought of as describing the behavior of an average agent. Section 3.2 suggested that the representative agent equilibrium is a good approximation when agents have similar propensity to consume, but when agents are heterogeneous the equilibrium predicted by the representative agent model becomes less accurate. In the following computational experiments, households have identical parameter values but they can have different positions in the network. In other words, the heterogeneity in the model stems solely from the way households and firms are connected to each other. This allows to isolate the network effect in the sense of Blanchard (2018).

If we hypothesize that the asymmetry of the network, which corresponds to lower regularity in interactions between economic agents, may constitute an obstacle to the descriptive power of the RA model, then the parameter that should allow us to differentiate between different network structures is precisely its degree of symmetry. In this way, we will be able to verify how the quality of the RA model approximation depends on the symmetry of the network. For example, in the case of maximum symmetry, where a single company employs all workers (star), or in the case of identical companies employing the same number of workers (multiple stars), the RA model is expected to approximate the MA model outcome satisfactorily.

[17] The fluctuations in output are mainly due to the dynamics in the topology of the network.

[18] Since $Y_{\mathrm{RA}}(\infty) \geq Y_{\mathrm{MA}}$ for every MA model (more details in this section), then $\Delta_Y \in [0, 1]$. An alternative choice is: $\Delta_Y = \frac{|Y_{\mathrm{RA}}(\infty) - Y_{\mathrm{MA}}|}{Y_{\mathrm{MA}}}$. This formulation might be even more appropriate, as the "true" value is $Y_{\mathrm{MA}}$, however the (larger) error would not be confined in the interval [0, 1].

Therefore, an effective parameter for cataloging networks is their degree of symmetry, or regularity,[19] which we can measure with the variance in the number of workers between different companies.

$$\sigma_G = \frac{1}{|F|} \sum_{f \in F} \left( |H_{\mathrm{Jf}}| - \langle |H_{\mathrm{Jf}}| \rangle \right)^2 \tag{10}$$

Variance $\sigma_G$ is equal to zero when the network is perfectly symmetric (multi stars), and it is maximum when $|F| - 1$ firms have just one employee, which is the minimum requirement, and one firm employs the remaining $1 + |H| - |F|$ workers.

As a side note, the idea of studying the impact of symmetry assumptions is widely used in physics. According to Donoghue (1992), a proposed symmetry may be broken when some interaction does not obey it. The use of symmetry or average techniques, such as RA models, could still be useful if the interaction that breaks the symmetry is relatively small. In that case, one can analyze the theory in the limit where the symmetry is valid and treat the breaking interaction as a perturbation in a first approximation.

**Proposition 1** *If the population of the MA model is composed just by one household and one firm, if the constraint on household's wealth $w_h$ is not binding (see Eq. 4), and if the firm is able to produce the expected demand[20] then the MA model coincides with the original RA version of Eq. (1), with solution (2). In other words, the RA version model can be considered as a special case of the model when $|H| = |F| = 1$.*

The aggregate demand can be obtained combining Eq. (4) with the assumptions that $|H| = |F| = 1$ and that the wealth $w_h$ of the household is not binding (as in the original RA model). Then, the law of motion of output can be derived by introducing the aggregate demand faced by the firm (Eq. 5) into Eq. (7), along with the usual assumption of the Keynesian cross diagram that supply is always able to match demand. Therefore, Eq. (1) is obtained. Morevoer, all the simulations with $|H| = |F| = 1$ confirm that the MA model behaves exactly as the RA one.

The next step is to explore whether and how the deviation $\Delta_Y$ from the RA equilibrium depends on the degree of irregularity of the network, measured by the variance $\sigma_G$ of the number of firms' employees in randomly generated networks. Figure 3 shows the results for zero-intelligence agents of types 1 and 2, defined according to Table 2. The networks are arranged in increasing quantiles according to their value of $\sigma_G$. Therefore, each box on the right always contains networks with more asymmetrical structures relative to its left neighbor. The leftmost box only contains cases of perfect symmetry, i.e., $\sigma_G = 0$, for reasons clarified in the following proposition.

[19] The concepts of symmetry and regularity are used interchangeably throughout the paper.

[20] To produce the expected (past) demand, the term $\beta \cdot (1 + extra) \cdot |H_{Jf}|$ of Eq. 7 should not be binding. It is worth noting that the aggregate Keynesian cross diagram of Eq. 1 implicitly satisfies all these conditions.

**Proposition 2** *For every non zero intelligence definition of household's rationality (see Table 2): $\sigma_G = 0 \implies \Delta_Y = 0$. In other words, if the network structure is perfectly symmetric ($\sigma_G = 0$), the deviation $\Delta_Y$ from the RA equivalent equilibrium is equal to zero.*

In the leftmost boxes of Fig. 4a and b, characterized by $\sigma_G = 0$, the median and mean deviation from the rational agent (RA) equilibrium are always zero ($\Delta_Y = 0$).[21]

This proposition states that the equilibrium output of the RA equivalent perfectly approximates the network model when it is completely symmetrical, i.e., when all firms have the same size and therefore the same potential production. The rationale for this result is that in a scenario where all firms have the same size and are connected to consumers symmetrically (meaning each firm has the same number of households connected by consumption links), the production of each firm can be evenly split among households without any rationing of consumers. Therefore, there exists a simple configuration where all firms sell the same fraction of production to their identical customers, which guarantees achieving the RA equilibrium without any rationing of households, who purchase the same fraction of production.

The basic example is having only one firm, which sells the same fraction of production to its identical customers. In this case, there are no problems of aggregation and no reason to deviate from the RA equilibrium. The same holds for $|F|$ identical firms, which at equilibrium will have the same number of customers,[22] purchasing the same quantity of goods.

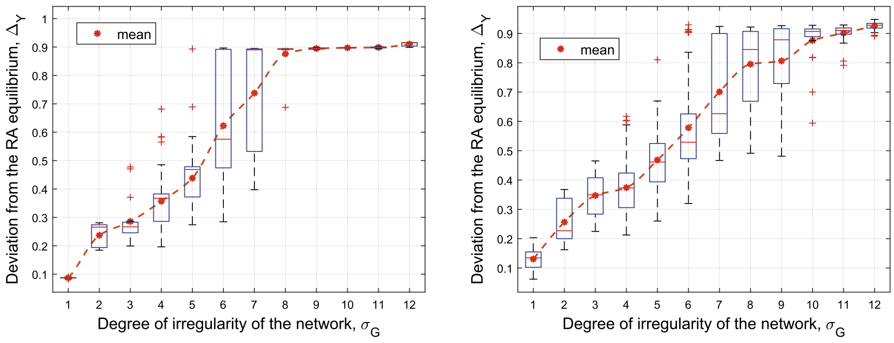
This result does not hold for zero-intelligence households (see Fig. 3) because they are unable to recognize out-of-equilibrium conditions. They are either too static (fixed links case), not reacting at all when rationed in consumption, or too dynamic (random links case), reacting even when they should not. In any case, when $\sigma_G = 0$, the deviation $\Delta_Y$ is very small even for zero-intelligence households.

**Proposition 3** *When the rationality of the households is low, the higher the regularity of the network, the smaller the deviation from the RA equilibrium.*

The proposition is validated by a visual inspection of Figs. 3 and 4a. This is one of the key results of the paper, especially if examined with Proposition 4. It shows that, even when households are homogeneous, i.e., endowed with the same parameter set, the predictive power of the RA equivalent model is poorer when the topology of the network is less regular. The main reason lies in the inefficient allocation of consumption across firms by households, due to their low rationality combined with the asymmetry of the network. If there are large and small firms in the economy, households are not able to allocate correctly their consumption budget among the

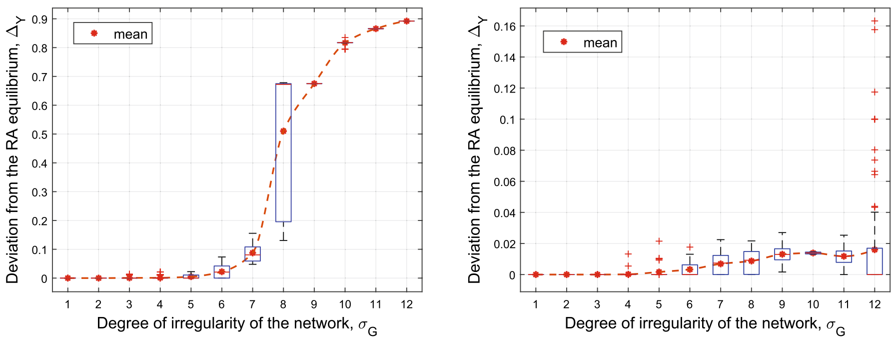
[21] Visual perception of Fig. 4 is confirmed by numerical outcomes of the computational experiments, showing that $\sigma_G = 0 \implies \Delta_Y = 0$.

[22] Consumption links for each household are $\frac{|F|}{2}$ (see Table 2).




(a) Random links (b) Fixed links

**Fig. 3** Deviation from the RA equilibrium $\Delta_Y$ as a function of the irregularity of the network $\sigma_G$. The cases of zero-intelligence agents of type 1 (random links) and 2 (fixed links) are presented




(a) Bounded rational (b) Semi rational

**Fig. 4** Deviation $\Delta_Y$ from the RA equilibrium as a function of the irregularity of the network $\sigma_G$. The cases of bounded rational and semi rational agents are presented

existing firms. This result becomes more relevant when compared to Proposition 4, and will therefore be discussed after presenting it.

**Proposition 4** *When the rationality of the households is high, the deviation from the RA equilibrium is low for every level of regularity of the network.*

The proposition is proved by visual inspection of Fig. 4b, which shows the deviation from the RA equilibrium as a function of the irregularity of the network in the case of semi-rational agents. This deviation is very small (always less than 2%), irrespective of the regularity of the network. The last two results show that the RA model is able to approximate the equilibrium output when the network of interactions is regular or when the households are rational enough. In the case neither of these conditions is fulfilled, the RA equilibrium becomes inaccurate.

The deviation from the RA equilibrium output, $\Delta_Y$, can also be viewed as an "output gap", where the RA equilibrium output represents potential output. The MA model equilibrium output is always lower, due to coordination failures in the network structure. In this perspective, households with low rationality require a very regular market structure to properly allocate demand and approach potential output. In contrast, rational agents do not need a regular structure because they can adapt to the market structure, even if irregular, thereby achieving potential output. This feature resembles the argument in Gode and Sunder (1993), where allocative efficiency depends on the market structure, which thus acts as "a partial substitute for individual rationality." In this work, a regular structure serves as a partial substitute for individual rationality.

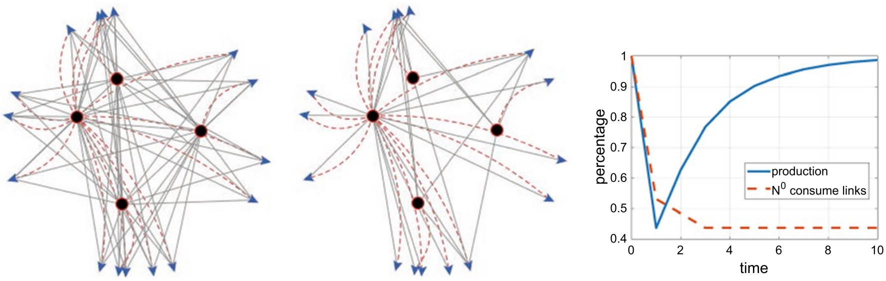
When the network is asymmetric, larger firms that employ more workers face reduced demand while smaller firms experience excess demand. This, in turn, creates income inequality among households as workers at larger firms receive less revenues. In the absence of market mechanisms to counterbalance this asymmetry—for example a labor market—large companies' sales will be below their potential production and worker incomes in those companies will decrease. Low-income workers will be unable to consume according to their desired demand, as shown in Fig. 11a, and will be forced to rely on their wealth. Once wealth is exhausted, they will be forced to reduce their consumption, leading to a decrease in aggregate output, as high-income households will not compensate for the lack of demand.[23]

It is important to emphasize that the inequalities in the model arise exclusively from an endogenous process due to the presence of the network. Although initialized with identical parameters, households acquire diversified incomes and wealth over time depending on their position within the network, which determines their different interactions.

Households' rationality acts as a mechanism that helps offset the network asymmetry. In fact, semi-rational agents orient their consumption links to purchase more from large companies where goods are available. This increases large companies' sales, revenues, wages, and reduces the output gap.

Figure 5 shows how consumption links orientate in a network consisting of four companies and sixteen semi-rational households that initially consume from all firms. One firm employs thirteen workers while the other three firms have one worker each, creating an irregular network structure. As shown in Box 5c, the economy's output initially collapses due to "coordination failure" of households consuming too little from larger firms and too much from smaller ones. However, over time semi-rational agents reduce links with small firms and focus more on larger firms, causing the aggregate output to grow towards the RA equilibrium. As seen by comparing Fig. 5a and b, the network adapts and the final consumption link structure balances out or neutralizes the initial network asymmetry.

[23] This dynamic, which leads to a reduction in output due to low-income households' lack of demand, not compensated by high-income households, is discussed in more detail in Sect. 4.3, which includes capitalists.




(a) Initial graph (b) Final graph (c) Dynamics

**Fig. 5** Sample model with 16 households (triangles) and 4 asymmetric firms (circles). Households cut consumption links (straight lines) if rationed. Production, after an initial collapse, converges to the RA equilibrium

### 4.1.1 Rationality of firms: the labor market

This section presents a brief digression from the main framework of the paper. It shows that similar results are obtained if firms, instead of households, are assumed to have higher rationality. In fact, assuming that firms do not hire or fire workers (i.e., firms exhibit low rationality) imposes a rigidity on the economic system. Relaxing this assumption by introducing a rudimentary labor market allows firms to modify employment levels based on economic feedback.

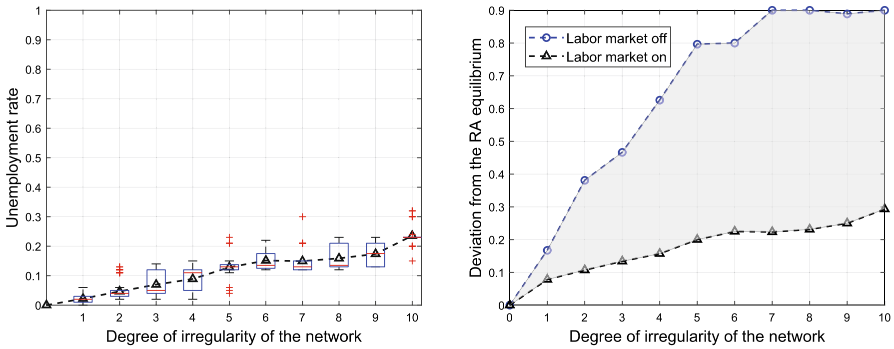
A simple decision-making process for firms is then designed: a company calculates its excess workers by comparing its current workforce to the needed workforce to produce the faced demand:

$$\Delta|H_{\mathrm{Jf}}|(t) = \mathrm{int}\left(\frac{\beta \cdot |H_{\mathrm{Jf}}(t)| - z_{\mathrm{f}}(t)}{\beta}\right). \tag{11}$$

Firms with an excess of workers ($\Delta|H_{\mathrm{Jf}}|(t) > 0$) will fire them, whereas firms facing a lack of workers ($\Delta|H_{\mathrm{Jf}}|(t) > 0$) will hire the correspondent number of workers, if available. Assuming that the goods market (consumption) goes on a weekly basis, the labor market goes on a monthly basis, i.e., firms modify their labour force every four consumption steps.[24]

The results reveal that endowing firms with higher rationality yields similar effects to those observed for households' rationality. When the network structure becomes irregular, zero intelligence households are unable to allocate consumption accurately, which leads to a rapid decrease in GDP, as illustrated in the upper line of Fig. 6b. Conversely, when the labor market is operational, firms can adjust the labor force based on adaptive expectations, leading to a significant improvement in the economy's performance (refer to the lower line of Fig. 6b). As the asymmetry of the network increases, the shaded area widens, indicating that the labor market enables firms to counterbalance the asymmetry of the economic system, similar to the

[24] This choice is mainly an aesthetic detail, but results are robust with respect to the relative frequency of the two markets. Of course, lower labour market frequency means lower overall efficiency.




(a) Unemployment rate (b) Labour/no-labour output gap

**Fig. 6** Unemployment rate (on the left) and the deviation $\Delta_Y$ from the RA equilibrium (on the right) as a function of the irregularity of the network $\sigma_G$. The shaded area represents the gap between the model with or without labour market. The cases of zero-intelligence fixed links agents is presented

approach illustrated in Fig. 5, where reallocation of consumption links is replaced by reallocation of job links.

Nevertheless, the irregularity of the network still impacts the economy's performance, as demonstrated in Fig. 6a. When the initial job link arrangement is irregular, firms attempt to correct it (as evident from the shaded area of Fig. 6b), but this results in a loss of workers, demand, and production, leading to higher levels of unemployment rate.

#### 4.1.2 On the absence of prices

The "labor market" presented in the previous section is a mechanism to determine the demand for workers by firms, with the supply consisting of all available unemployed households. The cost of labor is not explicitly considered, and firms simply distribute all their revenues to their workers, without adjusting wages. As a result, wages do not play a role as a coordination mechanism. The same is true for the price of the consumption good, as firms cannot adjust prices.

From the perspective of this work, prices can be seen as an additional form of rationality that is present in the economic system. If firms were endowed with pricing decision rationality, the economy could benefit from an additional mechanism for smoothing out the complexity of the system, similar to the other forms of rationality introduced in the paper. Although pricing mechanisms could be incorporated into the model, doing so would deviate from the paper's aim, which is to provide a simple extension of the Keynesian cross diagram. As such, the paper retains all the main properties of the original model, including the absence of prices.

### 4.2 Time series inspection

This section integrates the previous findings by examining time series generated from simulations of the MA model. The aim is to substantiate the results presented in the box-plots of Sect. 4.1, highlighting certain features that are only discernible in the time trajectories.

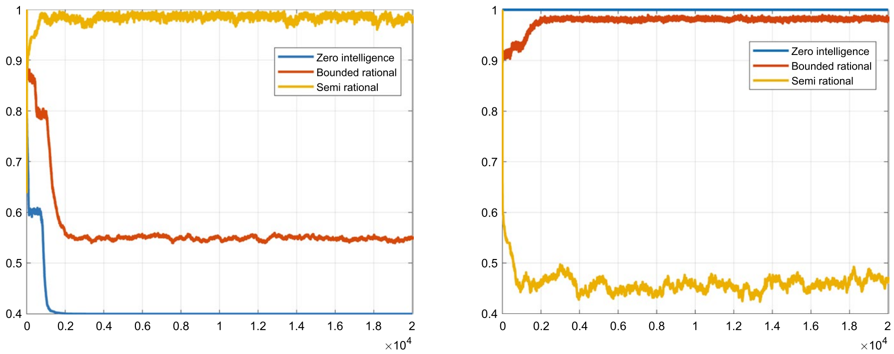
It is useful to recall that the results of the boxplots were obtained by aggregating the final values of individual trajectories when they reached a quasi-equilibrium state, as described in Definition 2. Each trajectory corresponds to a specific configuration of the network, randomly generated using appropriate initialization techniques. The various networks generated in this manner are then aggregated into different quantiles based on the dispersion measure of firms' size, as described in Eq. (10).

Figure 7a illustrates the output[25] dynamics for the three rationality schemes introduced in the paper: bounded rationality, semi-rationality, and zero intelligence. The network regularity is consistent across all three cases. Output decreases to 40% of the representative agent equilibrium in the case of zero intelligence, hovers around 55% with bounded rational households, and fluctuates just below 1 in the semi-rational case. Initially, output declines in all three cases due to a mismatch between the configuration of consumption links and firms' sizes. In other words, households tend to consume too much from smaller companies and too little from larger ones. Figure 8b shows that the output tends to decrease immediately due to an initial shock that we might call a "network configuration" shock, arising from the cited mismatch. Then, depending on the degree of rationality, the agents might be able to react to the initial "configuration" shock by adjusting consumption links to reduce individual rationing and, therefore, increase aggregate demand and production.

Returning to Fig. 7, it clearly emerges how different rationality schemes lead to different capacities for adapting to network asymmetries. In particular, Fig. 7b points out the different strategies of adaptation by showing the dynamic evolution of the aggregate number of consumption links in the economy, normalized to their initial quantity. Zero-intelligent households do not change their number of consumption links over time, being therefore unable to adapt to asymmetries in firm size. This implies a misallocation of aggregate demand, which cannot be satisfied and decreases over time due to a vicious circle of lower demand, lower production, lower distributed income, and lower demand again. More rational agents, especially semi-rational ones, can cut their links with companies that cannot serve them and consume only from companies that can satisfy their demand. Figure 7b shows that their number of consumption links decreases to less than 50% of the initial ones, pruning dead branches. Bounded rational agents also prune dead branches, but they always seek to connect with new companies, therefore being somewhat inefficient.

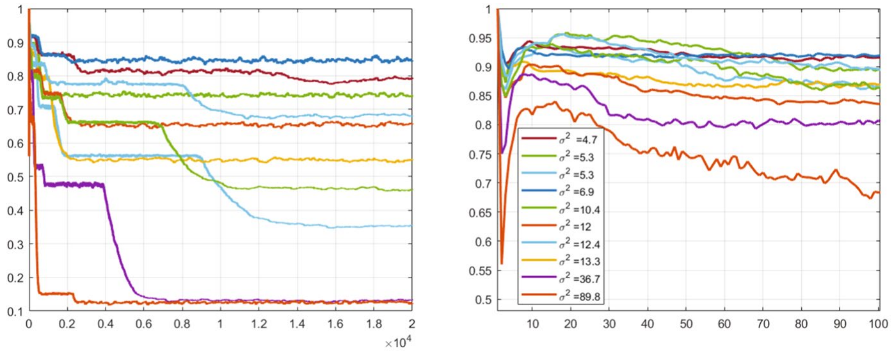
Figure 9a shows the aggregate share of planned consumption, as described by Eq. (4), that is not satisfied by firms' supply due to network irregularities. In the long

[25] Output is expressed as a percentage of the RA equilibrium.




(a) Output (b) Consumption links

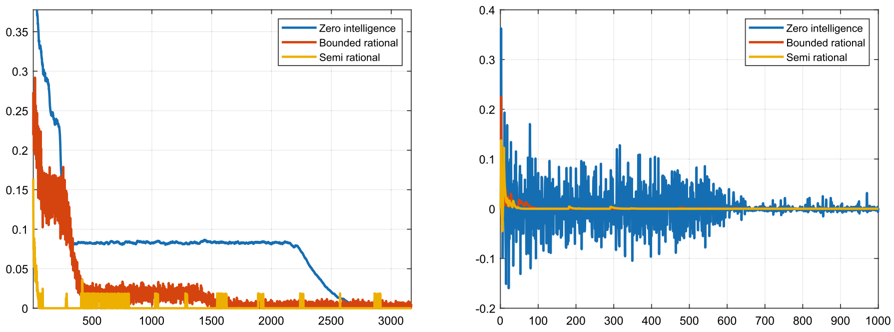
**Fig. 7** The time evolution of output, normalized to the RA equilibrium output, and the number of consumption links, normalized to their initial quantity. Results are presented for different rationality schemes and for the same network regularity




(a) Output (b) Output (first 100 periods)

**Fig. 8** The time evolution of output, normalized to the RA equilibrium output, in the case of bounded ration agents, for different firms' size variance

run, this variable, which represents an aggregate measure of household rationing, should converge to zero because at equilibrium, aggregate demand equals aggregate supply. However, what matters here is the time needed to converge to equilibrium, as it strongly affects the equilibrium level itself. Zero-intelligence agents take a considerable amount of time to reach the no-rationing condition, semi-rational agents are much quicker, while bounded rational agents fall in between. The integral of these curves should be considered to understand the effects of prolonged rationing, which implies lower sales by firms (see Fig. 7a) and lower income distributed to households. If rationing is prolonged, production will eventually be reduced due to the vicious cycle explained before. If rationing is not prolonged, as in the case of semi-rational agents, households are able to recover by resetting consumption links, counterbalancing job-link asymmetry (see Fig. 5a), and increasing aggregate demand




(a) Households' rationing (b) Firms' rationing

**Fig. 9** Aggregate measures of households and firms rationing

very close to the representative agent case. Figure 9b completes the picture by illustrating the gap between production, as defined in equation 7, and the effective sales of firms. The rationing measure for firms tends toward zero, with small oscillations observed in the case of zero intelligent agents. This behavior is due to the random nature of link movements in this specific scenario (refer to Table 2).

Finally, Fig. 8a (Fig. 8b is a zoomed-in view focusing on the first 100 time steps) presents the output dynamics as a function of the degree of regularity of the network. These figures should be interpreted in conjunction with the previous box-plots in Sect. 4.1, as they show their dynamical counterpart. When the network is more irregular, the performance of bounded rational households is weaker, for the reasons already mentioned. Nevertheless it's worth noting that the variance of Eq. (10) is an ex-post measure of a previously generated network, which does not identify it unambiguously, as it is possible to have different network configurations with the same variance. This is the reason why for $\sigma^2 = 5.3$ we observe two trajectories with different equilibrium outcomes.[26]

### 4.3 Inequality: labor and capital income

We have established that rational behavior can counterbalance the endogenous rise of income inequality. However, what happens when inequality is introduced as a structural element of the model? We achieve this by creating two categories of income that flow from firms to households: wages $l_h$ and dividends $d_h$. While all households work in the firm, standard workers receive only wages, whereas shareholders (or capitalists) receive dividends as well. Hence, each firm $f$ pays a portion of its revenue as wages $l_f$ and distributes the remainder (profits) to shareholders in the form of dividends $d_f$. To this end, I follow a standard procedure (see (Blanchard 2017)), introducing the concept of markup $\mu$ as an indicator of the proportion of

[26] Note that these values of $\sigma^2$ are rounded to the nearest tenth.

revenues paid to firms, which are subsequently distributed to shareholders. Assuming that all firms have the same markup $\mu$, the wage bill and profits (paid as dividends) of firm *f* are expressed as follows:

$$\textbf{wage bill: } l_{\mathrm{f}}(t+1) = \frac{r_{\mathrm{f}}(t)}{1+\mu}; \quad \textbf{profits: } d_{\mathrm{f}}(t+1) = \frac{\mu \cdot r_{\mathrm{f}}(t)}{1+\mu}. \tag{12}$$

It is important to note that in this context, the wage does not serve as a coordination mechanism, but rather depends solely on the exogenous markup $\mu$. The markup, in turn, represents the level of competition in the economy in a highly stylized manner.

The implications and limitations of this setting will be discussed later, when the results are presented and analyzed. Its significance in this study is primarily associated with the possibility to investigate the impact of various levels of income concentration on the economy by adjusting the markup and the percentage of capitalists in each firm.

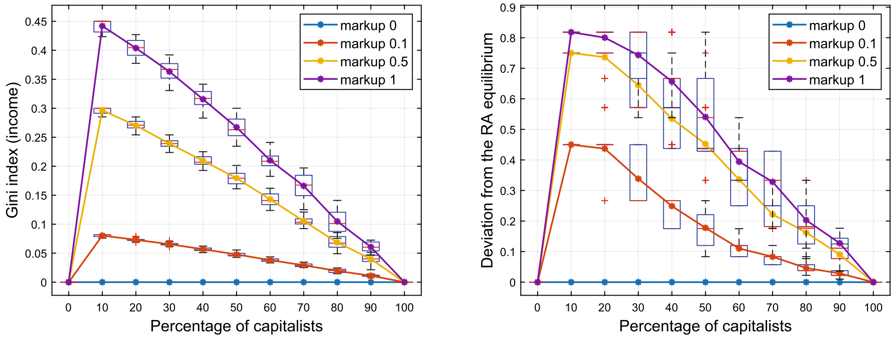
For the sake of simplicity, a few additional assumptions are introduced: (1) the shareholders of a firm *f* are also workers of firm *f*, (2) the markup and the percentage of shareholders out of total workers are static and equal for all firms; thus the number of shareholder may vary from one per firm to all workers of the firm; implying that the minimum number of shareholders in the economy is $|F|$, (3) households are semi-rational, which is the highest rationality level considered in the paper, leading to a negligible RA deviation, i.e., the RA a model is always a good approximation for homogeneous households (see Proposition 4). These assumptions can be easily relaxed and do affect only marginally the core results of this section

**Proposition 5** *In the presence of capitalists, which receive income in form of dividends, there is a significant deviation from the RA equilibrium. This deviation is larger when the markup is high and when the percentage of capitalists is low.*

This result is validated by visual inspection of Fig. 10, which present the case of an asymmetric network ($\sigma_G \neq 0$). In particular, the left box of the figure shows how the percentage of capitalists and the markup affect income inequality (measured by the Gini index), while the right box shows how they affect the deviation from the RA equilibrium $\Delta_Y$.

For a 0% or 100% percentage of capitalists, no income inequality and no deviation from the RA equilibrium arise. These two cases lead to identical outcomes in Fig. 10 because 100% of capitalists means that dividends are distributed as income to all households.

A big jump is clearly visible from 0 to 10%, corresponding to the case of one capitalist per firm, which is the minimum number of capitalists in the model. In the 10% case, income inequality is the largest and the prediction of the RA equilibrium the poorest. Going below the 10% level of capitalists would imply that some firms have no capitalists among their workers, and that a few households are shareholders of many firms. In this case inequality and deviation from the RA equilibrium would be even more pronounced. When the percentage of capitalists increase, both income




(a) Gini index (income) (b) $\Delta_Y$

**Fig. 10** $\Delta_Y$ and Gini index with respect to the percentage of capitalists in the case of semi-rational agents and symmetric network

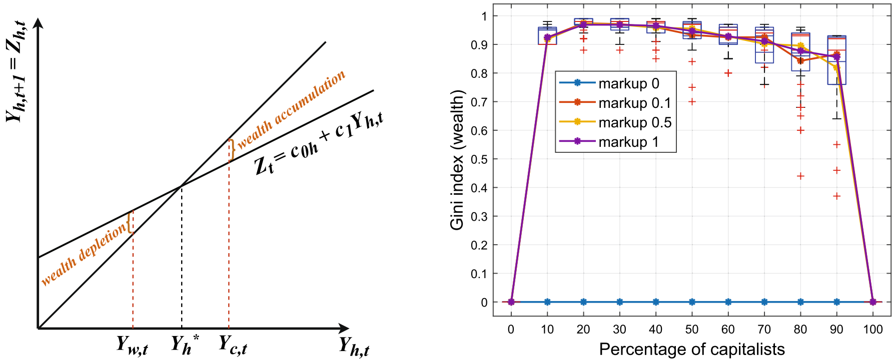
inequality and deviation from the RA equilibrium decline, until the zero inequality case of 100% capitalist is reached.

Proposition 2 remains valid under the assumption of a perfectly symmetric network and the absence of structural inequality, caused by the presence of capitalists. However, in the presence of structural inequality, Proposition 2 no longer holds, and the deviation from the RA equilibrium is significant. Even if households have homogeneous parameters and the network is symmetric, the equilibrium output is lower than the RA prediction, or potential output.

This can be demonstrated by examining Fig. 11a, which illustrates the out-of-equilibrium dynamics of the two household types, namely workers and capitalists, which have homogeneous parameters $c_{0\,\mathrm{h}}$ and $c_1$. Capitalists earn higher income ($Y_{c,t}$) and have a target consumption that is lower than their income. Consequently, they accumulate wealth (see Fig. 11b), which is not used to generate demand. On the other hand, low-income or non-capitalist workers have a demand for consumption goods that is higher than their income $Y_{w,t}$, and they must use part of their wealth to consume the desired quantity. They consume their wealth until it is depleted, at which point they are unable to purchase the target amount of consumption goods. This mechanism results in a decrease in demand by low-income workers, which reduces firms' sales, revenues, and future production, leading to a lower equilibrium output.

To be more precise, the demand of each household $h$ at time $t$ is determined by equation 4: $z_h(t) = \min\left[c_{0\,h} + c_1 y_h(t), w_h(t)\right]$. When $z_h(t) - y_h(t) < 0$, the household is consuming less than its income and accumulating wealth, and this occurs when $y_h(t) > \frac{c_{0h}}{1-c_{1h}}$. In particular, if the parameters are homogeneous across households, i.e., $c_{0\,h} = \frac{c_0}{|H|}$ and $c_{1\,h} = c_1$, this happens when $y_h(t) > y_{RA}$, where $y_{RA}$ is the RA equilibrium income per capita, represented as $Y_h^*$ in Fig. 11a. Therefore, each household with an income higher than the average accumulates wealth, as $\Delta w(t) = y_h(t) - c_h(t) > 0$, and consumes $c_h(t) \le z_h(t)$. Similarly, each low-income household depletes its wealth to achieve a desired consumption level that exceeds its income. Eventually, the household will be rationed, becoming unable to consume the desired quantity and reducing aggregate demand and production.

Figure 11b highlights the significant wealth inequality resulting from the accumulation of wealth by capitalists. The accumulation of wealth is fueled by excess




(a) Wealth dynamics (b) Wealth inequality

**Fig. 11** Wealth dynamics for **c**apitalists and **w**orkers, and wealth inequality at the equilibrium in a perfectly symmetric network

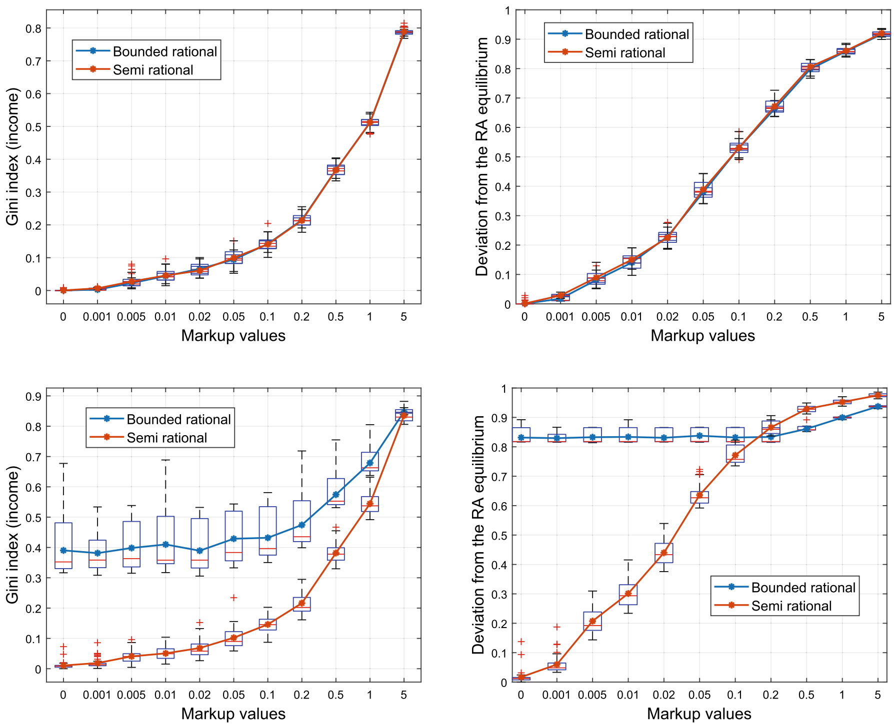



**Fig. 12** Income Gini index and $\Delta_Y$ vs. markup in regular (up) and irregular (down) networks

savings of capitalists, which do not contribute to aggregate demand and remain unused in the economy. It should be noted that the model does not account for potential measures that could mitigate the unproductive accumulation of wealth by capitalists.

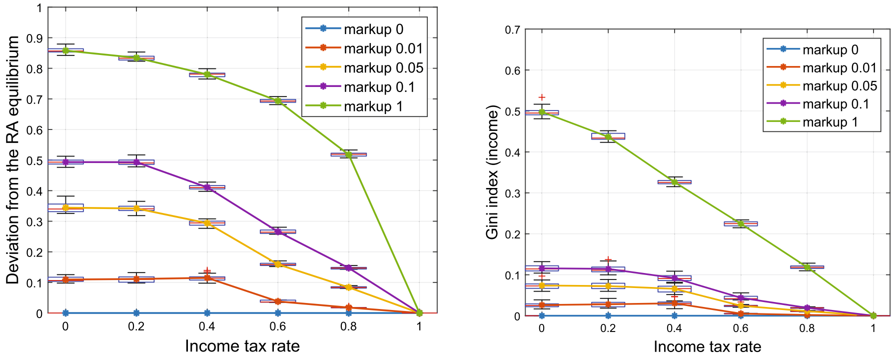
Figure 12 shows the Gini index of income and the deviation from the RA equilibrium for different level of inequality, measured by the markup. The percentage of capitalists is fixed to 10% of households. There are some non trivial interactions between rationality, regularity and inequality, which are pointed out by the figure. First, when the network is regular, i.e., firms have similar size, the economic outcomes for semi rational or bounded rational households are almost indistinguishable. This is due to the fact that rationality is not needed to behave correctly in a simple world. However, when the network is not regular, a significant difference between higher or lower rationality emerges. For low markup values, more rational agents are able to coordinate and reach a correct allocation of the consumption budget, which leads to lower inequality[27] and higher output. In particular, when the markup is zero and there are no capitalists in the economy (bottom-left of figure 12), the 0.4 value of the Gini index for bounded rational households entirely arises from the network asymmetry. Conversely, for high markup values, when inequality is mostly fostered by the presence of capitalists, and not by coordination failures triggered by the asymmetry of the network, rationality of households becomes a useless attribute to reduce the output gap.

### 4.4 Redistribution

The results of the previous section demonstrate that income concentration reduces GDP. The primary reason is that low-income households do not have sufficient resources to buy the amount of goods they desire, leading to a reduction in demand and production. This lack of aggregate demand can be addressed in the model by implementing redistribution mechanisms that allow low-income households to match their desired consumption level. The two primary tools that can serve this purpose are taxation or credit; in both cases, purchasing power would be transferred from those who have it in excess to those who lack it.

In order to host a credit sector, the model should be substantially enriched, as many essential ingredients are missing, e.g., economic growth, money, and inflation. In particular, the absence of income growth prevents households to repay any debt with positive, or even zero, interest rate. Households would actually use credit to reach their desired consumption level, but without income growth they will never be able to save in order to repay it. Conversely, designing a public sector responsible for fiscal policy is a straightforward task. To simplify matters, I assume that the government aims at zero-budget target and collects taxes, which it transfers back to households.

[27] The income inequality for bounded rational is explained by lack of coordination that leads to the existence of larger firms that do not sell enough goods and that, therefore, pay a lower salary.




(a) Gini index (income) (b) $\Delta_Y$

**Fig. 13** $\Delta_Y$ and Gini index for different values of the income tax in the case of bounded rational agents and irregular network

Out of the various possible fiscal architectures, I present an example of a government that collects taxes through a progressive tax system with a fixed tax rate $\tau$ and a tax deduction equivalent to half the average income. The government then uses all the collected taxes to provide a universal basic income, distributed equally among households.

Figure 13 displays the results, showing the Gini index of income and the output gap as a function of the tax rate. The higher the tax rate on income, the greater the redistribution of income from wealthy to poor households, leading to improved economic outcomes in terms of output and inequality. It is noteworthy that the redistribution policy remains effective even if implemented later in time, after wealth has already concentrated among a few capitalists. This is because capitalists, with lower after-tax income, may need to spend out of their wealth to attain their desired level of consumption, thereby injecting their accumulated wealth into the economy as new demand. Meanwhile, workers have sufficient income to meet their desired consumption and increase aggregate demand.

## 5 Conclusions

This study presents an extension of the Keynesian cross diagram, where the implicit hypothesis of representative agents is relaxed and the aggregate demand is the sum of local demands of multiple households. Firms and households are connected through job links and consumption links, according to network structures that can have different degrees of symmetry (or regularity). Households are endowed with several levels of rationality, which reflect their capacity of allocating the consumption budget across various firms. The model collapses into the classic Keynesian cross diagram when the number of both households and firms is equal to one.

The study sheds light on the conceptual relation between agents' rationality and the regularity of economic interactions, which can be considered as an approximation of world's complexity. If the world is complex (asymmetric network) and households are not rational enough, the GDP is lower than the potential output, which is the one predicted by the representative agent model, and corresponds to the perfect allocation of the consumption budget. If the world is less complex, or if the agents are more rational, the GDP is closer to the potential output.The paper reveals a clear and natural trade-off between the complexity of economic choices, represented by the asymmetry of the network structure, and the rationality of the agents, which corresponds to their ability to make correct decisions in a complex environment. Under this respect the study resonates with the concept proposed by Gode and Sunder (1993) that markets act as partial substitutes for individual rationality. Furthermore, the results demonstrate that the assumption of a representative agent, which overlooks coordination failures, is inadequate when the combination of bounded rationality and system complexity is significant.

The second main result of the paper concerns the impact of income inequality on GDP, in the presence of capitalists, who receive dividends from companies. The model suggests that GDP declines when income inequality is higher. This is due to the wealth accumulation process of high income households, who consume a smaller fraction of their income, even if the propensity to consume is equal for all. Symmetrically, low income households are not able to match their desired consumption because they become eventually wealth constrained. On the whole, aggregated demand becomes lower. A redistribution mechanism, here implemented by means of a government that collects a progressive tax and pays a universal basic income, reduces inequality and restores higher GDP levels.

Results should be read with a grain of salt. The presented models are the extension of an abstract framework, and the contribution of the paper should be considered under a conceptual perspective and not under an operational one. In the real world, the notion of complexity is not limited to firms' size heterogeneity or to consumption budget allocation problems. On the other hand, the rationality of human beings can be more powerful than the mere ability to solve a basic allocation problem. Nevertheless, this paper is able to quantify, in a simple and specific case, the cost of the RA assumption in terms of prediction error.

As in the original Keynesian cross diagram, the models are demand driven and do not consider the relation between capitalists' accumulated wealth and investments, which can affect both the demand and the supply sides of the economy. However, the MA extensions of the Keynesian cross diagram provide a description of the effects of income inequality on output, which the original model is not even able to conceive. Furthermore, even if capitalists' wealth can be reinvested, it is hard to imagine how it could solve the problem of the lack of consumption goods demand by low income households, at least in a model that does not envisage income growth. Capitalists' excess savings might be available for consumption of low income households at some cost, but sooner or later these households will face again wealth constraints, unless their income growth is large enough to repay the debt. These type of problems may be addressed in future developments of the model.

It might seem excessive to derive policy implications from the model, as it does not rigorously reflect the functioning of real economies. Nevertheless, I think that a few basic conclusion can be drawn: (i) income inequality generates poor economic results, especially if coupled with bounded rationality (ii) perfect rationality alone cannot defend against structural inequality, (iii) fiscal policies that redistribute income foster aggregate demand, (iv) excess savings of high income households can be detrimental to the economy.

Finally, this paper aims to develop a framework that allows for the comparability of RA and MA models, demonstrating that MA models may serve as useful extensions of RA models. The recent events with significant economic impacts, such as the financial crisis, climate change, and the Covid-19 pandemic, underscore the importance of enriching economic models in this direction. The methodology employed in this paper, applied to the Keynesian cross diagram, could be extended to other representative agent macroeconomic models, revealing limitations of the original approach and suggesting new avenues for future research.

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