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Public science vs. mission-oriented policies in long-run growth: An agent-based model

Andrea Borsato [a,b,*], André Lorentz [b]

[a] University of Bergamo, Department of Economics and Statistics, Via dei Caniana 2, 24127 Bergamo, Italy
[b] Université de Strasbourg, Université de Lorraine, CNRS BETA, Bureau d'Economie Théorique et Appliquée, 61 Avenue de la Forêt Noire, 67085 Strasbourg Cedex, France

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ABSTRACT

This paper offers a contribution to the literature on science policies and on the possible trade-off between broad science-technology policies and mission-oriented programs. We develop a multi-country, multi-sectoral agent-based model that represents a small-scale monetary union. Findings are threefold. Firstly, *symmetric* science policies from governments significantly reduce cross-country growth divergence. Secondly, even if economic growth is largely driven by the sectors with absolute advantages, having some flow of open science investments is sufficient for the other industries to survive and innovate. Thirdly, science policy limits monopolistic tendencies and reduces income inequality. Yet, the working of the model suggests that supply-side science policies should be paired with demand-side policies to meet grand societal challenges.

1. Introduction

In early 1942, the US administration appointed the Major General Leslie R. Groves and the nuclear physicist, Prof. J. Robert Oppenheimer to recruit and coordinate a vast group of scientists to the development of the atom bomb. Thus began the Manhattan Project, the first, important mission-oriented program. The challenges, the endeavours and the scientific success out of the Project inspired many Western governments to extend and implement the range of programs with similar organisations and capabilities. The European Commission (2018c, p. 2) defines *mission-oriented* initiatives as "large-scale intervention aiming for a clearly defined mission (i.e. goal or solution) to be achieved". Under the aegis of the public sector, such programs concern ambitious, exploratory, cross-disciplinary activities to address societal and technological targets, from the development of the computer industry (Mowery and Langlois, 1996) and the Apollo Program (Mazzucato, 2011) across the Fifties and the Sixties, up to contemporary challenges, i.e., energy and climate change (Anadón, 2012; Mowery et al., 2010). At the same time, governments spend considerable funds on basic research in universities and institutes, and there is extensive evidence that basic research provides direct as well as indirect economic benefits (Ergas, 1987; Salter and Martin, 2001).

However, the analysis of a possible trade-off between broad spectrum science and technology (S & T) policies and the research with a mission orientation is still scant in the economic literature.[1] Even scantier is the analysis of the impacts of such policies and their plausible trade-off at a macroeconomic level on economic growth, structural change, and specialisation patterns. On the one hand, an increasing body of literature focusses on the European Monetary Union to discuss what regulatory framework and what policies could fuel economic growth, debt sustainability, and also reduce income inequality (Carnevali et al., 2019, 2021; Ciarli et al., 2010; Sawyer and Passarella, 2021). On the other hand, there is the stream of research that investigates public research and innovation policies within countries (Mazzucato, 2016). The latter has often showed the importance of targeting investments to the pursuit of specific *missions*, as witnessed by extensive analyses on the US economic history (Mowery and Rosenberg, 1999). It is also true that lots of microeconometric evidence highlights that corporate practitioners draw heavily on research performed in domestic universities and other public organisations as source of knowledge to back their innovative activity (Arora et al., 2015; Arundel and Geuna, 2004; Beise and Stahl, 1999; Bianchini and Llerena, 2016; Bianchini et al., 2019; Narin et al., 1997).

This paper is a step forward to fill that gap. We develop a multi-country, multi-sectoral agent-based model of endogenous structural change, composed of countries joined by a Monetary Union. In this framework, besides the population of firms, workers and consumers,

* Correspondence to: Via dei Caniana 2, 24129 Bergamo, Italy.
E-mail addresses: andrea.borsato@unibg.it (A. Borsato), alorentz@unistra.fr (A. Lorentz).

[1] We use terms as *open science*, *public research*, *broad spectrum S & T* policies interchangeably.

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the national governments enter the economy through investments in research and innovation. They devote a share of GDP to finance either broad spectrum S & T policies or mission-oriented programs to target specific sectors and objectives. In line with Dawid and Delli Gatti (2018), Dosi and Roventini (2019) and Fagiolo and Roventini (2017) we believe that the implementation of an agent-based setting is particularly suitable to the task since the user knows by construction the micro data generating process and can explore the features of macro variables as properties emerging out of evolutionary dynamics.

Our model is evolutionary micro-founded in that both technological and structural changes result from evolutionary micro-processes. Innovations are the engine for both productivity gains and changes in the characteristics of goods and services, themselves source for changes in the structure of expenditures. The impact of innovations on the dynamics of the system are catalysed by the market selection mechanisms and triggered by individual behaviours. The setting includes a Kaldorian flavour in the sense that the dynamics at work are demand driven, and the allocation of income defines and transforms the structure of expenditures, shaping the industrial structure of the economies. Industries are interconnected by the structure of demand (Lorentz and Savona, 2010). From this viewpoint, we revolve around the idea that the structure of domestic demand catalyses the growth impulses generated by external demand, generating economic growth. Exports growth is sustained by gains in competitiveness engendered by technological change, themselves fostered by the increases in resources generated by economic growth. The combination of those mechanisms insure self-sustained growth.

Among the several results, we contend that the sole intervention of national governments through symmetric research investments is sufficient to lower GDP growth divergence across countries, likely stabilising them too.[2] Furthermore, the relationship between the share of investment to mission-oriented research and the coefficient of variation in GDP growth is U-shaped when the public sector focusses on pushing the technological frontier ahead. The enhancement of growth divergence suggests that a mix of broad spectrum and targeted policies seems more pivotal to softening divergence patterns. However, we likewise exhibit that science policies drive productivity-growth divergence. The more governments bring oxygen to an industry trying to support firms innovative search, the greater the divergence between countries. Declining sectors may either be those with a low expenditure share in the consumption bundle because of a lower quality or industries in which domestic firms are not competitive in international markets. It is yet true that even though productivity differentials exist and persist across industries and countries, such policies make sectoral gains more concentrated around a common average pattern. Conversely, sectoral productivity differentials are enlarged by rising shares of mission-oriented projects in government expenditure. In this case, even if economic growth is largely driven by sectors with absolute technological advantages, a flow, however tiny, of open-science investments allows other, weaker industries to survive and innovate. Science policy alone manages to limit and counteract monopolistic tendencies, triggering competition and country's diversification. Still, the strength of this mechanism depends on the allocation of resources between broad spectrum policies and mission-oriented programs.

Nevertheless, science policies do not affect the structure of consumption. Therefore, to be effective in dealing with societal challenges, they should be coupled with demand-side policies, governance, and consumer's involvement, as recently suggested by European Commission (2018a,e). All these results are also strengthened by the ability of our model to match a wide spectrum of stylised facts concerning economic growth and specialisation patterns at country, industry and firm level.

The article is organised as follows: Section 2 reviews the relevant literature; Section 3 describes the theoretical setting; Section 4 presents the results out of the baseline scenario; Section 5 develops the experiments on *symmetric* science policies and discusses the results; Section 6 concludes and offers some implications for policy and future research. The Appendix and the online Supplementary Material offer further statistics.

2. Relation with the literature

We contribute to several strands of research. First and foremost, we contribute to the understanding of the impacts of S & T policies on macroeconomic dynamics. The role of governments in funding research is at the core of the economic analysis back to the late Fifties. On the one hand, the neoclassical arguments *à la* (Nelson, 1959) and Arrow (1962) reported to the difficulties of appropriating the benefits out of research with the consequent market failure in which private firms underinvest in innovative search: from which a general plea for public funds. On the other hand, there is all the bulk of evolutionary literature on innovation and technical change *à la* (Dosi and Nelson, 2010; Mazzucato, 2016; Metcalfe, 1995; Rosenberg, 1982), according to which direct and indirect innovation policies require and imply an active role of national governments to shape technological landscapes and search regimes, and to take risks that the private sector does not want to absorb in a first stance (Dosi et al., 2023). The evolutionary theory does not look at governments as solution to a market failure per se, but as the source for the enhancement of competitive performance and the promotion of structural change (Metcalfe, 1995). To paraphrase (Rosenberg, 2009), scientific knowledge is not a costless good available to anybody, but it is embodied in specific researchers and institutional networks, and to master it investments are required. Therefore, corporations prefer entering a new market only after the great bulk of uncertainty has already been handled by the public sector (Cimoli et al., 2009, ch. 2). In this case, government innovation policies create new technologies, new markets and new industries (Foray et al., 2012; Mowery, 2009).

Close to the evolutionary perspective in its analysis of the relation between economic growth, development, and technical change, is the *technology gap* approach *à la* (Abramovitz, 1986; Fagerberg, 1994; Gerschenkron, 1962). This literature starts from the observation that differences in technological levels and trends characterise the international economic system. These differentials are at the core of economic growth divergences between *leaders*, i.e. countries standing at the technological frontier, and *latecomers*, i.e. countries on a lower technological level. The possibility for the latter to catch up with the leaders depends on their ability to mobilise resources for transforming social, institutional and economic structures (Fagerberg, 1987). However, this is possible if and only if latecomers succeed in developing *social capabilities* in the forms of competencies at firm level, high-quality educational systems and efficient financial markets (Abramovitz, 1986).

Among this very large literature, this work shares some commonalities with Foray and Llerena (1996) and the tradition around the "Schumpeter meeting Keynes" (K+S) models (Amendola et al., 2024; Dosi et al., 2010, 2023; Dosi and Roventini, 2019; Dosi et al., 2022). Foray and Llerena (1996) revisit (Aoki, 1986) to link the level of the information structure to the degree of centralisation of decision. Crucial determinants were found in the learning capabilities of the firms and the government response time. They compared two different policy scenarios, i.e., mission-oriented and diffusion policies, whose design is very similar in scope to ours.

The family of K+S models bridges Schumpeterian technology-fuelled innovation theories with Keynesian engines that trigger long-term economic growth (Dosi et al., 2010). In particular, Dosi et al. (2023) study the impact of alternative innovation policies on both the

[2] We identify with symmetric policies the cases in which both countries adopt the same choice regarding the share of investment in GDP and its allocation between open science and mission-oriented programs. Conversely, policies are considered as asymmetric when countries adopt different targets in mission-oriented programs. The analysis on asymmetric policies does not offer further remarkable insights: results are available on request.

short and long-run performance of an economy. The paper depicts a country in which the public sector intervenes through the creation of a National Research Lab and a public capital-good enterprise, whose aim consists of disseminating knowledge and creating avenues for radical innovations. This policy setting is then compared to a more traditional one in which the State provides R & D subsidies or investment tax discounts. The overall findings support the idea that public research bodies improve economic performance more than traditional pigouvian solutions: the outcome is a higher growth potential along with a public deficit kept under control. Also, the public research lab is most efficient in promoting energy efficiency without negative impacts on macroeconomic and public finance conditions (Amendola et al., 2024). Our paper slightly differs in the schedule of the experiments, since Amendola et al. (2024), Dosi et al. (2023) do not analyse the trade-off between broad spectrum and mission-oriented policies, and focus on a closed economy only. Our framework, instead, takes these issues into account and provide the conditions under which a too-large commitment to mission-oriented programs can foster productivity growth divergences both across countries and across sectors. Moreover, our article pinpoints to the crucial role of open science in triggering competition, reducing productivity differentials and income inequality.

This paper contributes to the literature on growth dynamics, structural change and coordination issues as empirically identified by Allen (2001) and Dosi et al. (1994a,b), all in the vein of the seminal work of List (1856), and formally addressed in the evolutionary macroeconomic literature. All these works consider structural changes as the results of evolutionary transformative engines as the main drivers for economic growth either through the internal transformation of the sectoral structure of the economies (Metcalfe et al., 2006; Saviotti and Pyka, 2004a,b) or through their specialisation patterns through trade (Dosi et al., 1994a; Verspagen, 1992). The frame developed in this paper draws on and combines these two traditions. Drawing on Ciarli et al. (2010), Ciarli and Lorentz (2010), Ciarli et al. (2019), Lorentz et al. (2016), Lorentz (2018), various developments of a micro-to-macro approach to the dynamics of structural change, driven by the interplay between transformations in the structures of production and productivity dynamics and those of effective demand responding to the transformation of preferences and the structure of earnings, provides us with the foundations for the internal transformations of our economies. As for the second drivers of structural change, our frame relies on the works of Llerena and Lorentz (2004) and Lorentz (2015a,b), whose theoretical setting shows that the main driver for specialisation also generates growth rate differences among economies. When emerging out of the heterogeneity of technical change at the microeconomic level, specialisation engenders cross-country growth rate differences that yet are only transitory. Conversely, permanent divergences in economic and productivity growth are fuelled by demand factors as represented by heterogeneous income elasticities (Lorentz, 2015a). This study presents similar results in the benchmark model, but it leads to different conclusions when turning to S & T policies, which are quite able to engender persistent productivity-growth divergence across countries even with public intervention.

Finally, the model clearly belongs also to the literature on open-economy agent-based models which tackle regional as well as monetary-unions issues (Caiani et al., 2018; Caiani and Catullo, 2023; Dawid et al., 2014; Dawid and Delli Gatti, 2018). For instance, using a two-region macroeconomic model, Dawid et al. (2014) provide insights on short-to-long period outcomes of policies fostering the improvement of human capital and the adoption of new technologies across richer and poorer regions. The labour market is the key variable for when it is fully integrated between regions, such policies enhance divergence patterns and make the rich ever richer and poor regions ever poorer. Conversely, Caiani et al. (2018) analyse the relationship between fiscal policies, wage dynamics, growth performance, and debt sustainability in a framework that closely resembles the European Monetary Union. Our work, even though it does not account for debt-sustainability issues or labour-market dynamics, depicts the working of an integrated economic system and is in agreement with the mentioned papers in underlining the important call for coordinated and redistributive policies at the supranational perspective.

3. An evolutionary model of structural change with a Kaldorian flavour

We propose here a multi-country, multi-sectoral model of economic dynamics with endogenous structural changes. In line with the evolutionary literature, we build the model around three populations of agents: private firms, households and a public sector. These populations interact within the country they are located as well as between countries. The aggregation of these population dynamics determines the macro-level dynamics of the system.

Private firms produce differentiated goods for a single industrial sector. These goods are consumed by both domestic and foreign households. Households are divided into consumer/worker groups sharing a similar level of income and a common structure of expenditures defined by an Engel-curve-like mechanism. All of the countries share a common currency. The interaction among countries are therefore limited to trade in goods and services. In this respect, the model accounts for the dynamics of a single currency system in line with the European Monetary Union.[3]

The model is evolutionary micro-founded in that both technological and structural changes result from evolutionary micro-processes. The model also includes a Kaldorian flavour in the sense that the dynamics at work are demand driven, and the allocation of income defines and transforms the structure of expenditures, shaping the industrial structure of the economies. Furthermore, the efficiency and competitiveness gains of firms, and of the economies a whole, on international market fosters the expansion of demand. The interplay of these three mechanisms allow for a Kaldorian cumulative causation dynamics.

Formally the model is structured as follows. We consider a set of C economies integrated in an single currency economic system through trade relations. An economy is referred to using the index $c \in [1; C]$. From the perspective of the economy c, the variables indexed $\bar{c}$ refer to foreign economies. Each economy can produce and consume goods and services from each sector $j \in [1; J]$ and counts a population of I firms as active in each of the J sectors. A firm $i \in [1; I]$, producing in sector j and based in the economy c is referred to with the subscripts i, j, c. Households are classified in H consumer/worker groups. A group of consumers h gathers all the workers of the tier $k = h$ of all the I firms in all the J industries. The total number of households groups in an economy is given by the highest number of worker tier Λ found among the I firms in the J sectors of an economy c. The index t refers to the time step. Fig. A.5 portrays the model.

3.1. Private firms: production and innovation

Private firms define the path of technical change through R & D and the economy's production capacity through their investment in capital stock. Firms are boundedly rational, heterogeneous in both the efficiency of their production capacity (i.e., labour productivity) and the characteristics of the goods or services they provide (i.e., satiability level). The mutations in both factors result from: (i) technical change emerging at the firm level in which firms develop new production processes that require investments in physical capital; (ii) product innovation that modifies the nature of the goods produced, affecting the attractiveness of the latter to the consumer.

[3] For simplicity, we assume trade costs within the Union away from this analysis. We believe that one key principle of the European Monetary Union is to limit as possible trade costs across countries. For further details on this issue, see Lorentz and Ciarli (2014).

3.1.1. Firms characteristics

The production process is represented at time t by a constant returns to scale production function with labour as a unique production factor. Capital is accumulated to build the production capacity, defining labour productivity:

$$Q^P_{i,j,c,t} = A_{i,j,c,t-1} \cdot L_{1,i,j,c,t} \tag{1}$$

in which $Q^P_{i,j,c,t}$ is firm capacity, $A_{i,j,c,t-1}$ is labour productivity and $L_{1,i,j,c,t}$ is the labour force.[4]

The unit of nominal output ($Y_{i,j,c,t}$) is defined by the share of effective demand directed at the firm at time t. The effective demand for any sector ($Y_{j,c,t}$) is determined at the macro-economic level while the amount of effective demand allocated to each sectoral firm is computed as a share of sector j demand given by their relative market share ($\frac{z_{i,j,c,t}}{z_{j,c,t}}$):

$$Q_{i,j,c,t} = \frac{Y_{i,j,c,t}}{p_{i,j,c,t-1}} = \frac{z_{i,j,c,t}}{z_{j,c,t}} \cdot \frac{Y_{j,c,t}}{p_{i,j,c,t-1}} \tag{2}$$

where $p_{i,j,c,t-1}$ corresponds to firm price.

The employment level can be expressed as a function of the share of effective demand:

$$L_{1,i,j,c,t} = \frac{1}{A_{i,j,c,t-1}} \cdot Q_{i,j,c,t} = \frac{z_{i,j,c,t}}{z_{j,c,t}} \cdot \frac{Y_{j,c,t}}{A_{i,j,c,t-1} \cdot p_{i,j,c,t-1}} \tag{3}$$

We follow Ciarli et al. (2010), Lydall (1959a,b) and Simon (1957) to represent the organisational structure of firms. Firm size, number and complexity of hierarchical organisational layers (i.e., the proportion of executives and workers) affect the structure of earnings. For every layer of workers employed in the production of goods or services ($L_{1,i,j,t}$), the firms need a layer of *executives* to manage every group of ν employees. This second layer of employees requires a third layer of executives for every group of ν employees in the second layer, and so on. The number of required layers defines firm organisational complexity. The number of employees in each of the layer can formally be given as a function of $L_{1,i,j,t}$:

$$L_{\Lambda,i,j,c,t} = \frac{L_{\Lambda-1,i,j,c,t}}{\nu} = \frac{1}{\nu^{\Lambda-1}} \cdot \frac{Q_{i,j,c,t}}{A_{i,j,c,t-1}} \tag{4}$$

where Λ is a fixed parameter defining the total number of layers required to manage the firm. The total number of employees ($L_{i,j,t}$) is given by the sum of all the layers of employees in the firm:

$$L_{i,j,c,t} = \sum_{k=1}^{\Lambda} L_{k,i,j,t} = \frac{Q_{i,j,c,t}}{A_{i,j,c,t-1}} \cdot \sum_{k=1}^{\Lambda} \frac{1}{\nu^{k-1}}. \tag{5}$$

The first tier of workers sees its wage ($w_{1,i,j,t}$) set at the industry level:

$$w_{1,i,j,c,t} = w_{j,c,t-1} \tag{6}$$

As we move upstream in the organisational hierarchy, the wage increases by a factor b, which determines the skewness in the wage distribution (Lydall, 1959a,b; Simon, 1957).

$$w_{\Lambda,i,j,c,t} = b^{\Lambda-1} \cdot w_{j,c,t-1} \tag{7}$$

The total wage bill for the firm at time t is a function of effective demand:

$$\sum_{k=1}^{\Lambda} w_{k,i,j,c,t} \cdot L_{k,i,j,c,t} = \sum_{k=1}^{\Lambda} \left(\frac{b}{\nu}\right)^{k-1} \frac{w_{j,c,t-1}}{A_{i,j,c,t-1}} \cdot \frac{z_{i,j,c,t}}{z_{j,c,t}} \cdot \frac{Y_{j,c,t}}{p_{i,j,c,t-1}} \tag{8}$$

Firms set their prices applying a mark-up (μ_j) to unit costs:

$$p_{i,j,c,t} = \left(1+\mu_j\right) \cdot \frac{\sum_{k=1}^{\Lambda} w_{k,i,j,c,t} \cdot L_{k,i,j,c,t}}{Q_{i,j,c,t}} = \left(1+\mu_j\right) \cdot \frac{w_{j,c,t-1}}{A_{i,j,c,t-1}} \cdot \sum_{k=1}^{\Lambda} \left(\frac{b}{\nu}\right)^{k-1} \tag{9}$$

The current level of profits earned by the firm can be computed as a function of the effective demand addressed to the firm:

$$\pi_{i,j,c,t} = \frac{z_{i,j,c,t}}{z_{j,c,t}} \cdot Y_{j,c,t} \cdot \left(1 - \frac{w_{j,t-1}}{A_{i,j,t-1} \cdot p_{i,j,c,t-1}} \cdot \sum_{k=1}^{\Lambda} \left(\frac{b}{\nu}\right)^{k-1}\right) \tag{10}$$

3.1.2. Investment decisions

Firms use resources accumulated selling their production to build up and improve their capacity, and the characteristics of the goods or services they sell. The firms build their production capacity accumulating capital goods that they develop for production. Each capital good embodies a level of productivity. The labour productivity level of the firm for the production layer of workers results from the aggregation of the levels of productivity embodied in each capital good, weighted by the amount invested in exploiting this capital in building the production capacity:

$$A_{i,j,c,t} = \frac{I_{i,j,c,t-1}}{\sum_{\tau=1}^{t-1} I_{i,j,c,\tau}} \cdot a_{i,j,c,t-1} + \left(1 - \frac{I_{i,j,c,t-1}}{\sum_{\tau=1}^{t-1} I_{i,j,c,\tau}}\right) \cdot A_{i,j,c,t-1} \tag{11}$$

in which $a_{i,j,c,t-1}$ represents the labour productivity embodied in the capital good developed by the firm i during the period $t-1$. $I_{i,j,c,t}$ represents the level of investment in capital goods of the firm.

Each capital good is developed in-house by firms and then introduced in their production technologies. In other words, firms are integrated. This process is decomposed in two phases. First, firms explore and develop new capital goods. This phase takes place within the R & D activity. The second stage consists of introducing the outcome of the R & D activity within the production process. This stage is costly and requires firms to invest in the exploitation of the latest capital good vintage. The level of investment determines the relative importance of the latest capital goods in the production process and determines the actual productivity gains.[5]

Firms also have to develop the characteristics, or quality index of their product: they first invest in capital goods, in order to gain from the already developed vintages, and then invest in R & D. The R & D investments are then shared between the development of capital goods and attempts to improve the quality index of the product of the firm.

Investments are constrained by the availability of the financial resources that correspond to accumulated profits ($\Pi_{i,j,c,t}$). Investments in capital goods correspond to a share ι of firms' resources. Given the

[4] The specification of the production function behind both the Hicksian production function (Amendola and Gaffard, 1998), or the Kaldorian technical change function (Kaldor, 1957; Kaldor and Mirrlees, 1962) considers that capital does not substitute for labour but is accumulated to build up the production capacities of the firms. In line with both the Neo-Austrian approach of Amendola and Gaffard (1998), as well as the Keynesian inspired approach of Pasinetti (1983), also found in Llerena and Lorentz (2004) and Lorentz (2018), the building of the production capacities results from investments rerouting resources from profits and R & D to accumulate capital goods, developed by the firms themselves, as a vertically integrated entity. This implies that the production capacities are solely driven by induced investments and, contrary to models like the K+S family, Ciarli and Lorentz (2010), Ciarli et al. (2019), Caiani et al. (2018) and Caiani and Catullo (2023) there is no constraint to the production capacities due to the availability of the capital goods.

[5] The capital vintages accumulated through this process being developed in-house, there is no capital availability issues constraining production. On the contrary, the accumulation of capital is solely constrained by the expansion of demand. In other words, the accumulation of capital is the result of induced investments in a traditional Kaldorian or Keynesian fashion.

financial constraint the investment level in capital good is formally represented as follows:

$$I_{i,j,c,t} = \min\left\{\iota \cdot Y_{i,j,c,t}; \Pi_{i,j,c,t-1} + \pi_{i,j,c,t}\right\} \tag{12}$$

A share ρ of the firm's resources are then devoted to the investments in R & D. These R & D investments are assigned indifferently to the development of the production capacity or process innovation, or to the research leading to product innovation, these are respectively formalised as follows:

$$R_{i,j,c,t} = \min\left\{\rho \cdot Y_{i,j,c,t}; \Pi_{i,j,c,t-1} + \pi_{i,j,c,t} - I_{i,j,c,t}\right\} \tag{13}$$

Accumulated profits are defined as:

$$\Pi_{i,j,c,t} = \Pi_{i,j,c,t-1} + \pi_{i,j,c,t} - I_{i,j,c,t} - R_{i,j,c,t} \tag{14}$$

Seemingly, we assume that half R & D expenditure is devoted to intrafirm innovative search and imitation.

3.1.3. R & D, process and product innovations

The formal representation of the R & D process is explicitly inspired by evolutionary modelling of technical change (Dosi et al., 2010, 2022; Llerena and Lorentz, 2004; Nelson and Winter, 1982). We consider the probability of success of research as increasing function of R & D investments. Firms also benefit from public investments in S & T. Formally the branch of the R & D activity responsible for the development of process innovation can be represented by the following algorithm:

1. The probability of success in developing a prototype of capital good is[6]:

   $$P^a_{i,j,c,t} = 1 - e^{-\delta_a \cdot (R^{\varphi_1}_{i,j,c,t} \cdot S^{\varphi_2}_{j,c,t} \cdot S^{\varphi_3}_{c,t})} \tag{15}$$

   in which firms investments in R & D ($R_{i,j,c,t}$) are complemented by the public investments in S & T oriented towards the sector j ($S_{j,c,t}$), and the generic and fundamental public investments in S & T ($S_{c,t}$). The parameters $\varphi_1 \in [0;1]$, $\varphi_2 \in [0;1]$ and $\varphi_3 \in [0;1]$ sum to one and control the contribution of each source of knowledge, internal, external, specialised and generic to the probability of success of R & D. This formal representation implies that without own R & D investments firm cannot benefit from the public S & T investments, reflecting as well the idea of a required absorptive capacity to benefit from the latter, as well as a non-null investment in both specialised and generic knowledge from the public sector; δ_a is a parameter.
2. If R & D is successful, the embodied level of productivity ($a'_{i,j,c,t}$) for the prototype of capital good is stochastic and drawn from the following distribution:

   $$a'_{i,j,c,t} \sim N(a_{i,j,c,t-1}; \sigma^{a,inn}_{i,j,c}) \tag{16}$$

   The prototype of capital good is then introduced into the production capacity of the firm if it allows for productivity gains hence:

   $$a_{i,j,c,t} = \max\{a'_{i,j,c,t}; a_{i,j,c,t-1}\} \tag{17}$$

Likewise, firms have some probability to imitate competitors conditional to the imitation expenditure. The procedure mimics the above but for the stochastic process as in Eq. (16). In fact, we follow Llerena and Lorentz (2004) since the standard deviation from a firm draws the imitated prototype of capital good corresponds to:

$$\sigma^{a,imi}_{i,j,c,t} = \sigma_0 \cdot \left(\bar{a}_{j,t} - a_{i,j,c,t}\right) \tag{18}$$

in which $\bar{a}_{j,t}$ represents the market average productivity level embodied in the latest vintage. Then, firms adopt the best prototype of capital goods out of period innovation and imitation.

The satiability of goods is a function of the characteristics of the goods, that result from firms R & D activity (Witt, 2010). Product innovations allow firms to escape the satiation of their sector by expanding the range of needs or wants their products are able to satisfy. The degree of satiability $\theta_{i,j,c,t}$ is embodied in each vintage of products. Symmetrically to process innovation, the product improvement process also benefits from public investments in S & T:

1. The probability of success in developing a prototype of consumer good is:

   $$P^\theta_{i,j,c,t} = 1 - e^{-\delta_\theta \cdot (R^{\varphi_1}_{i,j,c,t} \cdot S^{\varphi_2}_{j,c,t} \cdot S^{\varphi_3}_{c,t})} \tag{19}$$

   in which δ_θ is a parameter.
2. If R & D is successful, the satiability embodied in the prototypes ($\theta'_{i,j,c,t}$) for the consumer product is stochastic and drawn from the following distribution:

   $$\theta'_{i,j,c,t} \sim N(\theta_{i,j,c,t-1}; \sigma^{\theta,inn}_{i,j,c}) \tag{20}$$

   The prototype of good is then produced and marketed if it allows to escape from satiation:

   $$\theta_{i,j,c,t} = \max\{\theta'_{i,j,c,t}; \theta_{i,j,c,t-1}\} \tag{21}$$

As above, firms have some probability to imitate according to the amount of R & D expenditure on imitation. The satiability degree out of imitation is drawn from a stochastic process whose standard deviation ($\sigma^{\theta,imi}_{i,j,c}$) reflects the corresponding gap from the market average $\bar{\theta}_{j,t}$:

$$\sigma^{\theta,imi}_{i,j,c} = \sigma_0 \cdot \left(\bar{\theta}_{j,t} - \theta_{i,j,c,t}\right) \tag{22}$$

Firms opt for the best quality level and produce accordingly.

To sum up on this point, the functional forms adopted in Eq. (15) and later in Eq. (19) are not very different from the ones devised in many existing evolutionary or agent-based models, including in the well diffused K+S family. In fact, all these models have in common very similar mechanisms: R & D expenditure (either in spendings, or in human resources) enters in levels, or in accumulated levels for some models, in the exponential probability function. In our case, we augment this expression with public spending in a Cobb–Douglas fashion. We believe this choice is appropriate to ensure both a form of complementarity and partial substitutability between the different sources of funding for research — private, originated at the firm level; public as directed at the specific sector the firm is active in, and public as generic and not targeted at any specific sectors. On the one hand, a firm's innovative capability is constrained by its R & D investments, assuming any public spending away. On the other hand, public expenditure is useless in isolation, i.e., without the establishment of intra-firm research facilities. In this respect, public spending augments and strengthens the capabilities already in place, or stated differently, without an in-house research spending, firms cannot benefit from any publicly funded research, mimicking here an absorptive capacity (Cohen and Levinthal, 1990).

For similar reasons, we cannot set an additive schedule which corresponds to perfect substitutability between funding sources. Indeed, this latter case implies that public funding allows for firm innovation even in the absence of in-house R & D laboratories, that is without any innovative effort by the firm, fully in contradiction with all the empirical literature on management and organisation studies (Mowery, 1983a,b, 1995; Rosenberg, 2009; Teece, 2010).[7]

[6] When public spending is null in either open science or mission-oriented research or both, we normalise the expenditure to 1: in this case, a successful draw is still attainable with private spending only. The same applies for consumer goods.

[7] For further details on the mechanisms surrounding the innovation process in these models, see also Ciarli et al. (2010, 2019), Llerena and Lorentz (2004),

3.2. Domestic consumption by households and income dynamics

The structure of the final demand is driven by the structure of households expenditures and the changes in these expenditures driven by the dynamics and distribution of income. The households in each country are divided into groups of consumers/workers. Each group constitutes a specific class of households with a homogeneous structure of expenditures as well as a homogeneous set of income.

3.2.1. Households consumption behaviour and the structure of expenditures

Each consumer class corresponds to a specific layer of worker. $C_{j,c,t}$ corresponds to the sum of the expenditures devoted to the goods provided by a sector coming from each of the $h \in [1; H]$ consumer/worker class. All the income $W_{h,c,t}$ perceived by a class is consumed. A given share $c_{h,j,c,t}$ class is devoted to the expenditure in goods of any sector j. Formally:

$$C_{j,c,t} = \sum_{h=1}^{H} c_{h,j,c,t} \cdot W_{h,c,t} \tag{23}$$

The expenditures shares for each of the goods from the J sectors and for each of the H groups of households follow an Engel curves-like dynamics: as income raises, the expenditures by households increase up to a satiation level. Above it, for any further increase in income, the level of expenditures remains unchanged (Kaldor, 1966).

The characteristics of the consumption goods define this level of satiability. Moreover as income rises, households tend to imitate those of higher classes of income (Pasinetti, 1983; Verspagen, 1992; Ciarli et al., 2019):

$$c_{h,j,c,t+1} = c_{h,j,c,t} \cdot \left(1 + \eta \left(c_{h+1,j,c,t} - c_{h,j,c,t}\right) \cdot \frac{\Delta W_{h,c,t}}{W_{h,c,t-1}}\right) \ \forall h \in [1; \Lambda - 1] \tag{24}$$

$$c_{\Lambda,j,c,t+1} = c_{\Lambda,j,c,t} \cdot \left(1 + \eta \cdot \left(\bar{c}_{j,c,t} - c_{\Lambda,j,c,t}\right) \cdot \frac{\Delta W_{\Lambda,c,t}}{W_{\Lambda,c,t-1}}\right) \tag{25}$$

in which η is a parameter and $\bar{c}_{j,c,t}$ is the asymptotic distribution defined by the technological characteristics of the goods. This distribution is a function of the relative satiability of each category of goods:

$$\bar{c}_{j,c,t} = \frac{\theta_{j,t}}{\sum_j \theta_{j,t}} \tag{26}$$

The level of satiation results from the aggregation of the satiability levels embodied in the products:

$$\theta_{j,c,t} = \sum_{c} \sum_{i} z_{i,j,c,t} \cdot \theta_{i,j,c,t} \tag{27}$$

3.2.2. Wage dynamics and income distribution

For a given sector j wage dynamics are correlated with the productivity growth rate ($\frac{\Delta A_{j,c,t}}{A_{j,c,t-1}}$) of the sector and with the productivity growth rates of the whole economy ($\frac{\Delta A_{c,t}}{A_{c,t-1}}$). The effect of these two variables on wage dynamics is weighted by the parameter $\gamma \in [0; 1]$. When $\gamma = 0$, the wage dynamics for every sector only depend on the productivity growth rate of the economy as a whole (i.e., as a centralised wage negotiation system). When $\gamma = 1$, the wage dynamics for every sector only depends on the productivity growth rate of the sector (i.e., as a decentralised wage negotiation system). Wage dynamics of the sector j in economy c is represented as follows:

$$\frac{\Delta w_{j,c,t}}{w_{j,c,t-1}} = \gamma \cdot \frac{\Delta A_{j,c,t}}{A_{j,c,t-1}} + (1-\gamma) \cdot \frac{\Delta A_{c,t}}{A_{c,t-1}} \tag{28}$$

The total number of workers in a class h, $L_{h,c,t}$ is a function of all the demand addressed to each sector $Y_{j,c,t}$:

$$L_{h,c,t} = \sum_{j=1}^{J} \sum_{i=1}^{I} L_{h,i,j,c,t} = \sum_{j=1}^{J} \frac{Y_{j,c,t}}{z_{j,c,t}} \cdot \sum_{i=1}^{I} \nu^{1-h} \cdot \frac{z_{i,j,c,t}}{p_{i,j,c,t-1} \cdot A_{i,j,c,t}} \tag{29}$$

Similarly, the income ($W_{h,c,t}$) of each class h of consumers/workers becomes:

$$W_{h,c,t} = \sum_{j=1}^{J} \sum_{i=1}^{I} w_{h,i,j,c,t} \cdot L_{h,i,j,c,t} \tag{30}$$

Substituting Eq. (30) in Eq. (23) and re-arranging, we obtain:

$$C_{j,c,t} = \underbrace{\left[\sum_{h=1}^{H} c_{h,j,c,t} \cdot \sum_{j=1}^{J} \frac{w_{j,c,t-1}}{z_{j,c,t}} \cdot s_{j,c,t} \sum_{i=1}^{I} \left(\frac{b}{\nu}\right)^{h-1} \cdot \frac{z_{i,j,c,t}}{p_{i,j,c,t-1} \cdot A_{i,j,c,t}}\right]}_{\chi_{j,c,t}} \cdot Y_{c,t} \tag{31}$$

where $\chi_{j,c,t}$ corresponds to the Keynesian marginal propensity to consume.[8]

3.2.3. Imports and exports dynamics

Domestic consumption is either satisfied by domestic suppliers or by imports ($M_{j,c,t}$):

$$M_{j,c,t} = m_{j,c,t} \cdot C_{j,c,t} \tag{32}$$

The share of imported goods ($m_{j,c,t}$) is a function of competitiveness of domestic firms, approximated by the sectoral market share $z_{j,c,t}$:

$$m_{j,c,t} = (1 - z_{j,c,t}) \tag{33}$$

Country exports ($X_{j,c,t}$) correspond to the share ($z_{j,c,t}$) of the imports of products from the expenditure category j from all the other countries ($\tilde{c} \in [1, C] | \tilde{c} \neq c$):

$$X_{j,c,t} = z_{j,c,t} \cdot \sum_{\tilde{c}} M_{j,\tilde{c},t} \tag{34}$$

Imports by foreign economies are constructed symmetrically to the imports of the domestic economies.[9] We can therefore rewrite the expression for the exports of sector j as follows:

$$X_{j,c,t} = z_{j,c,t} \cdot \sum_{\tilde{c}} (1 - z_{j,\tilde{c},t}) \cdot \chi_{j,\tilde{c},t} \cdot Y_{\tilde{c},t} \tag{35}$$

3.2.4. Market dynamics

The level of effective demand is shared among firms and/or economies according to their market shares. The dynamic of market shares accounts for the relative competitiveness of firms and/or economies, i.e., their market share raises as long as the firms/economies competitiveness is higher than average. More formally, the market

Lorentz (2015a,b) and Lorentz et al. (2016, 2019). Moreover, the process and product innovation probabilities in no way display a tendency to reach unit values as the amount R & D spending keeps growing over time. Quite the opposite, values show some convergence to a probability of about 0.3 and 0.6 for process and product innovation, respectively. The same reasoning applies to the imitation schedule. For what concerns the role of the parameters δ_a and δ_θ, they do not impact on the underlying structure of the model in its main properties. The probability to innovate and imitate remains and stabilises around reasonable values significantly lower than 1. Related plots, also considering the additional role of public expenditure, are available on request. On the role of parameters in determining this specific dynamics of agent-based models, see also Caiani et al. (2016).

[8] This representation of the Keynesian marginal propensity to consume resembles Kaldor (1955) perspective in which the dynamics of the propensity is defined at sectoral level. Moreover, the aggregation of profit shares at firm level ensures that this propensity is positive but below unity.

[9] Considering here an integrated economic system with a single currency, we can assume a fixed exchange rate equal to one for all economies composing the system.

share of the economy in a sector is a proxy for the price competitiveness of the economy in that sector and is given by the sum of the market shares of the domestic firms active therein:

$$z_{j,c,t} = \sum_{i} z_{i,j,c,t} \tag{36}$$

Each firm's market share is defined through a replicator dynamic, function of firm's relative competitiveness ($\frac{E_{i,j,c,t}}{\bar{E}_{j,t}}$):

$$z_{i,j,c,t} = z_{i,j,c,t-1} \cdot \left(1 + \phi \cdot \left(\frac{E_{i,j,c,t}}{\bar{E}_{j,t}} - 1\right)\right) \tag{37}$$

where $p_{i,j,c,t}$ is the price of its product, $E_{i,j,c,t}$ stands for firm i, in sector j, level of competitiveness:

$$E_{i,j,c,t} = \frac{1}{p_{i,j,c,t}} \tag{38}$$

and $\bar{E}_{j,t}$, the average competitiveness on the international market, is computed as follows:

$$\bar{E}_{j,t} = \sum_{c,i} z_{i,j,c,t-1} \cdot E_{i,j,c,t} \tag{39}$$

3.3. Aggregate demand and GDP dynamics

As for most of the Post-Keynesian growth models, the balance-of-payment constraint has to be satisfied. The sum of all sectors exports therefore has to equal the sum of all sectors imports:

$$\sum_{j=1}^{J} X_{j,c,t} = \sum_{j=1}^{J} M_{j,c,t} \tag{40}$$

$$\sum_{j=1}^{J} z_{j,c,t} \cdot \sum_{\tilde{c}} (1 - z_{j,\tilde{c},t}) \cdot \chi_{j,\tilde{c},t} \cdot Y_{\tilde{c},t} = \sum_{j=1}^{J} (1 - z_{j,c,t}) \cdot \chi_{j,c,t} \cdot Y_{c,t} \tag{41}$$

From the balance-of-payment constraint, we derive the level of nominal GDP of the economy:

$$Y_{c,t} = \frac{1}{\left(1 - \sum_{j} z_{j,c,t} \cdot \chi_{j,c,t}\right)} \sum_{j} z_{j,c,t} \cdot \sum_{\tilde{c}} (1 - z_{j,\tilde{c},t}) \cdot \chi_{j,\tilde{c},t} \cdot Y_{\tilde{c},t} \tag{42}$$

Eq. (42) presents a typical Post-Keynesian relation: domestic GDP is a function of exports, with a typical Harrodian trade multiplier linking GDP to exports. This multiplier is a function of the structure of aggregate demand, as measured by the distribution of expenditure shares and of the competitiveness of the economy.[10]

3.4. Policy instruments and scenarios

At each time steps the government spends a share g_c of GDP in its S & T policies to fund either mission-oriented policies or generic and fundamental research. The outcome of fundamental research is assumed to be absorbable by every sectors in the same range. Mission-oriented policies are assumed to be directed at specific sectors and its benefits can only affect the firms in the sectors that were targeted by the policy. We do not explicitly model a counterpart to the public spendings (via taxes for example) as we aim at focusing on the effect of the direction of the public spendings rather than the redistributive effect due to a tax funded policy. Furthermore, we focus on *symmetric* policies, i.e., the cases in which both countries adopt the same choice regarding the share of investment in GDP and its allocation between open science and mission-oriented programs.

The policy scenarios to be considered consists in a two stage decision:

1. Defining the amount of public spendings to mission-oriented and to generic and fundamental S & T policies. The parameter $\psi_c \in [0;1]$ defines the share of spendings devoted to mission-oriented research in country c; $1 - \psi_c$ corresponds to the share of public investment spent in generic and fundamental research and the total investment in generic research is:

$$S_{c,t} = (1 - \psi_c) \cdot g_c \cdot Y_{c,t} \tag{43}$$

2. Defining the sector targeted by the public spending with mission-oriented S & T policies. We schedule three different scenarios to target the mission-oriented policies:

   (a) *Pushing the technological frontier ahead*: the policies are targeted to support the most advanced technology, regardless of the competitiveness of the firms:

$$S_{j,c,t} = \begin{cases} \psi_c \cdot g_c \cdot Y_{c,t} & \text{if } \theta_{j,t} = \max\{\theta_{1,t}, \dots, \theta_{J,t}\} \\ 1 & \text{otherwise} \end{cases} \tag{44}$$

   (b) *Creating/sustaining a position of leadership*: the policies are targeted to support the most competitive sector, regardless of product quality and technological advancement:

$$S_{j,c,t} = \begin{cases} \psi_c \cdot g_c \cdot Y_{c,t} & \text{if } z_{j,c,t} = \max\{z_{1,c,t}, \dots, z_{J,c,t}\} \\ 1 & \text{otherwise} \end{cases} \tag{45}$$

   (c) *Supporting/relaunching declining sectors*: the policies are targeted to support the least competitive sector, limiting the consequences of international competition avoiding the dislocation of a declining sector of the economy c, regardless of product quality and technological advancement:

$$S_{j,c,t} = \begin{cases} \psi_c \cdot g_c \cdot Y_{c,t} & \text{if } z_{j,c,t} = \min\{z_{1,c,t}, \dots, z_{J,c,t}\} \\ 1 & \text{otherwise} \end{cases} \tag{46}$$

4. Stylised facts, growth, specialisation and technical change: the baseline scenario

We perform the model with computer simulations as usual in the reference literature. Table A.5 gathers baseline parameter values. The benchmark scenario is performed along 2000 period simulations across 50 Monte Carlo runs. Our artificial system counts five economies and four industrial sectors.[11] Each economy is producing and consuming the

[10] We refer here to the principle of cumulative causation as Kaldor (1966) and Kaldor (1972), in which the growth dynamics of an economy is driven by the co-evolution of the effective demand dynamics and structural changes and the dynamics of technological change and productivity gains. More precisely, we rely here on its interpretation by the Balance-of-Payment constrained growth literature (Dixon and Thirlwall, 1972; McCombie and Thirlwall, 2004); the mechanisms through which the external demand triggers a chain reaction in the internal components of effective demand and how these adjustments in internal demand occur in this and similar models are fully addressed in Lorentz and Borsato (2023) and Lorentz et al. (2019). Harrod (1933) and McCombie (1985) and McCombie and Thirlwall (1997) show the mechanisms ensuring that the equilibrium imposed by Eq. (42) aligns with GDP as defined by a standard national accounting framework. See Thirlwall (2012) for an historical survey of this literature.

[11] The model gets stable rather quickly, where with *stability* we refer to "a situation in which something such as an economy, company, or system can continue in a regular and successful way without unexpected changes" (Cambridge Dictionary). As we will see, most statistics in Figs. 2 to 4 display stable patterns according to this definition, especially in the later phase of simulation periods. The only potential expection concerns to productivity growth at country level. In this respect the transient phase of the model regards

output of each of these sectors and counts ten active firms per sector. An economy is then composed of forty firms and each sector counts fifty firms. This benchmark focusses only on the private economy. In the benchmark setting, no national government is involved. We set the initial conditions such that firms start homogeneously: the heterogeneity emerges as outcome of the interactions and different decision rules. Likewise, there is not initial specialisation.[12] We follow Ciarli et al. (2019) in the characterisation of sectoral expenditure shares. In that work, the authors divided the economy in ten industries producing most of the goods entering the British consumption bundle. They used the UK Family Expenditure Survey (FES) 2005–2006 to compute the initial consumption shares across ten aggregate consumption categories for the top centile and the bottom decile of UK consumers. Since we are concerned with four sectors only, we took the values that refer to expenditure shares for food, motoring, leisure and power.

Kaldor (1960, 1961) argued that any theoretical model should be able to account for a spectrum of historical facts. As first step in our analysis, we discuss the dynamic properties of our evolutionary setting of growth and specialisation, and whether it respects some historical regularities also in line with recent advances in ABM empirical validation (Fagiolo et al., 2019; Fagiolo and Roventini, 2017). Table 1 summarises the facts matched by the framework.

4.1. Growth patterns and properties of aggregate time series

Fig. 1 shows the general pattern of output, consumption, and investments. The model generates an endogenous and self-sustaining growth path characterised by tiny fluctuations (Dosi et al., 1994a,b; Durlauf, 1994).[13] Fig. 2 develops and presents Kaldor's facts (Kaldor, 1960, 1961). The first fact is about the shares of national income received by labour and capital which should remain constant over long periods of time. We notice the labour share in GDP converges to a positive value in both countries after a span of fluctuations.[14] Secondly, the capital-labour ratio grows over time. The endogenous growth of GDP and labour productivity coincides with a deepening in the capital intensity of the economies (Kaldor, 1960, p. 260). This also means that the rates of investment in machineries are robustly correlated with economic growth (De Long et al., 1992). Thirdly, the model engenders for both countries endogenous productivity growth rates and rates of return on investments which stabilise around positive and long-run values.

The literature typically observes co-movements in most economic aggregates, e.g., GDP, investment, consumption, labour productivity (Dosi et al., 1994b). Fig. S1 in the Supplementary Material plots the autocorrelation structure for de-trended labour productivity, consumption, physical investment, R & D investment, output and the corresponding cross-correlation between their cyclical components and that of GDP for a sampled country.[15] The simulated series are quite similar to real series (Assenza et al., 2015) with the first-lag autocorrelation of at least 0.8. Moreover, both types of investment and consumption are pro-cyclical and synchronised with the business cycle as in Dosi et al. (2018, 2019, 2021) and Wälde and Woitek (2004).

4.2. Patterns of specialisation and technological change

Fig. 3 provides some indicators that portray development and growth dynamics at country level. The first chart is about the inverse Herfindahl index for output. This index estimates the number of sectors in which production is concentrated. This indicator is defined in the interval $[1; 4]$. When it equals 4, the national economy produces the same level of output along the four industries: no specialisation occurs. Conversely, when it equals unity, the economy is highly specialised in a particular sector. The concentration index for three countries out of five converges to a value greater than 1. Despite concentrated, this means that some forms of oligopolistic competition is at work. The remaining two economies approach to monopoly. Additionally, every economy tends to specialise in one sector with a *national champion*. Yet, since the number of countries is greater than the number of industries, some countries likely develop some technological advantage that allows a firm to benefit from a strictly positive flow of demand.

Next two plots in Fig. 3 confirm this belief. On the one hand, the coefficient of variation in labour productivity growth between sectors within countries points to the heterogeneity of productivity dynamics across sectors. Specialisation is driven by absolute advantages first, and the corresponding aggregate growth of income and resources afterwards implies the domestic demand for other industrial goods to grow accordingly.[16] This demand is to be satisfied and all the resources which are not absorbed by the favoured industry is distributed among the remaining ones. Hence we observe a second order specialisation process: although the remaining sectors are more and more *abandoned*, and their share in value added reduces over time, the growth rate of demand for their products is significantly positive. A non-zero growth prevents the explosion of the coefficient of variation in productivity growth and allows for its long-term stabilisation.[17] Likewise, we notice that the coefficient of variation is lower, as expected, for those countries that do not become a single-sector economy. Productivity improvements in at least another industry would reduce the average productivity

the first 500 periods at most. Afterwards, the growth pattern stabilises for at least 2500 periods – if we extend the simulation length to 3000 periods – and converges to a strictly-positive value without unexpected changes, although small fluctuations are still at work. We preferred keeping in Fig. 2 a *zoomed-in* plot to highlight the fluctuations in the growth path. The overall picture is available on request.

[12] What follows considers specialisation as the concentration of production in a limited number of sectors, namely the allocation of various activities across various economies as traditionally considered in the international trade literature. Additionally, with this initialisation, we implicitly account for the fact that "[O]ne can hardly identify, in general, persistent features of national growth patterns just conditional on initial performances [...]. Closer inspection of particular economies or groups of them does appear to show long-term persistence [...] but the causes of the phenomenon are plausibly country-specific rather than a common feature of the world economy" (Dosi et al., 1994b, p. 11).

[13] The simulated time series follow a unit root process according to the ADF test (Tab. S6 in the Supplementary Material), well in tune with the observed evidence (Nelson and Plosser, 1982). In addition to this, business-cycle fluctuations are not very clear from Monte Carlo averages, since the latter tend to wash away the variability. Sample simulations are available upon request.

[14] Growth theory and the literature on income inequality increasingly question this constancy: cf. Borsato (2021, 2022, 2023), Smith (2021) and Lorentz and Borsato (2023).

[15] We have obtained cyclical and trend components with the Hodrick–Prescott filter. Despite believed as inaccurate, performances of the HP filter were recently reconsidered in Franke et al. (2022). Correlation patterns for the remaining economies are available on request.

[16] That demand for other sectoral products grows at the same rate is showed in Fig. 3, bottom panels. The inverse Herfindahl index of the consumption shares is increasing above 3, i.e., households expenditure is distributed along the several goods produced. At the same time, the coefficient of variation of expenditure shares goes to one with no tendency to approaching zero, suggesting a permanent divergence in the way households allocate their expenditure across products. The lack of convergence to zero is visible as we extend simulation periods: results available on request.

[17] The patterns of specialisation within and between countries, and its *stickiness*, i.e., favoured sectors do not change over time, also are in tune with the stream of research on the rise of specific national systems of innovation based on the peculiarities of scientific and technical infrastructures, and institutional and policy features of each country (Lundvall, 1992; Nelson, 1993). Moreover, productivity differences hold at several levels of statistical aggregation (Dosi et al., 2021): see also Fig. S2 in the Supplementary Material.

Table 1
Empirical regularities reproduced by the model.

Empirical regularity	Tab., Fig.	References
Patterns of growth and aggregate time series		
Endogenous, self-sustained growth with fluctuations	Fig. 1	Durlauf (1994), Maddison (2010)
Growth divergence across countries	Fig. 4	Durlauf (1994), Maddison (2010)
Harrodian-Keynesian multipliers significantly above 1	Fig. 3	Deleidi et al. (2020)
Non-stationarity of macro series	Tab. S6	Hamilton (2020), Nelson and Plosser (1982)
Constant factor shares	Fig. 2	Kaldor (1960, 1961)
Growing capital-labour ratio	Fig. 2	Kaldor (1960, 1961)
Convergence to positive productivity growth rates	Fig. 2	Kaldor (1960, 1961)
Convergence to positive profit rates	Fig. 2	Kaldor (1960, 1961)
Correlation structure of key variables	Fig. S1	Assenza et al. (2015), Stock and Watson (1999)
Cyclicality of R&D	Fig. S1	Stock and Watson (1999), Wälde and Woitek (2004)
Patterns of specialisation and technical change		
Endogenous structural change	Fig. 3	Kuznets and Murphy (1966), Pasinetti (1983)
Innovation is correlated with performance on international markets	Fig. 4	Dosi et al. (1994b)
Countries develop absolute technological advantages	Fig. 3	Dosi and Nelson (2010)
Exporters are larger in size than non-exporters	Fig. 4	Bernard and Jensen (1999)
Patterns of specialisation are sticky	Fig. 3	Lundvall (1992), Nelson (1993)
Productivity differences at various levels of disaggregation	Fig.s S2, 3, 4	Dosi et al. (1994b)
Positive correlation between income inequality and concentration	Fig. S2, 3	Autor et al. (2020)

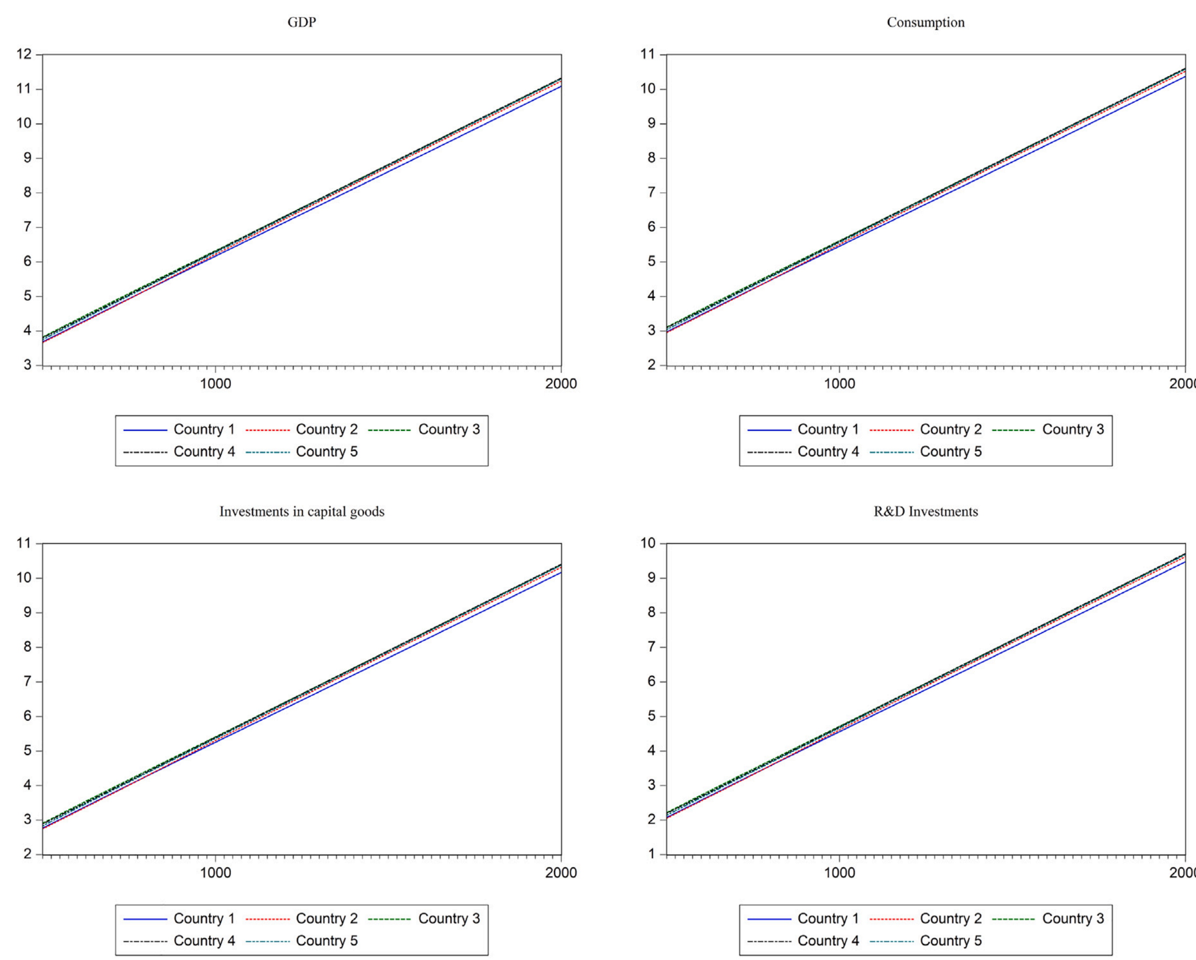

Fig. 1. Overall growth patterns.
Note: we represent average Monte Carlo replications and we have deleted the first 500 hundreds periods to focus on the long-run stable pattern of the log-transformed series.

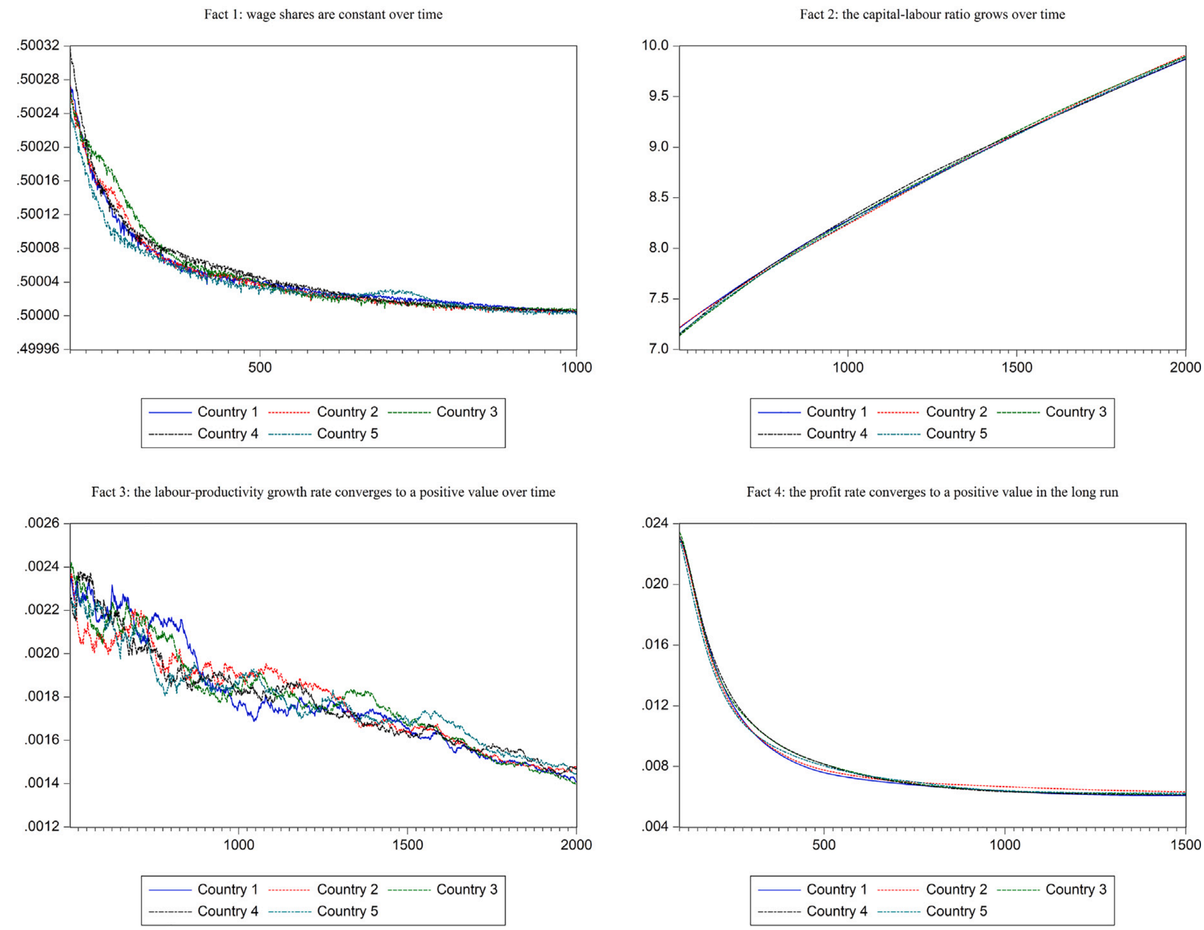

Fig. 2. Kaldor's facts.
Note: we represent average Monte Carlo replications to focus on the long-run stable patterns. We restrict the time span of wage share and profit rate to zoom in the converging pattern. The capital-labour ratio is expressed in log terms.

growth gap across sectors, hence decreasing the stabilisation level of coefficient.

On the other hand, Fig. 3 presents simulations of the Harrodian trade multiplier, which is significantly greater than 1 for all countries, though two of them converge to some greater value than others. Beyond constituting a rationale to supporting Keynesian policies, a stable Harrodian multiplier moves away the recent threats of Harrodian instability in agent-based models (Botte, 2019; Franke, 2019; Russo, 2020). Moreover, higher multipliers are positively associated with countries having lower degree of specialisation.

Last point is about income inequality: last plot in Fig. 3 reveals a coefficient of variation significantly higher than 1 for the wage bill across classes and sectors within any country. A pattern as such envisages a positive relationship between market concentration and income inequality (Autor et al., 2020; Caiani et al., 2019; Ciarli et al., 2010, 2019; Saez and Zucman, 2020). As an enterprise gets all the demand for a product, it keeps on growing in terms of employment and hierarchical structure. Nevertheless, the ceiling in the number of tiers makes the difference between the amount of income which is given to the lowest tier of workers and the amount of income to the last tier increase, leading to a high variation in the level of income of each class that persists at the aggregate level too (see also the corresponding graph in Fig. 4).

Yet, the empirical growth literature remarks that the long-term patterns for the largest set of countries show an increasing differentiation in terms of GDP and productivity growth: different economies grow at different and variable rates (Durlauf et al., 2009a; Dosi et al., 2019; Durlauf et al., 2009b; Fagerberg, 1987, 1994). Among the several stylised facts, this setting also exhibits divergent GDP and productivity growth patterns (Fig. 4). The coefficient of variation in productivity growth across countries reduces but tends to a strictly positive value. Therefore, we confirm the further evidence about endogenous divergence in growing economies. The cumulative causation in the dynamics of income elasticities explains long-run divergence.

Pre-existing models have considered the interplay between technological-change driven specialisation dynamics and divergence patterns in evolutionary, Schumpeterian dynamics with Kaldorian, balance-of-payment constrained growth frameworks (Lorentz, 2015a,b; Lorentz and Ciarli, 2014; Verspagen, 1992). While Verspagen (1992) points at the interplay of technological capabilities and the transformation in demand structures as sources of divergent patterns, Lorentz (2015a) refines the outcome showing that the divergence patterns solely driven by specialisation and technological advantage are only transitory. These patterns need to be combined with differences in income elasticities among sectors for specialisation mechanisms to translate into persistent divergence patterns, for evolving expenditure shares driven by demand shocks (Lorentz, 2015b) or imitation in consumption patterns (Lorentz and Ciarli, 2014), rather than fixed heterogeneous income elasticities, the frequency and amplitude of the shocks in expenditure shares (Lorentz, 2015b), or the speed of convergence (Lorentz and Ciarli, 2014) eventually prevent the structure of expenditure shares to stabilise. As the distribution of expenditure share stabilises, income elasticities tend to 1, the growth of expenditures for all sectors follows the growth of GDP, then the specialisation pattern only affects GDP levels, but all sector growing at the same rate, so does GDP. Similarly in our model, the dynamics of product innovation

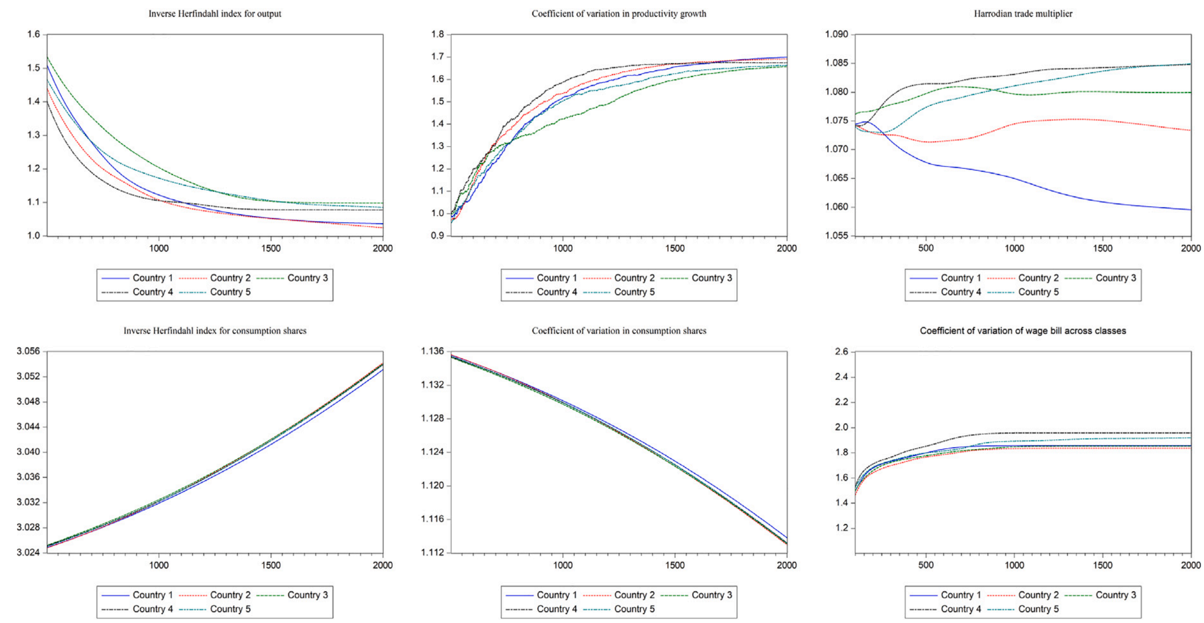

Fig. 3. Specialisation and technological change at country level.
Note: we represent average Monte Carlo replications and we have deleted the first 500 hundreds periods for all indicators but the Harrodian trade multiplier to focus on the long-run stable patterns.

allows the specialisation pattern to transitorily generate divergence in growth, due to a cumulative mechanism, until specialisation and the market structure stabilise. The mechanism of product innovation being symmetrically set, the changes occurring then are similar and symmetric, reducing the differences in income elasticities across sectors and, therefore, the impact of specialisation patterns and/or productivity differences on the divergence pattern.

The battery of experiments in Section 3.4 aims at testing the role of science policies in the specialisation and technical change paths. The following analysis is composed of two parts: the first is about the effects on economic growth and structural change, the second deals with the impacts upon market structure, income distribution, and consumption behaviour.

5. Experiments: broad S & T vs. mission-oriented policies

The experiments scheduled in Section 3.4 were organised on some criteria. The first concerns to symmetric policies where the countries joined in a monetary union apply the same science policy with respect to the magnitude of research investments as share of GDP, and of allocation of resources between mission-oriented projects and open science. In turn, mission-oriented investments target one of the following: most technologically advanced sector, most competitive sector, or the weakest industry in terms of market share.

We turn our attention to Table 2 to Table 4 which provide statistics at monetary-union level. Firstly, we delve into economic growth and structural change dynamics. Secondly, we investigate the implications for income distribution and consumption behaviour. Tab. S7 to Tab. S13 in the Supplementary Material support our main arguments.

5.1. Economic growth and structural change: any convergence out of symmetric policies?

When discussing the stylised facts, we have pointed out that national economies have diverging growth patterns which diminish over time but remains strictly positive. Turning our attention to the experiments and their effects on growth dynamics, we notice the following picture in Table 2.

Firstly, regardless of the experiment, any government that enters the economy with research investments reduces and stabilises growth divergence. From a baseline coefficient of variation of about 0.14, the system reaches a value in between 0.02 and 0.05 at most. The values are significantly different from the benchmark. This feature also holds for each pair of parameters (g_c, ψ_c).

Secondly, the relationship between the share of investment to mission-oriented projects with the coefficient of variation is U-shaped when governments try to push the technological frontier ahead. GDP growth divergence enhances for extreme values of ψ_c, suggesting that a mix of broad spectrum and targeted policies seem more efficient to dampen divergence. Conversely, no clear pattern emerges from increasing the share of GDP to be invested. Seemingly, sustaining a position of leadership and relaunching declining sectors provide almost the same qualitative result but together suit better in decreasing growth divergence with respect to fostering the technological frontier. Indeed, households allocate their labour income according to the quality of each good: targeting a sector according to its relevance in national production might gather public investments towards goods of relatively high quality. The country that by chance bets on these commodities benefit from stronger growth performance, thereby catching up with any prior best performer. Additionally, there is some but not shared evidence that targeting increasing funding to mission-oriented investments reduce growth divergence.[18]

We keep on delving into divergence dynamics by observing specialisation patterns (Table 3 and Tab. S8 in the Supplementary Material). Regardless of the setting, science and technology policies drive productivity-growth divergence. The coefficient of variation in productivity growth between countries shifts from the baseline 0.26 to a value in between 1.15 and 1.50. Although again no straightforward pattern arises for different combinations of (g_c, ψ_c), sustaining a leadership or relaunching laggard sectors now enhances productivity divergence

[18] The role of aggregate demand as engine of growth and propulsive fuel does not really change. Tab. S7 in the Supplementary Material reports to the long-run Harrodian multiplier: averages are not statistically different from benchmark values in most cases.

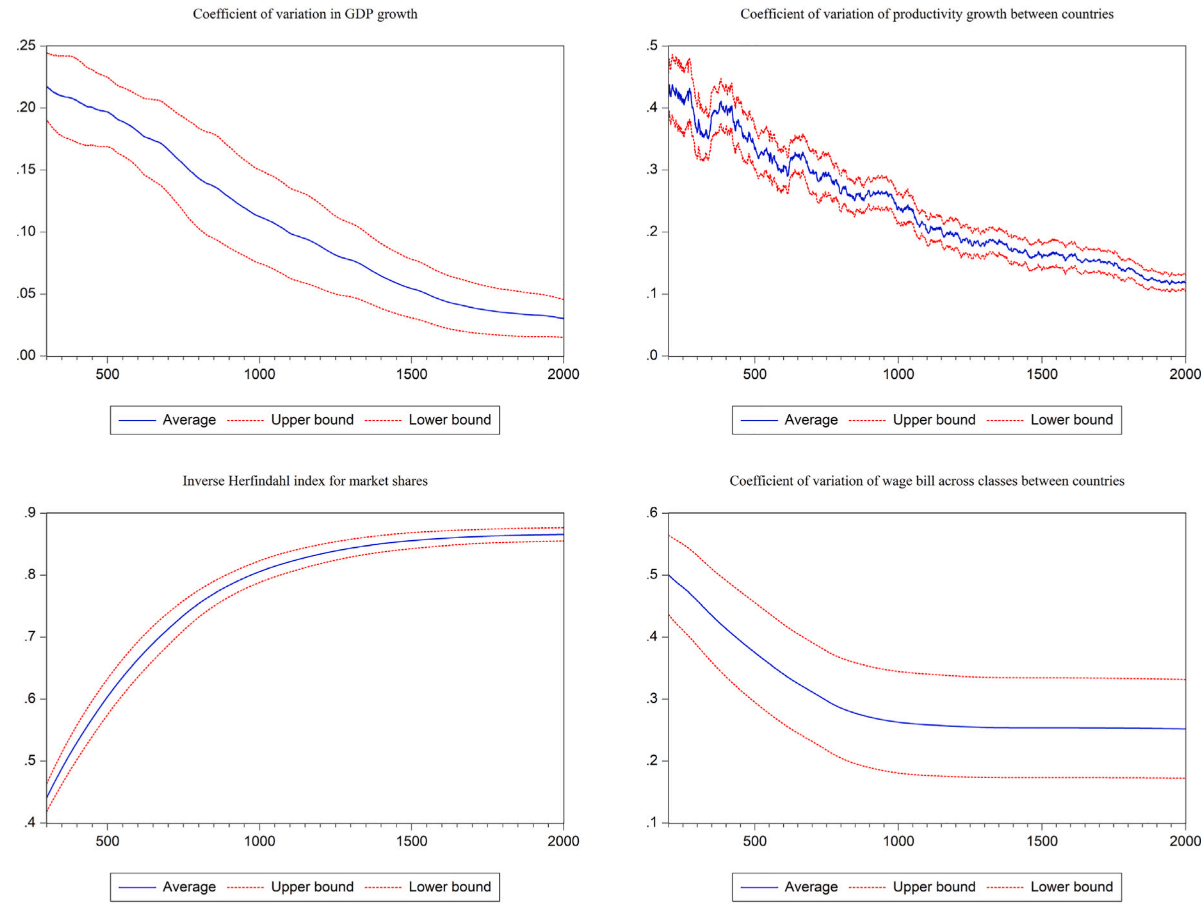

Fig. 4. Specialisation and technological change at monetary union level. Note: we represent average Monte Carlo replications to focus on the long-run stable patterns.

Table 2
Coefficient of variation of GDP growth across experiments.

ψ_c , g_c	0.02	0.04	0.06	0.08	0.1
Baseline average (sd): 0.139 (0.082)					
Pushing the technological frontier ahead					
0	0.049***	0.044***	0.042***	0.041***	0.046***
0.3	0.032***	0.031***	0.035***	0.041***	0.041***
0.5	0.026***	0.033***	0.046***	0.052***	0.049***
0.7	0.030***	0.033***	0.040***	0.040***	0.035***
0.9	0.027***	0.023***	0.033***	0.044***	0.037***
1	0.042***	0.049***	0.055***	0.038***	0.045***
Sustaining a position of leadership					
0	0.024***	0.032***	0.039***	0.039***	0.032***
0.3	0.024***	0.025***	0.026***	0.026***	0.026***
0.5	0.025***	0.025***	0.028***	0.035***	0.042***
0.7	0.025***	0.027***	0.025***	0.028***	0.034***
0.9	0.019***	0.024***	0.026***	0.031***	0.028***
1	0.031***	0.029***	0.024***	0.039***	0.035***
Relaunching declining sectors					
0	0.024***	0.031***	0.035***	0.036***	0.031***
0.3	0.023***	0.025***	0.026***	0.025***	0.024***
0.5	0.025***	0.022***	0.027***	0.035***	0.024***
0.7	0.024***	0.024***	0.024***	0.028***	0.040***
0.9	0.017***	0.023***	0.025***	0.031***	0.028***
1	0.031***	0.029***	0.024***	0.038***	0.035***

Note: mean values over 25 replications for the key indicator at Monetary Union level over 2000 simulation steps. The benchmark scenario considers g_c as null. The significance of the difference between the benchmark configuration and each pair of parameters is computed with a t-test: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

across countries. The more governments bring oxygen to an industry and try to sustain firms' innovative search therein, the greater country divergence. Declining sectors may either be those with a low share of expenditure in the consumption bundle because of lower quality or industries in which domestic firms have no chance to be competitive on international markets. Either way, public research investments look *wasted* towards sectors that undermine growth potentials. Yet, pushing the frontier ahead seems crucial to moderate divergence tendencies which are always at work with research intervention. In between, strengthening a leadership once again underlines the role of demand as engine of growth.

This outcome is paired with the corresponding shrinkage of the same divergence tendencies previously operating *within* countries. On the one hand, fostering the technological frontier and fuelling the position of leadership both increase divergence when combined with higher values g_c. As expected, divergence declines when the government targets declined sectors. Along with some evidence of reduced coefficients of variation for ψ_c values lower than 1, we contend that open science and the support to laggard sectors could be an effective means in limiting the intrinsic divergence mechanism. If there is at least a tiny flow of investments in public research whose achievements are available to all, this could still allow other industries to innovate. If all investments are mission-oriented, it is likely that weaker sectors do not grow and amplify productivity differentials.

For what concerns to specialisation patterns, we asserted that countries tended to specialise in a key sector. However, inverse Herfindahl indexes significantly greater than 1 meant that some oligopolistic structure where in place at market level. This argument is far more evident in Tab. S9 in the Supplementary Material, where the index related to output is of very greater magnitude, always around 3 on average.

Table 3
Coefficient of variation of productivity growth between countries across experiments.

ψ, g_c	0.02	0.04	0.06	0.08	0.1
Baseline average (sd): 0.264 (0.030)					
Pushing the technological frontier ahead					
0	1.146***	1.152***	1.160***	1.108***	1.074***
0.3	1.412***	1.365***	1.320***	1.108***	1.207***
0.5	1.400***	1.056***	1.206***	1.198***	1.050***
0.7	1.310***	1.330***	1.262***	1.160***	1.224***
0.9	1.362***	1.376***	1.262***	1.280***	1.228***
1	1.223***	1.195***	1.141***	1.236***	1.189***
Sustaining a position of leadership					
0	1.427***	1.348***	1.367***	1.281***	1.376***
0.3	1.550***	1.444***	1.475***	1.490***	1.422***
0.5	1.489***	1.489***	1.441***	1.366***	1.324***
0.7	1.548***	1.501***	1.499***	1.376***	1.333***
0.9	1.567***	1.568***	1.464***	1.458***	1.445***
1	1.407***	1.416***	1.478***	1.325***	1.278***
Relaunching declining sectors					
0	1.427***	1.352***	1.384***	1.289***	1.379***
0.3	1.555***	1.444***	1.475***	1.493***	1.429***
0.5	1.493***	1.511***	1.447***	1.367***	1.429***
0.7	1.558***	1.519***	1.504***	1.376***	1.333***
0.9	1.578***	1.579***	1.467***	1.458***	1.447***
1	1.408***	1.416***	1.479***	1.327***	1.279***

Note: mean values over 25 replications for the key indicator at Monetary Union level over 2000 simulation steps. The benchmark scenario considers g_c as null. The significance of the difference between the benchmark configuration and each pair of parameters is computed with a t-test: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Table 4
Coefficient of variation of wage bill between countries across experiments.

ψ_c , g_c	0.02	0.04	0.06	0.08	0.1
Baseline average (sd): 0.371 (0.230)					
Pushing the technological frontier ahead					
0	0.303	0.305	0.329	0.320	0.345
0.3	0.302	0.302	0.312	0.320	0.301
0.5	0.290*	0.268**	0.316	0.308	0.324
0.7	0.293*	0.299	0.315	0.334	0.317
0.9	0.282*	0.270**	0.328	0.319	0.325
1	0.323	0.311	0.292*	0.306	0.324
Sustaining a position of leadership					
0	0.303	0.293*	0.325	0.322	0.314
0.3	0.259**	0.264**	0.263**	0.280**	0.281
0.5	0.286*	0.269**	0.271**	0.298	0.325
0.7	0.261*	0.284*	0.272**	0.271**	0.294
0.9	0.237***	0.266**	0.273**	0.271**	0.267
1	0.286*	0.288*	0.282*	0.317	0.314
Relaunching declining sectors					
0	0.303	0.294*	0.323	0.322	0.314
0.3	0.259**	0.264**	0.263**	0.280**	0.281*
0.5	0.286*	0.271**	0.271**	0.298	0.281*
0.7	0.263**	0.284*	0.271**	0.271**	0.324
0.9	0.236***	0.265**	0.273**	0.271**	0.267**
1	0.286*	0.288*	0.282*	0.317	0.314

Note: mean values over 25 replications for the key indicator at Monetary Union level over 2000 simulation steps. The benchmark scenario considers g_c as null. The significance of the difference between the benchmark configuration and each pair of parameters is computed with a t-test: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Beyond offering some insights on the enhanced competition at market level, these results tell about the benefits from public research which diffuse across industries and enhances the probability to harvest the fruits from innovative search at firm level. This impacts negatively upon specialisation, since an economy becomes more diversified in its portfolio of productions.[19]

5.2. Income distribution, and consumption behaviour

We present in Table 4 and in Tab. S11 to Tab. S13 in the Supplementary Material the patterns of income distribution and consumption shares. At monetary-union level, we do not observe a strong impact on income inequality from the battery of experiments. The baseline coefficient of variation in the wage bill between countries was about 0.37. When the governments target a position of leadership or help declining sectors catch up, cross-country inequality slightly decreases and averages between 0.25 and 0.30. Furthermore, a positive relationship seems to exist between inequality and higher shares of public investments in GDP. Increasing investments enhance firms probability to innovate and grow larger, also boosting the organisational structure. The greater the amount of hierarchical layers, the larger the firm wage differential across countries, *ceteris paribus*. Yet, varying preferences between open science and mission-oriented policies seem to affect this overall pattern. At the same time, pushing the technological frontier ahead is ineffective in most cases: income inequality remains untouched.

We offer a similar interpretation for within-countries inequality dynamics. The winner-takes-all dynamics entailed a rise in the hierarchical complexity at firm level in the baseline scenario: the ceiling in the number of employment tiers allowed for a sustained accumulation of income in the top tier, which, when compared to the income earned at the bottom tier, led to high income inequality. Public policies reverse this tendency: a competitive market structure implies an agile hierarchical structure, namely smaller firms, hence the deviation in earnings by top and bottom tiers of the employment structure is reduced. This mechanism shrinks income inequality. Nonetheless, income inequality is fostered by increases in the share of investments in GDP. Indeed, it is positively correlated with a concentration of the market, even if the average value of the indicator is still significantly lower than the baseline's.

Finally, Tab. S12 and Tab. S13 in the Supplementary Material analyse how households allocate their consumption. No evident or remarkable outcome does emerge. In most cases, with few quantitative but not qualitatively exceptions, results are not statistically different from the baseline. Fig. 3 showed that consumers distributed their income along all the several goods in the market, while the relevance of each good in the consumption bundle displayed no convergence, i.e., goods with higher quality were always preferred. This statement is still valid after the experiments. Science policies by the governments do not significantly affect the expenditure patterns.[20] This outcome raises concerns about the sufficiency of supply-side science policies in facing grand societal challenges. As argued by Foray et al. (2012, p. 1701), among the many others: "[I]t is important that public R & D programs maintain good communications with users of technologies that the programs seek to help develop or improve, and that programme managers have a good understanding of user needs", with the corresponding recommendation of demand-side policies besides the supply-side's.

Next Section offers some implications for policy, sketches the future research questions and concludes the article.

[19] Tab. S10 in the Supplementary Material refers to the log-average capital-labour ratios. These indicators significantly decrease with respect to baseline average for any economies. Public investments fuel the degree of competition within markets. The magnitude of profits per-firm is lower. This feature results in lower firm capabilities both to hire scientists to carry out R & D at firm level and to exploit the innovation fruits through investments in capital stock. Profits constrain innovation possibilities when spread across a higher number of firms.

[20] Public policies could impact on the demand side of the economy *via* income elasticities and satiability level. In other terms, public funding enhances the probability of product innovation that increases the satiability level of each good. Greater values of this variable should drive consumption towards the related goods at the disadvantage of the other commodities. Yet, this does not happen, despite there is not any assumption in the model such that public policies have to be effective on the supply side of the economy only.

6. Conclusions and policy implications

The main purpose of this paper was to analyse the outcomes in terms of economic growth, structural and technological change as result of governments science policies. We were particularly interested in the emergence of trade-off, if any and which ones, as well as their macroeconomic impacts on countries integrated in a Monetary Union. The role of the public sector was restricted to the allocation of a share of GDP between open science and mission-oriented programs. Several relevant results with key policy implications emerge from our numerical simulations.

Firstly, we remark the role of national governments as source of lessened growth divergence. We have started our analysis by focussing on the private side of the economy only. In that baseline, countries used to specialise in the sectors in which they were most competitive. GDP growth divergence and persistent productivity differentials held across sectors. Government intervention by means of investments in science and technology policy along different shares of GDP, and the allocation of these resources between open science and mission-oriented research, have reduced growth divergence mechanisms. On the one hand, the pattern of divergence in GDP growth is smaller and statistically different from the baseline configuration. On the other hand, public policies, even when symmetric in terms of share of GDP invested and resources allocation, fuel a strong and persistent divergence in labour productivity growth. Since households prefer consuming high-quality goods, investing in the domestic most, or least, competitive industries might result in strengthening the national position in the production of goods which are gradually less important in the consumption basket. The dynamic increasing returns to scale that link demand growth with productivity gains would then diminish and trigger growth divergence.

The related policy implication is a call for coordination at a supranational level. A supranational institution such as the European Commission could schedule compensating mechanisms and incentives to strengthen technological transfers and collaborations across countries. We should remember in this case all the benefits in terms of productivity or innovation rates, however measured, from networks and spillovers: they are particularly important when the technological trajectories are highly indeterminate, i.e., when the range of development paths is large and the value of direct interactions increases (Salter and Martin, 2001). In other words, coordinated policies at supranational level can be useful not only to stop averse divergence dynamics or low-growth traps, but they can be crucial also for leading countries strongly engaged in mission-oriented programs which, by definition, cope with the emergence of new technologies. Furthermore and always with reference to the European Union, the technological diversity in terms of competences and learning processes across EU members should be a stimulus to devising *cohesion* policies *à la* Cohendet and Llerena (1997) in which the several European local systems of innovation interact and learn, "defining viable solutions for collective sharing of the mode of appropriation of new technologies, organising the mechanisms of normalisation and standardisation, anticipating the need of gateways technologies when lock-in mechanisms lead to a non-competitive array of technological solutions" (Cohendet and Llerena, 1994, p. 224).

Secondly, public investments in research decrease the productivity growth differentials between sectors. The benefits of open science policies, through their effect on the probability to innovate at business level, are evident: though productivity differentials still exist, sectoral gains are much more concentrated around a common average than before. Domestic industries tend to follow parallel technological trajectories. A second message out of the experiments is that the productivity *convergence* between sectors is a result of open-science policies. Indeed, even if economic growth is largely driven by the sectors with absolute advantages, or industries most helped by the government, having at least a little flow of open-science investments as percentage of GDP still allows other sectors to survive and innovate, preserving the variety of the economic structure.

This result adds a further rationale for the support of basic research by public funds, away from the old-fashioned market failure arguments. As clearly summarised by Salter and Martin (2001, p. 528), "These benefits are often subtle, heterogeneous, difficult to track or measure, [...] and should be viewed as a source of new ideas, opportunities, methods and, most importantly, trained problem-solvers". Basically, the building up of learning capabilities is the economic goal and most *visible* outcome of science policy.

Thirdly, science policy changes the overall structure of the markets. Monopoly dominated every market in the baseline setting. This is no longer true. Science policy alone is sufficient to limit monopolistic tendencies and trigger competition. Three important effects arise. Firstly, countries de-specialise: their economic activity is more diversified and less concentrated in a lower number of sectors. Still, such results are conditioned to the flow of open science. If a country supports the wrong industries and puts all the eggs in the same basket, this may result in a long-run trap, in which the country is anchored to unfavourable development trajectories. By contrast, diversifying, i.e., preserving open science for a wide array of sectors, countries keep competitive and active firms in the sectors in which they do not primarily specialise. Open science allows, once more, for the survival of sectors.

Fourthly, inasmuch as the benefits of broad spectrum S & T policies spread across sectors, our work agrees with the recommendations in Mowery et al. (2010), Soete and Arundel (1995, 1993) and European Commission (2018e), among the others. These contributions recognise the growing urgency of the societal challenges raised by the climate change and criticised the popular view according to which national governments should just undertake a new *Manhattan Project* or a new *Apollo Program* to cope with that. They believe this policy model as inappropriate in both the merit and the manners, for both programs were managed by federal agencies to achieve a specific technological solution for which the government was the sole customer. By contrast, the interests of many different actors are intertwined in societal issues such as the climate change. Rather than being circumscribed to a relatively short-period horizon, public research and innovation policies should be partnered with important private funds, which takes into consideration cost-effectiveness, ease of operation, and reliability systems for several decades (Mowery et al., 2010).

The analysis developed in our study fully agrees with these recommendations and totally supports the call for a governance structure of public R & D programs to encourage a broad dissemination of scientific research across industries. Behind reducing productivity growth differentials across sectors, open science triggers and fuels the Schumpeterian competition out of which new radical solutions to technological challenges might emerge.

Also, as recognised by official documents of supranational institutions (European Commission, 2018a,b,c,d,e; Soete and Arundel, 1993), supply-side policies alone are not sufficient. In our framework, as well as in real world, science policies seem not to be able to reorganise and change consumption habits: demand-side policies with citizens' engagement at the forefront is key to better identify, schedule, and device solutions to meet real and concrete societal needs.[21]

To conclude, despite our results seem to be robust across the scenarios, some caution is advisable. The financial side of the model is not developed, namely how governments obtain funds for investments, by taxes or debt, is not specified. The lack of a banking system as well constrains perhaps too much firms ability to undertake (radical) innovative search. Additionally, labour supply is fully elastic: a well-recognised benefit from science policies is the flow of skilled graduates which bring a knowledge of recent scientific research to firms, and the

[21] It is important to note that all these policy recommendations, in our opinion, would be useful to fix Europe's structural weakness in its system of scientific research and industry, as argued by Dosi et al. (2006) and Dosi et al. (2023).

Table A.5
Parameter setting.

Parameter	Description	Value
T	Time	2000
MC	Monte Carlo runs	50
i	Number of firms at country-sector level	10
j	Number of sectors at country level	4
c	Number of countries	5
b	Wage multiplier	1.5
ϕ	Market share sensitivity to competitiveness	0.09
ψ_c	Share of spending to mission-oriented policies	0
μ	Mark-up	1
ι	Share of firm's resources invested in capital goods	0.4
δ_a	Coefficient in R&D probability to innovate	0.05
δ_θ	Coefficient in R&D probability to innovate	0.05
γ_1	Coefficient in R&D probability to innovate	0.33
γ_2	Coefficient in R&D probability to innovate	0.33
γ_3	Coefficient in R&D probability to innovate	0.34
γ_w	Wage stickiness	0.75
g_c	Share of S&T in GDP	0
η	Convergence speed of expenditure share	0.4
ρ	Share of firm's resources invested in R&D	0.2
σ_0	Coefficient in the imitation stochastic process	0.25

ability to solve complex problems therein. Relaxing these constraints in future research would give us a better picture of the possible patterns that (will) characterise the international economic system in general, and the European Monetary Union in particular, in the next future.

CRediT authorship contribution statement

Andrea Borsato: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **André Lorentz:** Writing – review & editing, Validation, Supervision, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Chart of the model and parameter setting

See Fig. A.5 and Table A.5

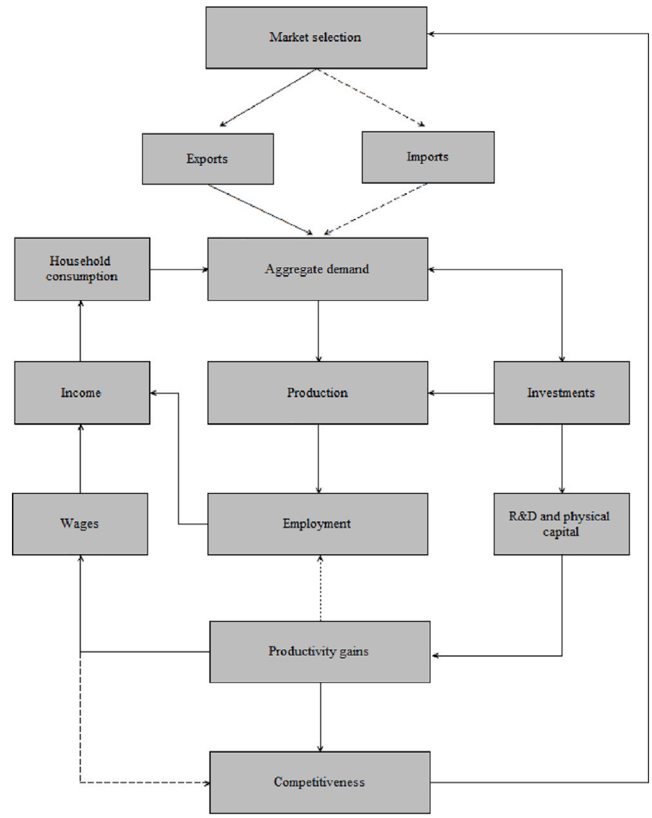

Fig. A.5. Chart of the model.
Note: continuous and dashed lines point to positive and negative effects, respectively.

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.strueco.2025.03.001.

Data availability

The pseudo-code for the simulation conducted in this paper is available upon request from the Authors.

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