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An evolutionary agent-based model of innovation and the risk-reward nexus

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Abstract The present paper studies the relative roles of public and private agents in the innovation process and their rewards. Building on an evolutionary framework, we account for the generation of skills as an endogenous process in innovation development, in which different agents contribute to value generation, but some are able to extract value more than proportionally. By focusing on the division of risks and rewards between public and private agents under different scenarios, we study the mechanisms by which some private agents access innovation surplus profits, obtaining conceptual insights into how innovation and its financing leads to inequality.

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1 Introduction

What are the distributional impacts of innovation? While this question is today being asked in the context of the jobs that might be destroyed by robots (Brynjolfsson and McAfee, 2012), there is not enough attention on the degree to which distribution and job creation may be affected by the way that the gains from innovation — with or without robots — are shared.

In order to assess the distribution of innovation gains between the actors involved, we need to understand more comprehensively how value is created and extracted throughout the innovation process. In fact, whereas private organisations invest in innovation only when they see an opportunity for profits, public organisations invest in technology from an early stage. Private organisations may gain disproportionately from this technological knowledge rendered available by the public sector, as expected returns become less uncertain.

The aim of this paper is to study the mechanism by which some agents access innovation surplus profits amplifying inequality by means of an evolutionary simulation model. We focus the model on the risk-reward nexus (Mazzucato, 2013; Lazonick and Mazzucato, 2013) operating throughout an endogenous innovation process in an industry with two different agent-types: (i) the public sector investing in frontier technology, (ii) private firms using and improving the new technology to produce a final product. We assess to what extent the profitability of private firms is conditioned by the role of the public sector investing in new technology. The model is focused on better understanding the distribution of gains between public and private actors, and the implications of this for innovation policy and inequality.

Representing the technology as an pseudo-NK landscape (Valente, 2014) we describe the interdependence across public and private organisations in the search for a dominant design, highlighting the collective character of innovation. Firms' positions in the technological landscape determine the quality of the final product, thus influencing market shares across competing firms and conditioning the path of expected profitability. Moreover, for given profitability levels, agents behave differently as regards the re-investment of profits into innovation development. Consequently, heterogeneity in investment heuristics affects the pace of knowledge accumulation and collective innovation. The public sector takes part in this cumulative process by investing directly in R&D, licensing to private firms access to the new technology, as well as through taxation.

In order to depict and characterise the industrial dynamics emerging from the model, we design a set of scenarios with associated simulations, aimed at understanding how the role of the public sector and the complexity of the technology shape the distribution of rewards between actors in the industry.

After this brief introduction, the rest of the paper is organised as follows. Section 2 motivates the framework. Section 3 introduces the model. In section 4 we present results of simulation exercises and discuss the emerging patterns. Finally, section 5 concludes.

2 The Risk-Reward Nexus

How should the wealth that an economy generates be distributed? Moral as well as economic arguments about who should be entitled to what – whether paid in wages, retained profits, or dividend payments – frequently seek to link rewards to contributions, for reasons of fairness or efficiency. But how these contributions are quantified depends first on how they are theorized. In this way, different theories of how value is created can be used to justify very different distributions of income and wealth. If entrepreneurs are believed to make extraordinary contributions to value creation, then maybe extraordinary rewards are justified?

Key to the problem is that in economic theory the public sector is, at best, seen as facilitating the process of wealth creation, but not being a key driver of the process itself. In microeconomics, it is seen as fixing markets, not creating them. In industrial-innovation economics, its role is limited to spending on public goods like basic science and de-risking the activities of innovators, and does not extend to being an innovator itself. In macroeconomics, it is seen as fixing the business cycle and as a lender of last resort. It is not seen as a lead risk-taker across the business cycle or an investor of first resort. And if or when a public agency does dare to make strategic choices and take risks, it is often accused of crowding out the private-sector actors, or of being too inept to 'pick winners'.

Yet the history of capitalism tells us a different story – the story of a public sector that has often been responsible for actively shaping and creating markets, not just fixing them. Indeed, markets themselves should be viewed as outcomes of the *interactions* between both public and private actors (Mazzucato, 2013).

Key to understanding the implications of this story is that public investments in areas like biotechnology, nanotechnology and the Internet were not limited to simply funding 'basic' research, a typical 'public good' in market failure theory (Arrow, 1962; Nelson, 1959). In the US, for example, government agencies funded areas along the entire innovation chain: both basic and applied research and, in many cases, provided downstream early stage high-risk finance to companies deemed too risky by the private financial sector.

The point is not that the private sector is unimportant, but that in new sectors like biotechnology, nanotechnology, and the emerging green economy, private businesses have tended to invest only after returns were in clear sight. The animal spirits of business investors are themselves an endogenous function of public investment, roused only after public investments have laid the groundwork in the highest-risk areas. This role of public investment is recognized in terms of the 'basics', such as infrastructure (without roads, businesses would have no way of transporting goods) and protecting private property. But beyond that it is largely ignored.

A better understanding of risk gives credit to the role of the public sector in innovative activities. Doing so makes it immediately logical for there to be a more collective distribution of the rewards, given that the presence of innovation is a result of a long-term cumulative, collective and uncertain process (and not just well-timed speculative finance). Central to this understanding is the need to better identify *how* the division of 'innovative labour' maps into a division of rewards. The innovation literature has provided many interesting insights on the former, for example the changing dynamic between large firms, small firms, government research and individuals in the innovation process. But there is very little understanding on how rewards are divided. And, as has been argued, governments and workers also make investments in the innovation process (if not greater investments) without guaranteed returns (Mazzucato, 2013).

The critical point is the relation between those who bear risk in contributing their labour and productive capacity to the innovation process and those who appropriate rewards from the innovation process. To understand this relation we build upon the risk-reward nexus framework (Mazzucato, 2013; Lazonick and Mazzucato, 2013). As a general set of propositions of the risk-reward nexus, when the appropriation of rewards outstrips the bearing of risk in the innovation process, the result is inequity; when the extent of inequity disrupts investment in the innovation process, the result is instability; and when the extent of instability increases the uncertainty of the innovation process, the result is a slowdown or even decline in economic growth. A major challenge is to put in place institutions to regulate the risk-reward nexus so that it supports equitable and stable economic growth. In the sections that follow, we introduce and discuss an evolutionary model that substantiates the dynamics just described. In particular, with the model we aim at understanding the public-private interaction mechanisms underlying the imbalance between risks and rewards, and the role of the public sector in their realignment.

3 The model

We present an agent-based simulation model of technological competition in an industry producing a final product. There are two agent types: A (public sector) and B (private firms). There is one instance of type-A and $n_B(t)$ instances of type-B, indexed as $i = 1, 2, \dots, n_B(t)$ for each time period t.[1]

3.1 Technology and innovation development

One crucial aspect by which innovation is an uncertain process stems from the non-linearity between an agent's R&D investment and the obtention of a product of higher quality.[2] Thus, a key channel through which risk is pervasive in innovation development lies in the *complexity of the technology* that maps research efforts to an output of higher quality.

In this sense, in our framework technology is represented by the fitness landscape of a pseudo-NK model (Valente, 2014): an N-dimensional multi-peaked surface (with a unique *global* peak) with K-interactions among dimensions (see Figure 1, for an example). The landscape is a correspondence that maps a position vector $\mathbf{x}^i(t) \in \mathbb{R}^N$ into a fitness value $\alpha^i(t) \in \mathbb{R}$. A technology consists of N components, whose combination (given by $\mathbf{x}^i(t)$) determines the quality of the final product obtained ($\alpha^i(t)$).[3]

Each dimension in the landscape represents a component of a new technology being introduced into the economy. Every agent (the public sector or private firm) explores the landscape, and each position (e.g. (x_1, x_2) in Figure 1) has a fitness score associated to it (the value on the vertical axis associated to (x_1, x_2) in Figure 1). The global peak represents the dominant design (Klepper, 1996)

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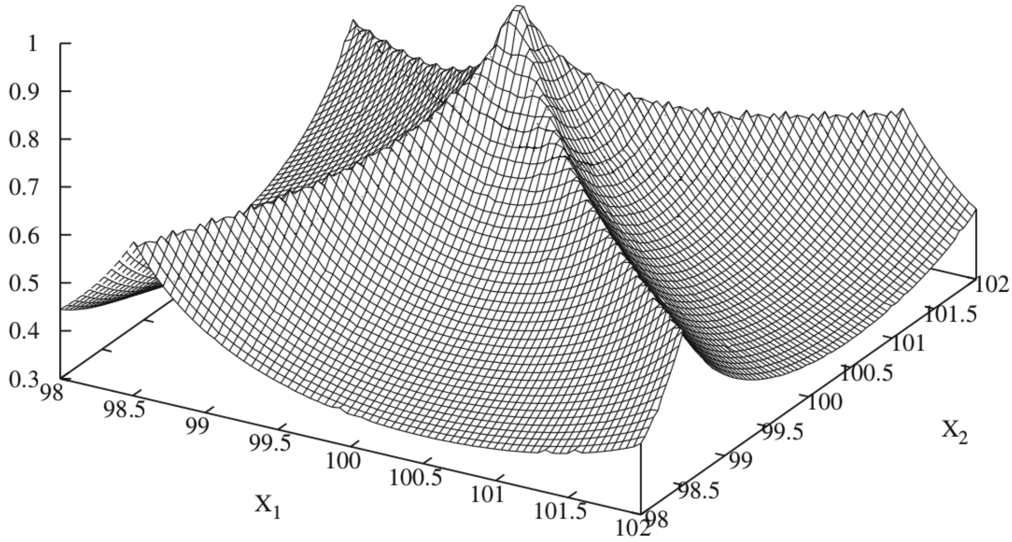
[1] The number of private firms $n_B(t)$ changes through time.

[2] In this model we mainly deal with product innovations rather than process innovations. Hence, our emphasis is on higher product quality rather than reductions in production costs.

[3] The pseudo-NK model is a variant of NK models (Kauffman, 1993) that improves on easiness of implementation, amongst other advantages. For details, see Valente (2014, pp. 112-3). A related exploration can be found in Ciarli et al. (2008). Moreover, the representation of production processes by means of an NK model from a neoclassical perspective can be found in Auerswald et al. (2000).

Figure 1: Example of fitness landscape for N=2 (Valente, 2014, p. 117)



of the new technology.

Technology components may be mutually dependent on each other. One of the channels to assess the complexity of the innovation process consists in the degree of connection between each pair of components that define the technology (i.e. each pair of dimensions of the landscape). For any given couple of dimensions j and k, a_{jk} represents the degree to which component j depends on component k, and this degree ranges from 0 (complete independence) to 1 (maximum interdependence). A high degree of interdependence between dimensions j and k means that a movement along dimension j, for different values of k, changes the impact of dimension j on fitness from negative (positive) to positive (negative).

Formally, in an N-dimensional landscape, each agent i has associated a landscape position vector at every time period t:

$$\mathbf{x}^i(t) = [x^i_j(t)] = (x^i_1(t), x^i_2(t), \ldots, x^i_N(t)) \tag{1}$$

The contribution to fitness of each dimension $j = 1, \ldots, N$ is given by:

$$\beta^i_j(\mathbf{x}^i(t)) = \frac{1}{1 + |x^i_j(t) - \gamma^i_j(\mathbf{x}^i(t))|} \tag{2}$$

where $\gamma^i_j(\mathbf{x}^i(t))$:

$$\gamma^i_j(\mathbf{x}^i(t)) = \Gamma_j + \sum_{k=1}^{N} a_{jk}(t) x^i_k(t) \tag{3}$$

is the *target* contribution to fitness of dimension j for agent i during t.

From the equations above, we can see that the contribution to fitness for agent i in dimension j, $\beta^i_j(\mathbf{x}^i(t))$, is the reciprocal of the absolute deviation of its current position $x^i_j(t)$ from a target $\gamma^i_j(\mathbf{x}^i(t))$ that provides the maximum contribution to fitness. Note carefully that this target depends on the current position of the agent in all other dimensions, making the assessment of fitness-improvement changes an interdependent process.

After computing $\beta^i_j(\mathbf{x}^i(t))$ for each dimension j, the fitness of agent i in an N-dimensional landscape is the average contribution to fitness across dimensions:

$$\alpha^i(t) = \frac{1}{N}\sum_{j=1}^{N} \beta^i_j(\mathbf{x}^i(t)) \tag{4}$$

At each time-period an agent obtains a fitness score $\alpha^i(t)$, which is the outcome of its landscape exploration. The exploration strategy of agent i to change its landscape position is that of 'one-bit mutation': at every time period t each agent takes a number of steps on the landscape. Each step consists in randomly choosing *one* of the N dimensions and moving along it by increasing/decreasing the intensity of use of the technology component associated to it. Such an increased intensity in one direction, *when* combined with the remaining $N-1$ components, may lead to *higher* or *lower* fitness. If the candidate position is fitness-improving with respect to the current one, the new position is adopted and $\alpha^i(t)$ has increased.

However, given the 'rugged' nature of the landscape, throughout this gradual and local search process firms risk facing a *lock-in* problem: landscape exploration may not lead to any increase in fitness at a *local* level. In this case, the flow of resources (e.g. R&D expenditure) that has gone into exploring the technology landscape does not lead to any improvement in the quality of the final product.

Thus, to monitor the process of innovation development at an *aggregate* level, we consider the average contribution to fitness across private firms:

$$\overline{\alpha}_B(t) = \frac{1}{n_B(t)}\sum_{i=1}^{n_B(t)} \alpha^i(t) \tag{5}$$

where $n_B(t)$ is the number active firms (type-B agents) exploring the landscape at time t; the contribution of the public sector:

$$\overline{\alpha}_A(t) = \alpha^A(t) \tag{6}$$

as well as the average contribution to fitness for the economy as a whole:

$$\overline{\alpha}(t) = \frac{1}{n_B(t)+1}\left(\sum_{i=1}^{n_B(t)} \alpha^i(t) + \alpha^A(t)\right) \tag{7}$$

The number of landscape steps (i.e. the number of one-bit mutations) that every agent i takes is an increasing function of its R&D expenditure:

$$\lambda^i(t) = \psi(RD^i(t)), \qquad \frac{d\psi}{dRD^i(t)} > 0 \tag{8}$$

i.e. the higher the R&D effort, the more steps a firm takes, having more chances of improving its fitness.

Hence, R&D intensity fuels the process of landscape exploration by which each agent accumulates skills and contributes to creating value in the economy (i.e. increasing the quality of its product). However, the value that is *created* within organisations (private firms and the public sector) through innovation development is *realised* (and extracted) via a process of market competition. We turn to this aspect below.

3.2 Final demand, market shares, value creation and extraction

We consider a single industry that produces a final product. The size of the market, i.e. total final demand $F(t)$ is functionally related to average product quality by a logistic curve (reflecting non-linearity and saturation effects):[4]

$$F(t) = \frac{100}{1 + e^{-\phi_1(\phi_2\overline{\alpha}(t)-\phi_3)}} \tag{9}$$

where product quality is given by the average contribution to fitness of the technology landscape, $\overline{\alpha}(t)$. Throughout our analysis, the quality of the final product for each firm is given by its contribution to fitness $\alpha^i(t)$. [5]

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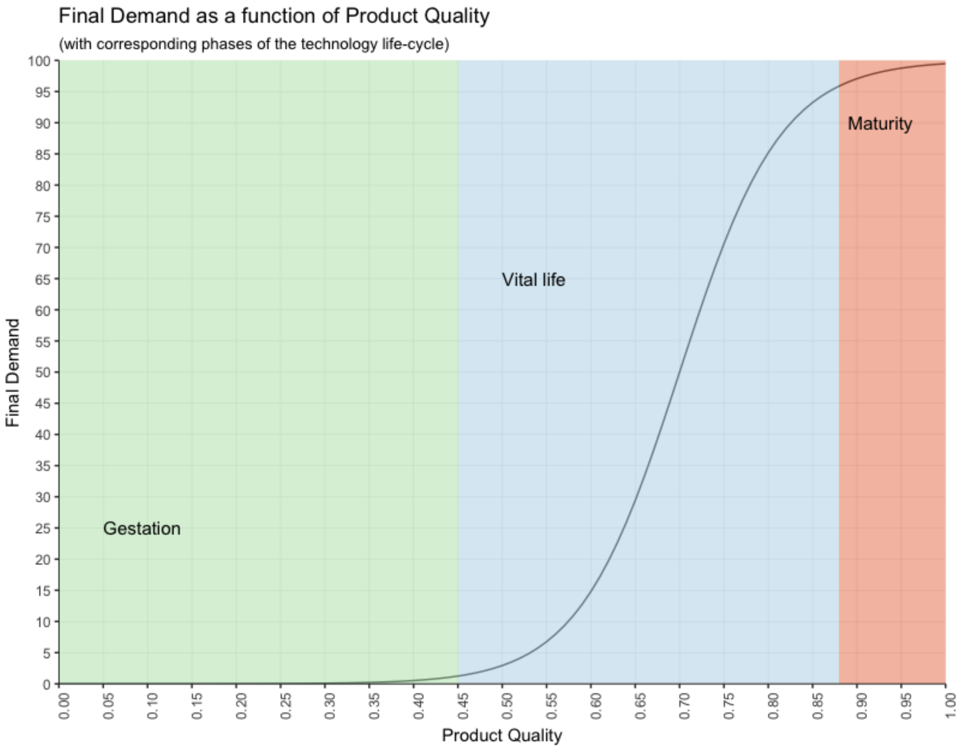
[4] Parameters (ϕ_1, ϕ_2, ϕ_3) govern the shape of the curve. In our implementation, $(\phi_1, \phi_2, \phi_3) = (0.35, 50, 35)$.

[5] Thus, this formulation explicitly links the co-evolution of demand *and* technology (c.f. Winter, 1984, p. 305), acknowledging that the pace and direction of technical change and the diffusion of the product are crucially related (Metcalfe, 1981).

Figure 2 illustrates the functional relation between the size of the market and average contribution to landscape fitness (i.e. product quality) distinguishing between stages of the technology life-cycle associated to the final product of the industry.[6] Note that final demand is comprised between $[0, 100]$, thus it may be interpreted as the percentage of adopters throughout the diffusion process of the product associated to the new technology.

Figure 2: Functional relation between Final Demand $F(t)$ and average product quality $\overline{\alpha}(t)$ over the technology life-cycle



Final demand addressed to each firm $f^i(t)$ is a share $\theta^i(t)$ in total final demand $F(t)$:

$$f^i(t) = \theta^i(t)F(t), \quad \text{such that} \quad \sum_{i=1}^{n_B(t)} f^i(t) = F(t) \tag{10}$$

where $\theta^i(t)$ is the market share of the i-th. firm at time t.

The evolution of market shares $\theta^i(t)$ is determined by a replicator equation (Metcalfe, 1998), which crucially depends on the extent to which the product quality of a firm, $\alpha^i(t)$, is above/below the (lagged) average for type-B agents,

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[6] The role of the public sector (type-A agent) during the gestation phase of the technology life-cycle will be detailed below.

$\overline{\alpha}_B(t-1)$:

$$\theta^i(t) = \theta^i(t-1)\left(1 + \chi\frac{\alpha^i(t) - \overline{\alpha}^B(t-1)}{\overline{\alpha}^B(t-1)}\right) \tag{11}$$

where χ is the intensity of replicator dynamics, $\alpha^i(t)$ is the product quality of the product of the i-th. firm at time t, and $\overline{\alpha}_B(t-1)$ is the (lagged) average product quality across $n_B(t-1)$ firms at time $t-1$.

Equation (11) crucially links technological competition to market competition. The process of technological exploration is non-linear and its outcome uncertain. For each firm, fitness-increasing movements in one direction are contingent on the position in other dimensions. Each agent's position in the landscape maps into a *fitness* score that measures distance to the *dominant design*, determining the quality of its final product, and hence its market share. Thus, firms with higher fitness gain market share at the expense of those whose fitness is stagnant.

The value created within each firm by means of quality improvements results in income generation when profits $\pi^i(t)$ are realised through sales $f^i(t)$, net of R&D expenditure for technological exploration $RD^i(t)$, taxes on revenues $\tau f^i(t)$, and the payment to the public sector of a license to access the new technology $c^i_A(t)$:[7]

$$\pi^i(t) = (1-\tau)f^i(t) - RD^i(t) - c^i_A(t) \tag{12}$$

The role of innovation development in market competition was established by equation (11), whereas the reverse feedback is obtained by linking current expenditure in R&D to the path of past sales:

$$RD^i(t) = \begin{cases} \underline{\eta}(1-\tau)f^i(t-1), & \text{if } \theta^{(i)}(t) < 1/2 \text{ and } F(t) > 50 \\ \overline{\eta}(1-\tau)f^i(t-1), & \text{otherwise} \end{cases} \tag{13}$$

where $(\underline{\eta}, \overline{\eta})$, with $\underline{\eta} < \overline{\eta}$ indicate alternative propensities to spend in R&D out of (net-of-taxes) sales. These parameters represent a *leakage* from the profits-investment nexus, by which only a part of past sales is invested in R&D and the reminder is extracted.

Decision rule (13) renders endogenous the process through which agents switch between two R&D spending regimes: if one firm has captured more than half of the size of the market, and the percentage of adopters is beyond

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[7] We will describe in more detail the role of taxes and licensing below.

50%, then the agent switches from a *high* ($\overline{\eta}$) to a *low* ($\underline{\eta}$) R&D expenditure regime. This regime switch is a mechanism that allows financial agents in control of a firm to *extract* a higher share of the value created by the agent.

3.3 Firm dynamics, entry and exit: competition regimes

Firm dynamics exhibits a process of cumulative causation. Firm i explores the fitness landscape describing its technological capacity to produce the final product. The fitness score it obtains, $\alpha^i(t)$ in (4), measures the distance to the dominant design. The distance to the dominant design sets the quality of the final product. Product quality differentials determine the evolution of market-shares, $\theta^i(t)$ in (11), distributing total final demand, $F(t)$ in (9), amongst active firms in the industry. Current firm sales $f^i(t)$ fuel next-period R&D spending, $RD^i(t+1)$ in (13). In this way, R&D expenditure maps into a number of landscape steps, $\lambda^{(i)}(t+1)$ in (8), determining a new fitness score $\alpha^i(t+1)$ that re-ignites the loop.

Entry of a new firm occurs at given time intervals. The new firm is randomly allocated to a landscape position $\mathbf{x}^i(t), i = n_B(t)+1$, which determines its fitness score, $\alpha^i(t), i = n_B(t) + 1$. If the entrant pays the license cost its location will be no worse than the position reached by the public sector, otherwise it will be drawn from a uniform distribution on an interval ranging between the maximum distance and the closest position to the dominant design, for each landscape dimension.[8]

Each entrant arrives to the market with a product which, *a priori*, resembles as much as possible the one produced by the incumbent with highest market share. Thus, inspired by Bass (1963), we assume it appeals to some consumers who switch to this new product. However, soon after entry, through the process of technological exploration and the associated quality, these consumers may find out that the entrant's product is not as good as the incumbent's, switching again to the higher-quality product of the latter. Formally, new entrants rip a percentage ϵ of the market share of the biggest incumbent:

$$\theta^i(t) = \epsilon\theta^{max}(t), \quad i = n_B(t) + 1 \tag{14}$$

where $\theta^{max}(t) = \{\theta^k(t) : \theta^i(t) \leq \theta^k(t), \forall i = 1, \ldots, n_B(t)\}$.

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[8] Formally, if firm i entering at time period t pays the license cost to the public sector, its initial landscape position for dimension j will be $x^i_j(t) = \min\{|x^A_j(t) - x^*_j|, |x^{env}_j(t) - x^*_j|\}$, where x^*_j is the position in dimension j associated to the fitness score of the dominant design and $x^{env}_j(t)$ is the *envelope* position for that dimension across agents at time t, i.e. $x^{env}_j(t) = \{x^k_j(t) : |x^k_j(t) - x^*_j| \leq |x^i_j(t) - x^*_j|, \forall i \in \{1, \ldots, n_B(t), A\}\}$.

As time goes by, due to the selection mechanism in equation (11), the incumbent may recover a privileged market position thanks to its above-average fitness score, and entrants may reduce their market shares if their product quality is below-average.

Finally, we assume a firm exits the industry when its market share falls below a minimum threshold:

$$\theta^i(T^i) = 0, \quad \text{if} \quad \theta^i(T^i) < \underline{\theta} \tag{15}$$

where T^i is the exit period for firm i.

Thus, by recalling that χ in (11) stands for the intensity of the replicator mechanism of market selection, the tuple of parameters $(\chi, \epsilon, \underline{\theta})$ defines the competition regime of the industry.

3.4 The public sector, licenses and knowledge spillovers

From the preceding subsections we have seen that the innovation process through landscape exploration involves high *risk* with uncertain *rewards* for private firms, due to the fact that R&D expenditure does not necessarily translates into product quality improvements (thus, higher market share and profits).

As has been extensively documented in Mazzucato (2013), processes of successful innovation have been triggered by the public sector. This agent explores the fitness landscape investing in R&D from an early stage, when low product quality makes it unprofitable and uncertain for private actors to invest in the new technology.

To represent this fact within the model, the public sector (type-A agent) starts landscape exploration at the gestation period of the technology life-cycle (see Figure 2) following the 'one-bit mutation' algorithm and expressions (1)-(4), obtaining average fitness (6). Only after the public sector reaches a fitness such that the size of the market for the final product — obtained through equation (9) — attains a minimum threshold, private firms (the $n_B(t)$ instances of type-B agents) start to explore the technology landscape. Thus, R&D performed by the public sector during the gestation period fuels knowledge accumulation that will be later exploited by private firms. But not only: even when private agents start exploring the landscape, continued R&D efforts by the Public sector contribute to increase current *average* fitness, increasing product quality and the size of the market for *private* firms.

The interaction between the public sector and private firms concerns crucially the access to the knowledge generated by the former. In particular, firms that pay a *license* to the public sector start from a landscape position that is no worse than that reached by type-A agent (i.e. knowledge spillovers are partially internalised). On the contrary, firms that do not pay a license start exploring the landscape from a random position, with a higher probability of facing relative backwardness. Moreover, in all cases, firms pay a (fixed) *tax* rate on sales to the public sector.

In accounting terms, the public sector spends $RD^A(t)$ in R&D to explore the technology landscape and receives income from the license for operating the new technology that some type-B agents pay $c^i_A(t)$, as well as collecting taxes from firms' sales. As a result, government income $Y^A(t)$ is given by:

$$Y^A(t) = \sum_{i=1}^{n_B(t)} \tau f^i(t) + \sum_{i=1}^{n_B^{Lic}(t)} c^i_A(t) - RD^A(t) \tag{16}$$

where $n_B^{Lic}(t)$ is the number of firms that pay the license cost to the public sector during period t.

Each firm that pays a license $c^i_A(t)$ to access the new technology will do so at its time of entry, but also every time it gets stuck in a local peak of the technology landscape, such that there is no one-bit mutation that may increase its fitness. In fact, by further paying an additional fee to the public sector, some private firms access the *current* state of knowledge accumulated by the government, and adopt a fitness-improving landscape position that allows them to exit this lock-in situation. The underlying assumption is that whenever the public sector gets stuck in a local peak, it has the resources to make a 'jump' to a relatively close landscape position and rekindle exploration from there.

Thus, the license cost set by the government and paid by each of the $n_B^{Lic}(t)$ firms in period t will be given by:

$$c^i_A(t) = \begin{cases} \xi K^A_{RD}(t) - \sum_{s=0}^{t-1} c^i_A(s), & \text{if first-access or jump} \\ 0, & \text{otherwise} \end{cases} \tag{17}$$

where ξ is a percentage applied to the accumulated (and capitalised) R&D expenditure by the public sector $K^A_{RD}(t)$:

$$K^A_{RD}(t) = (1-\delta)K^A_{RD}(t-1) + RD^A(t) \tag{18}$$

depreciating at rate δ.

If a firm pays a license to access the new technology, equation (17) states that it will pay $\xi K_{RD}^{A}(t)$ at the time of entry whereas, with each further payment to obtain the current state of knowledge, it will pay a fixed rate ξ on the *increment* of accumulated R&D that has taken place since the last time it had paid a license.

The decision rule of the public sector regarding the amount of R&D expenditure in every period is given by:

$$RD^{A}(t) = \max\left\{Y^{A}(t-1), \underline{RD}^{A}\right\} \tag{19}$$

where:

$$\underline{RD}^{A} = \iota^{*} K_{RD}^{*}(T)\frac{\delta}{1-(1-\delta)^{T}} \tag{20}$$

The logic of equation (20) runs as follows: consider a public sector that sets as its target to reach a share ι^{*} of *total* accumulated R&D expenditure $K_{RD}^{*}(T)$ by the end period T of the technology life-cycle, and to achieve it by investing a constant amount in every period. Then, that fixed amount $\underline{RD}^{A}$ would have to satisfy:

$$\begin{aligned}\iota^{*} K_{RD}^{*}(T) &= \sum_{s=0}^{T-1}(1-\delta)^{s}\underline{RD}^{A} = \\ &= \underline{RD}^{A} + (1-\delta)\underline{RD}^{A} + \cdots + (1-\delta)^{T-1}\underline{RD}^{A} = \\ &= \underline{RD}^{A}\sum_{s=0}^{T-1}(1-\delta)^{s} = \underline{RD}^{A}\left(\frac{(1-\delta)^{T}-1}{(1-\delta)-1}\right) = \underline{RD}^{A}\left(\frac{1-(1-\delta)^{T}}{\delta}\right)\end{aligned}$$

from where expression (20) follows.

Thus, decision rule (19) indicates that when the government is in deficit ($Y^{A}(t-1) < 0$) R&D expenditure will amount to $\underline{RD}^{A}$, and whenever the lagged surplus of the public sector is greater than $\underline{RD}^{A}$, the government will accelerate its investment in R&D by spending more than its initial target.[9]

Note that, as specified by (9), the key driver of final demand (i.e. the size of the market) is average product quality, $\overline{\alpha}(t)$ in (7). This average is the outcome of landscape exploration efforts fueled by R&D investments, and these investments depend on the path (size and distribution) of past sales by firms. Thus,

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[9] We assume that the government finances its deficit by obtaining access to resources to be repaid later on. In any case, public R&D expenditure is financed out of a combination of current taxation, public debt or a process of endogenous money creation.

rather than crowding out private R&D investment, public R&D expenditure increases the average fitness of the technology landscape, product quality and the size of the market, increasing firms' sales and *crowding in* further investment in R&D by private actors.

3.5 The sequence of accounts: skills, inequality and knowledge accumulation

So far we focused only on private firms (type-B agents) and the public sector (type-A agent). However, to complete the sequence of accounts in the model and study sources of inequality, we consider the institutional sector of households.

Household income is composed of wages $W(t)$ and dividends $Div(t)$:

$$Y^H(t) = W(t) + Div(t) \tag{21}$$

Wages are paid by the public sector and private firms, respectively:

$$W(t) = W^A(t) + W^B(t) \tag{22}$$

We further assume that R&D investment from both type-A and type-B agents consists in labour costs, i.e. wages paid to specialised R&D workers who perform research and applied development of new products.[10] Formally, we have:

$$W^A(t) = RD^A(t), \quad W^B(t) = \sum_{i=1}^{n_B(t)} RD^i(t) \tag{23}$$

Thus, higher investment rates not only accelerate landscape exploration but also imply a shift of household income towards wages. As a counterpart, it may be seen from decision rule (13) that when firms switch to a regime of lower R&D investment out of past sales (characterised by parameter $\underline{\eta}$), they exert a downward pressure on the share of wages in household income.

Another feature of the model consists in the fact that the generation of skills by specialised workers is an endogenous process that substantiates the exploration of the technology landscape. Skills developed by workers depend on the previous outcome of their own research. R&D efforts addressed to specialised labour that result in product quality improvements will be validated by the

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[10] In the US, the share of labour costs in total intramural R&D spending by the sector of business enterprises has risen from 46% (average 1981-1985) to 66% (average 2009-2013), source: OECD Dataset on Gross Domestic Expenditure on R&D by sector of performance and type of cost.

market via higher market shares, profits, investment *and* wages. Clearly, value extraction is maximised when the profits-investment nexus is at its minimum (i.e. as parameter $\underline{\eta}$ approaches zero).

Finally, dividends are determined by total profits across private firms:

$$Div(t) = \Pi(t), \quad \Pi(t) = \sum_{i=1}^{n_B(t)} \pi^i(t) \tag{24}$$

Operating on the relations just presented, it is straightforward to show that household income $Y^H(t)$ can be equivalently written as:

$$Y^H(t) = \Pi(t) + RD(t), \quad \text{with} \quad RD(t) = RD^A(t) + \sum_{i=1}^{n_B(t)} RD^i(t) \tag{25}$$

Moreover, household income $Y^H(t)$ together with government income $Y^A(t)$ exhaust total final demand $F(t)$:

$$F(t) = Y^A(t) + Y^H(t) = W(t) + Div(t) + Y^A(t) \tag{26}$$

Thus, to monitor the aggregate evolution of inequality between wages and dividends in the model we compute the share of wages in household income:

$$\Omega_W(t) = \frac{W(t)}{Y^H(t)} \tag{27}$$

Within the model, accumulation takes place through the capitalisation of R&D expenditures by both the public sector and private firms. Similarly to expression (18), the stock of capitalised R&D investment by firm i at time t can be written as:

$$K^i_{RD}(t) = (1-\delta)K^i_{RD}(t-1) + RD^i(t) \tag{28}$$

where δ is the corresponding depreciation rate.[11]

In addition to keeping track of accumulated R&D spending, we proxy knowledge accumulation by capitalising only those flows of R&D expenditure which

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[11] The treatment of R&D expenditure as a fixed asset in national accounts is a recent accounting convention that has only been introduced with the latest UN System of National Accounts 2008 (UN, 2009). For a critical discussion of this and other issues, see Mazzucato and Shipman (2014).

lead to an increases in average fitness, both for each private firm i:

$$K^i(t) = \begin{cases} (1-\delta)K^i_{RD}(t-1) + RD^i(t), & \text{if} \quad \alpha^i(t)/\alpha^i(t-1) > 1 \\ 0, & \text{otherwise} \end{cases} \tag{29}$$

as well as for the public sector:

$$K^A(t) = \begin{cases} (1-\delta)K^A_{RD}(t-1) + RD^A(t), & \text{if} \quad \alpha^A(t)/\alpha^A(t-1) > 1 \\ 0, & \text{otherwise} \end{cases} \tag{30}$$

3.6 Relative risks and rewards: the Risk-Reward Nexus

To assess the relative roles of type-A (public sector) and type-B (private firms) agents in the innovation process we introduce metrics that quantify the distribution of risk taking and profit sharing. We are interested in the relative risks and rewards between the public sector and private actors exploring the technology landscape.

Risk for private firm i is defined as:

$$\sigma^i(T^i) = (1 - \alpha^i(0))(\alpha^i(T^i) - \alpha^i(0)) \tag{31}$$

where T^i is the exit time of firm i from the market. Essentially, our risk measure is the product of: (i) the initial distance to the dominant design $(1 - \alpha^i(0))$ and (ii) the length (in terms of fitness improvements) of the path explored $(\alpha^i(T^i) - \alpha^i(0))$. Intuitively, firms that invested early in the technology will begin from a distant position to the dominant design, implying a higher risk. Moreover, conditional on its initial position, the more an agent has explored the more risk it has faced throughout the process.

The same measure of risk taking is applied to the public sector:

$$\sigma^A(T) = (1 - \alpha^A(0))(\alpha^A(T) - \alpha^A(0)) \tag{32}$$

where T is the end period of the analysis.

The *relative* risk between private firms and the public sector is given by:

$$\sigma^B_A(T) = \frac{\overline{\sigma}^B(T)}{\sigma^A(T)}, \quad \text{with} \quad \overline{\sigma}^B(T) = \frac{\sum_{i=1}^{N_B(T)} \omega^i_\pi(T)\sigma^i(T^i)}{\sum_{i=1}^{N_B(T)} \omega^i_\pi(T)} \tag{33}$$

where $N_B(T)$ is the total number of private firms that has populated the model between $[0, T]$, and $\omega_\pi^i(T)$ stands for:

$$\omega_\pi^i(T) = \frac{\sum_{t=1}^{T^i} \pi^i(t)}{\sum_{t=1}^{T} \Pi(t)} \tag{34}$$

i.e. the share of private firm i in accumulated profits.

Proceeding in a similar fashion, the reward of private firm i is defined by the time-average of accumulated profits over its lifetime:

$$\mu^i(T^i) = \frac{1}{T^i} \sum_{t=0}^{T^i} \pi^i(t) \tag{35}$$

whereas the reward of the public sector will be the time-average of accumulated government income over its lifetime:

$$\mu^A(T) = \frac{1}{T} \sum_{t=0}^{T} Y^A(t) \tag{36}$$

Then, the *relative* reward between private firms and the public sector is computed as:

$$\mu_A^B(T) = \frac{\overline{\mu}^B(T)}{\mu^A(T)}, \quad \text{with} \quad \overline{\mu}^B(T) = \frac{\sum_{i=1}^{N_B(T)} \omega_\pi^i(T) \mu^i(T^i)}{\sum_{i=1}^{N_B(T)} \omega_\pi^i(T)} \tag{37}$$

Finally, the *risk-reward nexus* is obtained by comparing rewards with respect to risk for each type-B (private firm i) and type-A (public sector) agent, respectively:

$$RRN^i(T^i) = \frac{\mu^i(T^i)}{\sigma^i(T^i)}, \qquad RRN^A(T) = \frac{\mu^A(T)}{\sigma^A(T)} \tag{38}$$

whereas the *relative* risk-reward ratio between private firms and the public sector is computed as:

$$RRN_A^B(T) = \frac{\overline{RRN}^B(T)}{RRN^A(T)}, \quad \text{with} \quad \overline{RRN}^B(T) = \frac{\sum_{i=1}^{N_B(T)} \omega_\pi^i(T) RRN^i(T^i)}{\sum_{i=1}^{N_B(T)} \omega_\pi^i(T)} \tag{39}$$

It emerges from the process of technological and market competition embedded in the model an *imbalance* between risks (represented by the distance from the dominant design of the new technology and the landscape path explored) and rewards (represented by profitability): private actors starting from the privileged landscape position achieved by the public sector may reap a higher share of profits while facing a lower risk. The metrics introduced allow us to quantify the extent of this imbalance throughout alternative scenarios of the model.

4 Simulation results

The model presented above cannot be solved analytically, due to the non-linearities arising from the equations representing agents' behaviour and their interdependence. Thus, we codify and implement the model in a discrete-time simulation platform.[12] We define alternative scenarios — each characterised by a parametric configuration — and perform extensive randomizations for each of them, in order to control for across-simulation variability. Thus, all results reported refer to across-run averages over 50 replications for each scenario considered (see, e.g. Dosi et al., 2010), unless otherwise specified.

In what follows, we first describe four alternative scenarios to study the role and contribution of public and private agents to the innovation process. Studying the dynamics of the model through time for a typical run of our 'benchmark' parametrization (Scenario 1), we analyse the mechanism by which some private agents access innovation surplus profits. We then specify metrics to assess risks, rewards, inequality and private/public shares in knowledge accumulation across scenarios. Finally, by (statistically) comparing outcomes for different parametrizations we get some insights on how innovation and its financing leads to inequality.

4.1 Alternative scenarios

We analyse four scenarios that depend on two dimensions: (i) the degree of involvement of the public sector in R&D investment (only early stage vs. throughout the innovation chain) and (ii) the complexity of the new technology introduced (medium vs. high complexity).

Between each ordered *couple* of scenarios (1 and 2, 3 and 4) there is a difference in dimension (ii), whereas *within* each couple the difference concerns dimension (i). In particular, scenarios are defined as follows:

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[12] All simulations have been programmed using the Laboratory for Simulation Development (LSD). For more information see `https://github.com/marcov64/Lsd`.

1. **Throughout** public R&D, **medium** tech-complexity:
   The public sector is involved in the process of technological exploration by directly investing in R&D throughout the innovation chain (Throughout public R&D), in a context in which the intensity of interdependence between components of the new technology (i.e. dimensions of the fitness landscape) is of medium complexity (medium tech-complexity).

2. **Early** public R&D, **medium** tech-complexity, **stringent** competition:
   The complexity of the technology is identical to that of scenario 1, the difference lies in the role of the public sector. In scenario 2, the public sector only performs direct R&D investment only in the early gestation stage of innovation development whereas, once demand is sufficient for private firms to enter the industry, the public sector lets innovation development be driven by the private firms (Early public R&D).

3. **Throughout** public R&D, **high** tech-complexity:
   The public sector is involved throughout the innovation chain by directly investing in R&D, in a context in which the complexity of the new technology is high (the contribution to fitness of movements in one landscape direction heavily depends on the relative position in other dimensions of the landscape).

4. **Early** public R&D, **high** tech-complexity:
   The complexity of the technology is identical to that of scenario 3, but the public sector only performs direct R&D investment in the early gestation stage of innovation development.

Table 1 reports a summary of the scenarios just described, to ease understanding and for later reference throughout the analysis of results.

Table 1: Simulation scenarios

Tech-Complexity	Public R&D	Scenario
Medium	Throughout	1
	Early stage	2
High	Throughout	3
	Early stage	4

Table 2: Parameters of the model

Parameter	Description	Equation	Range	Value
	Complexity of the technology: pseudo-NK landscape			
N	Landscape dimensions	(1)	≥ 2	2
K	Interactions among dimensions	(3)	≥ 1	1
a_{ij}	Intensity of interaction	(3)	$[0, 1]$	
	Scenarios 1 & 2			0.35
	Scenarios 3 & 4			0.60
	Competition regime			
$\underline{\theta}$	Minimum market share	(15)	$[0, 1]$	0.04
χ	Intensity of replicator dynamics	(11)	$[0, 1]$	0.50
ϵ	Proportion of market share ripped by entrants	(14)	$[0, 1]$	0.20
	Public policy			
τ	Tax rate on sales	(12)	$[0, 1]$	0.10
ξ	License fee rate to access the new technology	(17)	$[0, 1]$	0.03
ι^*	Target proportion of public R&D stock	(20)	$[0, 1]$	0.17
	R&D investment			
δ	R&D depreciation rate	(18)	$[0, 1]$	0.02
$\underline{\eta}$	Propensity to invest in R&D out of sales (Low)	(13)	$[0, 1]$	0.40
$\underline{\eta}$	Propensity to invest in R&D out of sales (High)	(13)	$[0, 1]$	0.70

Simulation steps = 150; entrants per entry-period = 2; entry interval = 4.

References for scenarios: **1**. throughout-publicRD, medium-tech; **2**. ealry-publicRD; medium-tech; **3**. throughout-publicRD, high-tech; **4**. early-publicRD, high-tech.

To substantiate this description, Table 2 reports the parameters of our setup, including a reference to the equation in the text where each parameter may be found, the range of possible values and the particular value(s) adopted for our simulations.

From Table 2 we see that the complexity of the technology stems from the value of parameter a_{ij} in equation (3). The higher a_{ij} the higher the dependence of the current dimension on the position in *other* dimensions to assess the contribution to fitness. A higher value of a_{ij} increases the *ruggedness* of the technology landscape. In our scenarios with medium complexity of the technology (scenarios 1 & 2), $a_{ij} = a = 0.35$, whereas in those with high complexity (scenarios 3 & 4), $a_{ij} = a = 0.65$.

4.2 The Risk-Reward Nexus in the benchmark scenario: depicting the mechanism to access innovation surplus profits

We first depict the evolution of some key variables of the model through time for a typical run of our 'benchmark' parametrization (Scenario 1), and analyse how some private agents obtain a share in innovation surplus profits greater than the risks taken in technological exploration, relative to other agents and the public sector.

A birds'-eye view is presented in Figure 3, consisting in four panels: final demand, fitness, competition and knowledge accumulation. Final demand for the industry's product, $F(t)$ in (9), is divided into its three income components: dividends, wages and government income: $Div(t)$ in (24), $W(t)$ in (22) and $Y^A(t)$ in (16), respectively. The outcome indicator of the process of technological exploration, landscape fitness, is depicted for the average of private firms, the public sector and the economy as a whole: $\overline{\alpha}^B(t)$ in (5), $\alpha^A(t)$ in (6), and $\overline{\alpha}(t)$ in (7), respectively. We consider two features of the competition regime: the Herfindahl index of market concentration and the number of active firms in the market, $n_B(t)$.[13] Finally, we depict the shares in accumulated knowledge of the public sector and private firms (distinguishing between those paying the license and those who do not).[14]

During the gestation stage of the new technology, landscape exploration is performed only by the public sector: final demand is at its minimum given

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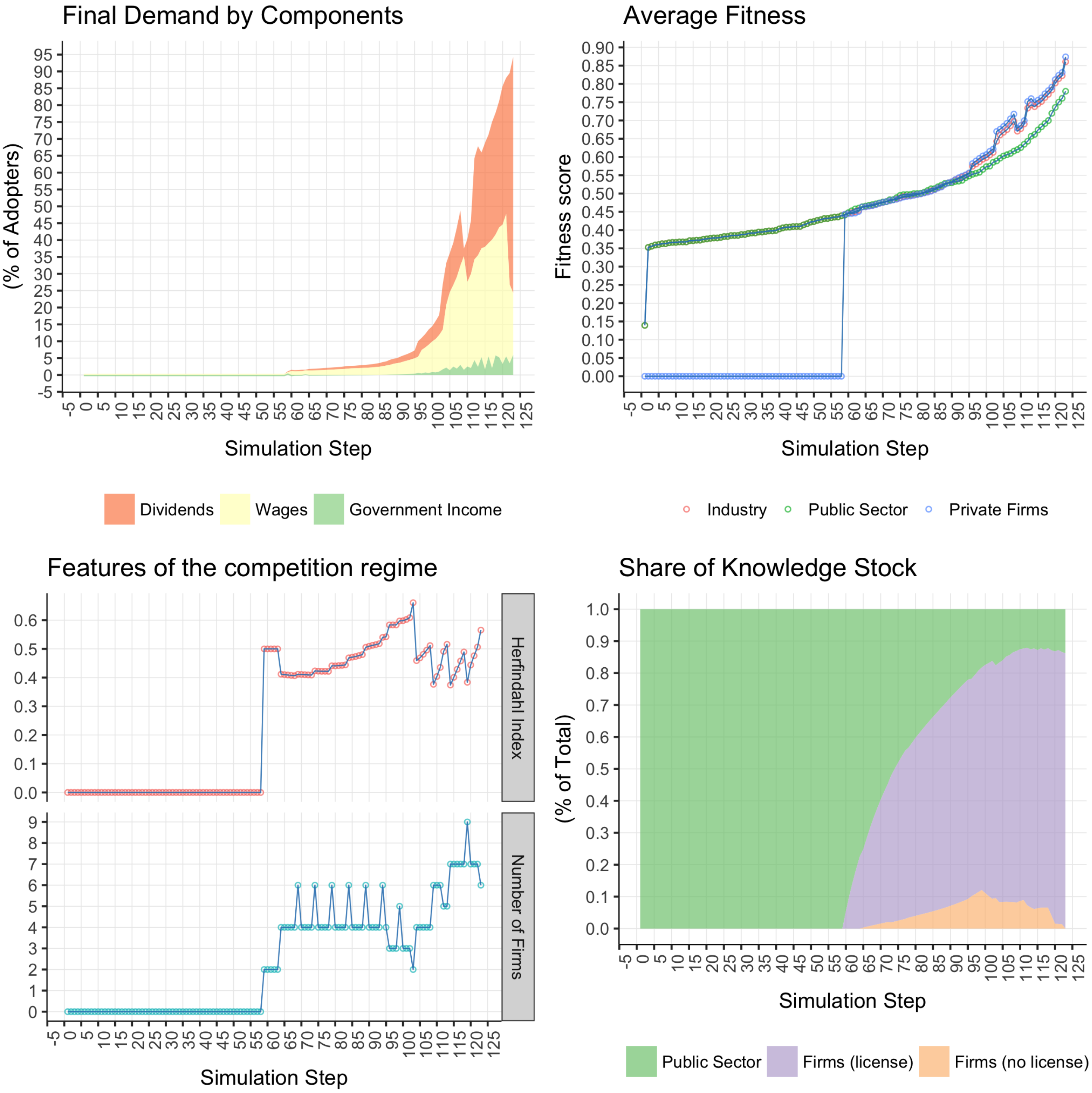
[13] We compute the Herfindahl index for each time period t as follows: $\sum_{i=1}^{n_B(t)} \theta^i(t)^2$, where $\theta^i(t)$ is the market share of firm i at time t, as specified in (11).

[14] The stock of knowledge of firm i as well as that of the public sector have been specified in expressions (29) and (30), respectively.

Figure 3: Final Demand, Fitness, Competition and Knowledge Accumulation

Scenario 1: Full-StateRD, medium-tech, stringent-competition



the insufficient product quality to trigger a positive percentage of consumers adopting the new product. It can be seen that throughout gestation ($t \in [0, 58]$), average landscape fitness is determined by the fitness of the public sector. Knowledge accumulation is entirely done by the public sector during this phase. At $t = 58$, average fitness (i.e. product quality) reaches a point associated to positive final demand,[15] allowing for private firms to enter the market at $t = 59$ and start a process of technological and market competition. The contribution to accumulated knowledge is now shared between the public sector and private firms,[16] and firms paying the license to access the knowledge reached by the public sector become the main contributor to the accumulation of new knowledge.

Between the entry of the first private actors (at $t = 59$) and $t = 95$, the fitness of the economy is mostly driven by that of the public sector: firms accumulate knowledge by investing in R&D at a faster rate than the public sector, to catch-up with the privileged position of the State. Concentration gradually increases as entrants fail in their attempt to compete with incumbents, and firms' propensity to invest in R&D implies a growing share of wages in the value of final demand.[17]

However, from $t = 95$ onwards the evolution of the industry exhibits higher instability: dividends reap increasing shares of income, the average fitness of private firms surpasses the public sector, market concentration fluctuates and knowledge accumulation by private firms slows down. To grasp the mechanisms leading to these outcomes, Table 3 reports a detailed picture of key indicators at the level of individual agents that will be useful to uncover the switchover in industry dynamics.

Each row of Table 3 corresponds to an agent (identified in column `[1]`) and columns `[2]` to `[9]` characterise its role within the industry. Agent 1 is the public sector and subsequent rows report private firms in increasing order according to their entry time. Agent 3 is the incumbent that obtains 79% of accumulated profits (column `[8]`), with the highest reward (column `[6]`). It has invested in R&D during an initial phase (which is reflected in the risks taken), but after reaching a sufficiently high market share it switches to a regime of low R&D investment propensity, extracting a greater share of income (in the form of dividends, as can be seen in Figure 3 from $t = 110$ onwards).

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[15] The functional relationship between product quality and final demand was specified in (9).

[16] Accumulated knowledge consists in capitalised R&D investment that increases landscape fitness, as specified in (29).

[17] As specified in (23), R&D expansion translates into wage payments to specialised workers in the industry.

Table 3: Risks, Rewards, Share in Accumulated Profits and Knowledge Stock

(Baseline results, scenario **1**: throughout-publicRD, medium-tech, stringent-competition)

Agent	Entry Time	Exit Time	Pays License	Risk	Reward	RRN	Profits Share	Knowledge Stock
				(time-average accum. in T)				
`[1]`	`[2]`	`[3]`	`[4]`	`[5]`	`[6]`	`[7]`	`[8]`	`[9]`
1	1	150		0.551	0.427	0.774	0.00	66.05
2	59	103	Yes	0.053	0.181	3.439	1.23	0.00
3	59	150	Yes	0.312	7.844	25.134	79.28	291.94
4	64	123	No	0.090	0.757	8.402	6.93	0.00
5	64	96	Yes	0.027	0.050	1.877	0.25	0.00
20	104	120	No	0.023	0.884	38.014	2.09	0.00
21	104	150	Yes	0.064	1.299	20.188	3.90	43.77
22	109	150	Yes	0.050	1.068	21.445	2.36	28.04
23	109	112	No	0.004	0.278	69.054	0.09	0.00
24	114	119	No	0.016	0.736	45.204	0.46	0.00
25	114	150	Yes	0.023	1.270	56.218	1.80	24.15
26	119	150	Yes	0.015	1.220	83.455	0.77	12.45
27	119	150	Yes	0.016	1.312	82.545	0.83	12.78
(Weighted) Average Private Firms				0.259	6.415	25.257		
Relative Risks and Rewards				0.470	15.023	32.631		
Failure Rate				0.538				

Specifications: Simulation steps = 150; entrants per entry-period = 2; entry interval = 4. Notes: Time period T represents the simulation step in which the dominant design has been reached by one of the private firms; columns `[6]-[8]` are time-averages of values accumulated up to period T; weighted averages are computed using the share in accumulated profits; the failure rate computes the proportion of firms that exited the market after only one period with respect to total private firms.

Its privileged position, though, has been achieved by taking advantage of early entry supported by the public sector.

To understand the switchover in industry dynamics, note the performance of private firms entering the industry from $t = 95$ onwards. Due to the effort (led by the public sector since the gestation phase) to increase product quality through landscape exploration, the size of the market increases at faster pace, new firms enter the market as old firms exit.[18] But firms paying the license to the public sector have a knowledge advantage: their late entry from a privileged starting position to explore the technology landscape allows them to reap higher profits with respect to the risks they incur.

In fact, entrants start from a landscape position that allows them to collectively surpass the fitness score of the public sector. The Risk-Reward Nexus (RRN, in column `[7]`) for private firms paying the license progressively increases with entry time: entrants reap market share of the biggest incumbent and obtain proportionally more profits than the risks they undertook through landscape exploration. Thus, there is an *imbalance* between risks and rewards (Mazzucato, 2013): the relative risks and rewards between private firms and the public sector in Table 3 report how private firms incur in only (almost) half of the risk taken by the public sector (0.47) but obtain an average reward which is 15 times higher.

After the industry switchover, the Herfindahl index shows higher volatility as competition gets more stringent between *new* entrants. However, the biggest incumbent (agent 3) slows down investment in R&D and accelerates value extraction when the size of the industry grows exponentially. Inequality sets in: the share of dividends takes over wages and firms which do not pay the license to the public sector exit the market (in aggregate terms their share in the knowledge stock in Figure 3 tends to zero). The extent of inequity disrupts investment in the innovation process and is mirrored by the appropriation of surplus profits from innovation by incumbents who benefited from the early exploration by the public sector, as well as by late entrants who take advantage of continuous exploration by the State.

Given the medium level complexity of the new technology, landscape exploration by private firms reaches the dominant design by $t = 123$. However, it remains to be seen how this stylised account of relative risks and rewards is modified when considering each of the alternative scenarios previously defined.

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[18] As reported in Table 3, the failure rate in the industry, defined as the proportion of firms that exited the market after only one period with respect to total private firms, reaches almost 54%.

How will the imbalance between risks and rewards change with a higher complexity of the new technology and, most importantly, when the public sector is only directly involved in R&D at an early stage of the innovation process? We turn to this question in the sections that follow.

4.3 Metrics

In order to compare alternative scenarios we introduce a set of metrics, specified in Table 4. We consider indicators regarding: inequality, knowledge accumulation, rewards, risks and the risk-reward nexus (RRN, hereinafter). In each case we compute time-averages of accumulated variables up to time-period T and/or at the values they adopt in T. Time period T represents the simulation step in which the dominant design has been reached by one of the private firms.[19]

The extent of inequality is captured by the shares of government income, wages and dividends in accumulated final demand (indicators 1.1-1.3). The wage share in household income (indicator 1.4) proxies the extent of value extraction: increasing dividends slow down R&D investment and the development of skills by R&D workers. Finally, the share in accumulated profits of private firms, distinguishing those with from those without a license to access the new technology (indicators 1.5-1.6) quantifies the advantage of the former over the latter, due to the presence of the public sector throughout the innovation process.

The process of landscape exploration leads to knowledge accumulation as long as landscape steps are fitness improving. The shares of the public sector and private firms (with and without a license) in the knowledge stock (indicators 2.1-2.3) assess the contribution of each agent type to the innovation process.

Whereas the indicators introduced so far contextualise important aspects to understand industry evolution under each alternative scenario, the key indicators of the model concern those quantifying rewards (indicators 3.1-3.3), risks (indicators 4.1-4.3) and the risk-reward nexus (indicators 5.1-5.3) for the public sector, private firms and the relation between them.[20]

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[19] Taking T as the end-period of our analysis is justified by the fact that the key aspects of technological and market competition are reflected in what happens up to the point when a firm reaches the dominant design. From that point onwards, it may as well happen that the public sector and private firms move on to develop another technology (exploring a new fitness landscape).

[20] The rationale for the metrics of rewards, risks and the risk-reward nexus can be found in the description of the model, in section 3 above.

Table 4: Simulation metrics: specification of indicators computed

(Time period T represents the simulation step in which the dominant design has been reached by one of the private firms)

Indicator			Formula	Reference Eqs.
Inequality	Shares in Accumulated Final Demand			
	1.1	Government Income	$\sum_{t=1}^{T} Y^A(t) / \sum_{t=1}^{T} F(t)$	(9), (16)
	1.2	Wages	$\sum_{t=1}^{T} W(t) / \sum_{t=1}^{T} F(t)$	(9), (22)
	1.3	Dividends	$\sum_{t=1}^{T} Div(t) / \sum_{t=1}^{T} F(t)$	(9), (24)
	1.4	Wage share in Household Income	$\sum_{t=1}^{T} W(t) / \sum_{t=1}^{T} Y^H(t)$	(21), (22)
	Share in Accumulated Profits			
	1.5	Private Firms (license)	$\sum_{t=1}^{T} \sum_{i=1}^{n_B^{Lic}(t)} \pi^i(t) / \sum_{t=1}^{T} \Pi(t)$	(12), (24)
	1.6	Private Firms (no license)	$\sum_{t=1}^{T} \sum_{i=1}^{n_B^{NLic}(t)} \pi^i(t) / \sum_{t=1}^{T} \Pi(t)$	(12), (24)
Knowledge Accumulation		Shares in Knowledge Stock	$K(T) = \sum_{i=1}^{n_B(T)} K^i(T) + K^A(T)$	
	2.1	Public	$K^A(T)/K(T)$	(30)
	2.2	Private Firms (license)	$\sum_{i=1}^{n_B^{Lic}(T)} K^i(T)/K(T)$	(29)
	2.3	Private Firms (no license)	$\sum_{i=1}^{n_B^{NLic}(T)} K^i(T)/K(T)$	(29)
Rewards	3.1	Private Firms	$\overline{\mu}^B(T)$	(35)
	3.2	Public Sector	$\mu^A(T)$	(36)
	3.3	Relative Rewards (Private/Public)	$\mu_A^B(T)$	(37)
Risks	4.1	Private Firms	$\overline{\sigma}^B(T)$	(31)
	4.2	Public Sector	$\sigma^A(T)$	(32)
	4.3	Relative Risk (Private/Public)	$\sigma_A^B(T)$	(33)
Risk-Reward Nexus	5.1	Private Firms	$\overline{RRN}^B(T)$	(38)
	5.2	Public Sector	$RRN^A(T)$	(38)
	5.3	Relative Risk-Reward (Private/Public)	$RRN_A^B(T)$	(39)

Notes: $n_B^{NLic}(t) = n_B(t) - n_B^{Lic}(t)$ represents the number of private firms that do not pay the license to access the new technology, present in time period t.

4.4 The Risk-Reward Nexus under alternative scenarios

The indicators presented in Table 4 apply to each simulation run for every alternative scenario. In order compare the scenarios summarised in Table 1, we compute across-run averages over 50 replications for each scenario and report these averages in Table 5.

Our main interest lies in statistically comparing scenarios 1 with 2 and 3 with 4, given that each couple differs only in the role of the public sector: in odd-numbered scenarios the public sector directly invests in R&D throughout the innovation chain, whereas in even-numbered ones the public sector only invests in R&D during the gestation phase of landscape exploration. Afterwards, it is only private firms that explore the technology landscape. To assess whether across-run averages are statistically different within each couple of scenarios we perform a Welch's unequal variances t-test and report p-values in the corresponding columns of Table 5.[21]

We structure the interpretation of results by answering three (related) questions in turn.

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[21] The null hypothesis being that means are not statistically different.

Table 5: Simulation results: alternative scenarios

(across-run averages over 50 replications for each scenario, p-values correspond to Welch's unequal variances t-test comparing scenarios 1 with 2 and 3 with 4, respectively)

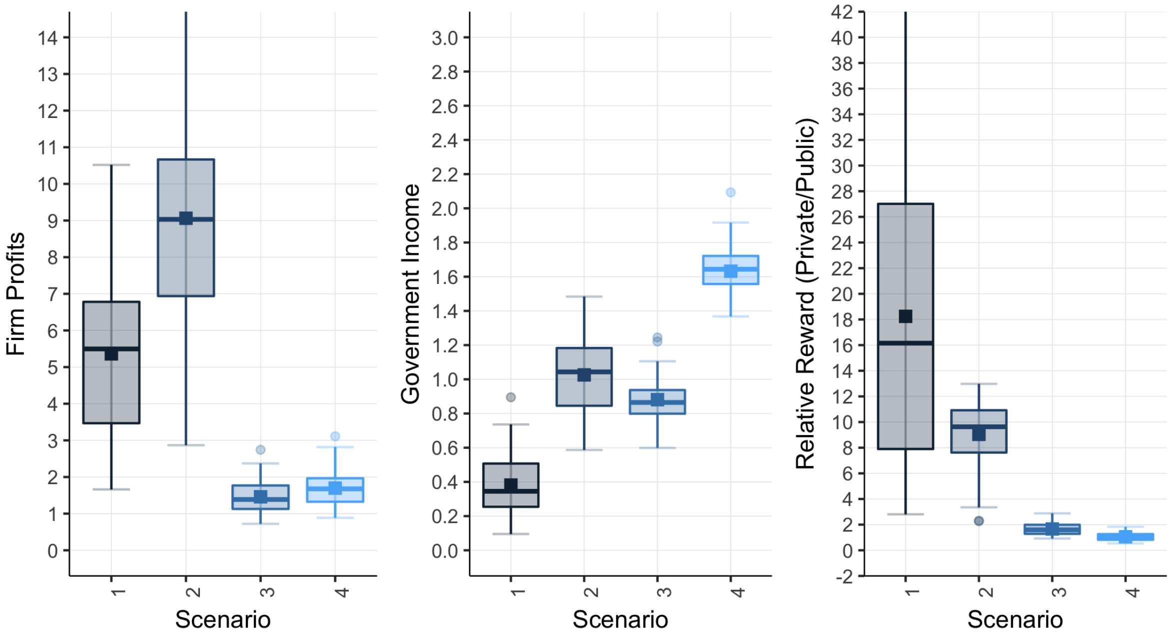
	Indicator	Scenario		Difference	Scenario		Difference
		1	2	p-value	3	4	p-value
Inequality	Shares in Accumulated Final Demand						
	1.1 Government Income	0.032	0.085	0.0000	0.048	0.098	0.0000
	1.2 Wages	0.557	0.447	0.0000	0.676	0.623	0.0000
	1.3 Dividends	0.401	0.457	0.0002	0.273	0.275	0.0002
	1.4 Wage share in Household Income	0.577	0.490	0.0000	0.711	0.691	0.0000
	Share in Accumulated Profits						
	1.5 Private Firms (license)	0.832	0.000	0.0000	0.714	0.000	0.0000
	1.6 Private Firms (no license)	0.168	1.000	0.0000	0.286	1.000	0.0000
Knowledge Accumulation	Shares in Knowledge Stock						
	2.1 Public	0.159	0.012	0.0000	0.311	0.046	0.0000
	2.2 Private Firms (license)	0.750	0.000	0.0000	0.547	0.000	0.0000
	2.3 Private Firms (no license)	0.090	0.988	0.0000	0.143	0.954	0.0000
Rewards	3.1 Private Firms	5.215	8.582	0.0000	1.578	1.739	0.0892
	3.2 Public Sector	0.390	1.066	0.0000	0.910	1.667	0.0000
	3.3 Relative Rewards (Private/Public)	16.925	8.640	0.0000	1.751	1.048	0.0000
Risks	4.1 Private Firms	0.200	0.250	0.0008	0.062	0.059	0.3923
	4.2 Public Sector	0.465	0.236	0.0000	0.341	0.214	0.0000
	4.3 Relative Risk (Private/Public)	0.447	1.100	0.0000	0.197	0.329	0.0000
Risk-Reward Nexus	5.1 Private Firms	42.139	38.370	0.6370	54.438	88.356	0.0728
	5.2 Public Sector	0.848	4.768	0.0000	2.852	9.482	0.0000
	5.3 Relative Risk-Reward (Private/Public)	47.033	8.509	0.0000	20.243	11.160	0.0108

References for scenarios: **1**. throughout-publicRD, medium-tech; **2**. early-publicRD; medium-tech; **3**. throughout-publicRD, high-tech; **4**. early-publicRD, high-tech.

4.5 How does the presence of the public sector directly investing in R&D alter the balance of risks and rewards?

In all cases, rewards within each couple of scenarios statistically differ.[22] Figure 4 displays boxplots for private, public and relative rewards across scenarios, providing a more detailed picture beyond across-run averages.

Figure 4: Private, Public and Relative Rewards



Bar: median, square: mean, rectangular box: 2nd-3rd quartile, whiskers: max-min, dots: outliers

The presence of the public sector throughout the innovation chain (odd-numbered scenarios) implies average rewards for private firms which are 60% (scenario 1) and 90% (scenario 3) those of the corresponding even-numbered scenarios (scenarios 2 and 4, respectively), in which the public sector *only* invests in early R&D. As regards the public sector, direct R&D efforts throughout the innovation process imply a surplus which is only 36% (scenario 1) and 54% (scenario 3) that of even-numbered scenarios, respectively. In relative terms, the average reward of the private relative to the public sector increases notoriously when the latter directly invests in R&D throughout the innovation process. With medium-level technological complexity relative rewards of scenario 1 are 1.96 times those of scenario 2. However, when the complexity of new technology is high, this gap is reduced to 1.67 times (comparing between scenarios 3 and 4). As expected, relative (private/public) rewards *decrease*

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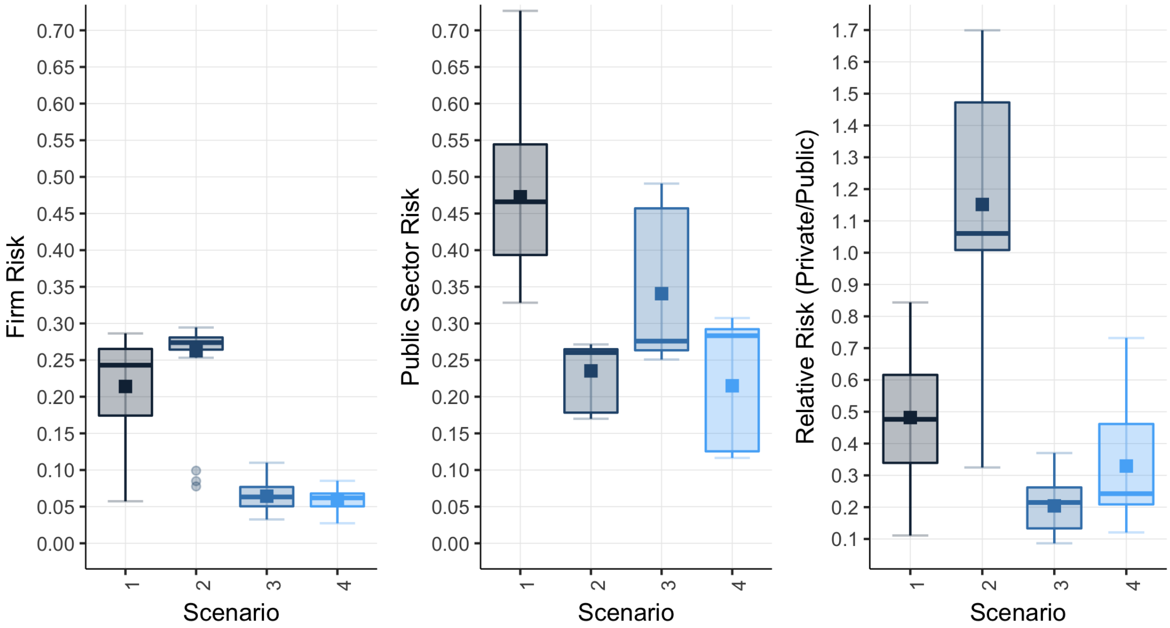
[22] Only in the case of rewards for private firms in scenarios 3 and 4, characterised by high complexity of the new technology, the difference is statistically significant at a 10% level.

when the public sector leaves the process of R&D (beyond the gestation phase) to private firms.

When we turn to risks, mean differences for public and relative risks are statistically significant in all cases, whereas for private firms this is so only for the comparison between scenarios 1 and 2: risks differences for private firms when comparing scenarios 3 with 4 are not statistically significant. Figure 5 displays boxplots for private, public and relative risks across scenarios, providing a more detailed picture beyond across-run averages.

Figure 5: Private, Public and Relative Risk



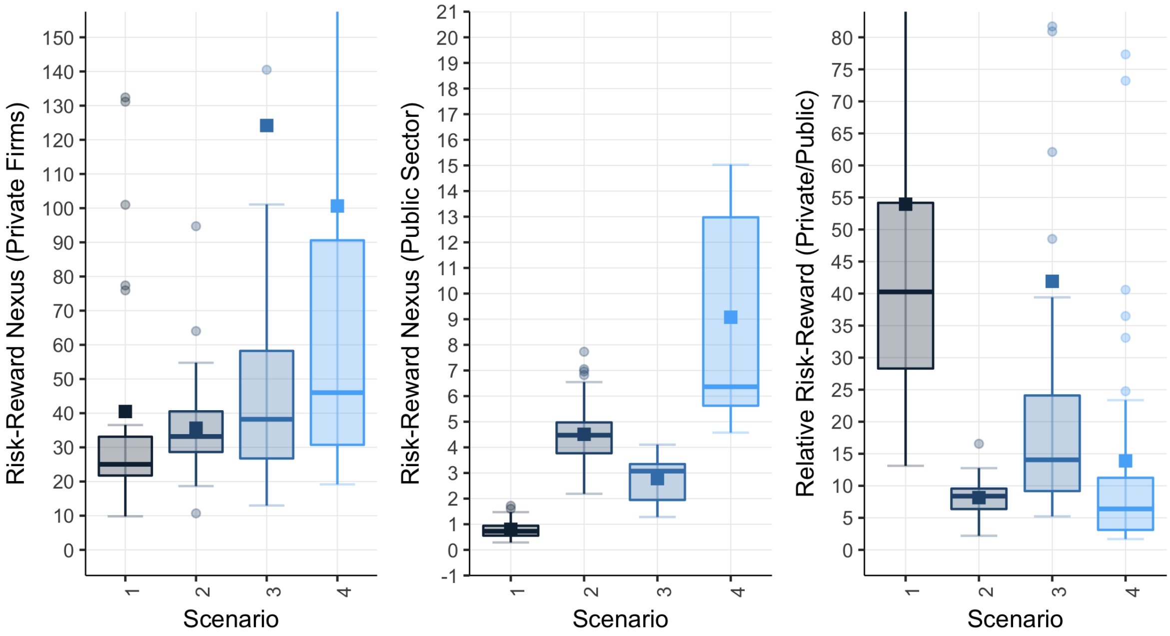
Bar: median, square: mean, rectangular box: 2nd-3rd quartile, whiskers: max-min, dots: outliers

As expected, risks increase for the public sector when directly invests in R&D throughout the innovation chain. Whereas this is the case for private firms in a scenario of medium-level technological complexity, risks of landscape exploration are not statistically different for *private* firms in scenarios of high technological complexity (scenarios 3 and 4). To explain this, note that high technological complexity forces firms to invest in R&D if they are to make fitness-improving landscape steps.

This notwithstanding, when comparing *relative* risks (which is always our main interest), an active presence of the public sector involves a sharp *decrease* in relative (private/public) risks across scenarios: there is an unambiguous increase in the risk taken by the public sector with respect to that of private actors.

More importantly, the joint consideration of rewards and risks by observing indicators 5.1-5.3 of Table 5 allows us to conclude that, when the public sector is directly involved in R&D investment throughout the innovation chain, the sharp *increase* in the relative (private/public) risk-reward nexus (rewards/risks) is statistically significant across scenarios.[23] Figure 6 displays boxplots for private, public and relative risk-reward nexus, providing a more detailed picture beyond across-run averages.

Figure 6: Private, Public and Relative Risk-Reward Nexus



Bar: median, square: mean, rectangular box: 2nd-3rd quartile, whiskers: max-min, dots: outliers

As regards the government, the higher risk incurred by taking an active part in R&D beyond the gestation phase is not compensated by a corresponding reward: the risk-reward nexus (rewards/risks) of the public sector *decreases* in odd-numbered scenarios.

Moreover, the rightmost panel of Figure 6 evinces the extent of the imbalance between risks and rewards when comparing private firms with the public sector. In scenarios of medium-level technological complexity (scenarios 1-2), the risk-reward nexus (RRN) is 5.52 times higher when the public sector actively invests in R&D. This gap is reduced to a factor of 1.8 in the presence of high technological complexity (scenarios 3-4).

Thus, we may conclude that the presence of the public sector directly investing in R&D alters the public-private balance of risks and rewards. If the State leaves the process of R&D investment to private firms, there is an *increase*

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[23] With the exception of the comparison between scenarios 1 and 2 for private firms, mean differences for private, public and relative risk-reward nexus are always statistically significant across scenarios.

in its relative income position. But by taking an active part in technological exploration, there is an *increase* in the relative risk it takes, which is not compensated by the rewards it obtains from tax revenues and license costs paid by private actors.

All in all, the relative risk-reward nexus (rewards/risks) increases in favour of private firms whenever the public sector directly invests in R&D throughout the innovation chain, and this increase is sharper the lower the complexity of the new technology (i.e. the ruggedness of the fitness landscape).

4.6 How does the financing of innovation by private actors lead to higher inequality?

Having ascertained the increasing imbalance between relative risks and rewards in favour of private firms when the public sector is actively involved in landscape exploration, we study how the division of innovative labour maps into a division of rewards (Mazzucato, 2013, p. 198). By observing indicators 1.1-1.6 and 2.1-2.3 in Table 5, we see to what extent the shares in accumulated income of the government investing in R&D and workers actively pursuing R&D efforts commensurate with their investment.

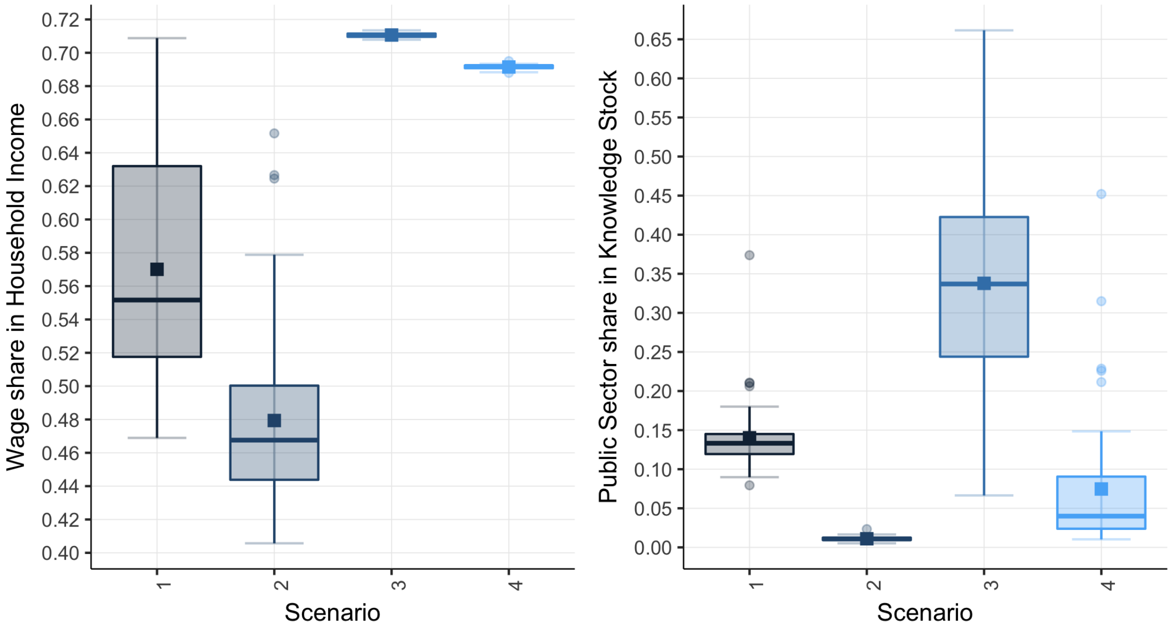
In all cases, mean differences between scenarios for indicators concerning inequality and knowledge accumulation are statistically significant. Under each scenario comparison, the active presence of the public sector investing in R&D throughout the innovation process significantly increases the wage share in (accumulated) income.

In the scenarios corresponding to our benchmark configuration (scenarios 1-2), the decrease in the wage share when R&D investment is left to private firms is of more than 10 percentage points (from 55% to 44% of accumulated income). Such a decrease is mirrored by an increase in the share of dividends (of 5.6 percentage points) and government income (of 5.3 percentage points). In fact, a State focusing merely in obtaining a fiscal surplus out of R&D efforts during the gestation phase results in a relatively lower wage share. Interestingly, distributive shifts between odd and even-numbered scenarios are milder when technological complexity is high.

These trends are confirmed when analysing the share of wages in household income (indicator 1.4 of Table 5). Figure 7 displays boxplots for the wage share in household income and the share of the public sector in the knowledge stock, providing a more detailed picture beyond across-run averages.

As expected, the share of the public sector in accumulated knowledge is

Figure 7: Inequality and Knowledge Accumulation



Bar: median, square: mean, rectangular box: 2nd-3rd quartile, whiskers: max-min, dots: outliers

higher in odd-numbered scenarios with respect to even-numbered ones. Whereas in scenarios 1 the share of the public sector is 16%, it accounts for 31% of the knowledge stock in scenario 3, i.e. when the complexity of the technology is high. To better grasp the imbalance between rewards and contribution to knowledge in this scenario, the public sector contributes to 30% of the stock of knowledge but gets only 15% of accumulated government income plus dividends.[24]

Note that we compare public/private shares in the knowledge stock and public/private shares in government income plus dividends, as *wages* are the vehicle effectively implementing R&D efforts accumulated by *both* private firms and the public sector. Workers are the ultimate source of skills and innovation development in our framework. Hence, by increasing the wage share with its direct action through R&D investment, the public sector drives the process of landscape exploration towards a situation in which the distribution of financial rewards reflects to a higher extent the distribution of contributions to the innovation process.

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[24] From the column corresponding to scenario 3 in Table 5, indicators 1.1 and 1.3, we have that 0.048/(0.048+0.273)=0.15.

4.7 How could the public sector design an adaptive policy to realign risks and rewards?

Throughout scenarios 1-4 the policy variables available to the public sector have been considered constant and equal across settings. Thus, a key aspect of our model that we explore in this section is the implementation of an *adaptive* policy strategy by the public sector to realign the imbalance between risks and rewards.

In particular, the public sector has two instruments to influence the appropriation of gains from the innovation process: the tax rate on revenues of private firms — τ in (12) — and the license fee rate charged to private firms in order to access the new technology — ξ in (17).

The idea of the simulation exercise below is to implement an adaptive policy rule such that the Risk-Reward Nexus of the public sector directly investing in R&D throughout the innovation chain (scenarios 1 and 3 in Table 1) *approaches* that obtained when the public sector is involved only in the early stages of R&D investment (scenarios 2 and 4 in Table 1).

To this aim, we define two additional scenarios — 5 and 6 — which resemble in every respect scenarios 1 and 3, the only difference being the implementation of an adapative policy strategy by the public sector. Table 6 summarises the characterisation of the scenarios considered in this section.

Table 6: Simulation scenarios: Adaptive vs. Static policy

Tech-Complexity	Public R&D	Policy	Scenario
Medium	Throughout	Adaptive	5
	Early stage	Static	2
High	Throughout	Adaptive	6
	Early stage	Static	4

The adaptive policy rule implemented by the public sector in scenarios 5 and 6 consists in adjusting (by 1 percentage point per period) rates (τ, ξ) through time, in correspondence with the gap in the public risk-reward nexus between the throughout R&D investment scenario (RRN^A) and the early R&D scenario ($RRN^{A,*}$).[25]

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[25] More precisely, the gap measured is that between the value of RRN^A within *each* simulation run and the average (across instances of every corresponding type of 'early R&D only' scenario) value of $RRN^{A,*}$, in each time-period.

Thus, for the case of the tax rate on revenues we have:

$$\tau(t) = \begin{cases} \tau(t-1) + 0.01, & \text{if } RRN^A(t-1) < RRN^{A,*}(t-1) \\ \tau(t-1) - 0.01, & \text{if } RRN^A(t-1) > RRN^{A,*}(t-1) \end{cases} \tag{40}$$

where $\tau = 0.1$ sets a lower bound to the downward adjustments.

$$\xi(t) = \begin{cases} \xi(t-1) + 0.01, & \text{if } RRN^A(t-1) < RRN^{A,*}(t-1) \\ \xi(t-1) - 0.01, & \text{if } RRN^A(t-1) > RRN^{A,*}(t-1) \end{cases} \tag{41}$$

where $\xi = 0.03$ sets a lower bound to the downward adjustments.[26]

Table 7 reports the results of the simulation exercise. Also in this case, in order to compare the scenarios summarised in Table 6, we compute across-run averages over 50 replications for each scenario, perform a Welch's unequal variances t-test between scenarios 5-2 and 6-4, and report p-values in the corresponding columns of the table.

The key result from Table 7 is that, by adapting taxation and licensing policies, the public sector can realign the Risk-Reward Nexus between 'early R&D only' and 'R&D throughout' investment scenarios. The average license fee rate across time and simulation runs should be increased from 3% to a range between 18.8% and 20.9% (row 6.1 of the table), whereas the average tax rate on revenues across time and simulation runs should be raised from 10% to a range between 26.9% and 29.6% (row 6.2 of the table).

By so doing, the public sector obtains a reward (row 3.2 of the table) in scenarios 5 and 6 which is statistically higher than that of scenarios 2 and 4. Such a higher reward corresponds to a higher risk (row 4.2 of table) taken by the public sector. Thus, the resulting Risk-Reward Nexus (row 5.2 of the table) in each 'R&D throughout' scenario, though statistically different, *approaches* the public Risk-Reward Nexus of the corresponding 'early R&D only' scenario.[27]

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[26] Values $\tau = 0.10$ and $\xi = 0.03$ correspond to the calibration adopted in the static policy setting, see Table 2 for details.

[27] Being a simulation model, it is not possible to obtain an *ex-post* closed form computation of the combination of (τ, ξ) that *exactly equalise* public RRN across scenarios. This is so because each adjustment to the policy variables will have implications on the dynamics of the system, as private agents change their actions in response to the ongoing change in policy variables.

Table 7: Simulation results: adaptive policy under alternative scenarios

(across-run averages over 50 replications for each scenario, p-values correspond to Welch's unequal variances t-test comparing scenarios 5 with 2, 6 with 4, respectively)

	Indicator		Scenario 5	Scenario 2	Difference p-value	Scenario 6	Scenario 4	Difference p-value
Rewards	3.1	Private Firms	4.440	9.062	0.001	1.257	1.696	0.014
	3.2	Public Sector	2.461	1.026	0.000	3.001	1.632	0.000
	3.3	Relative Rewards (Private/Public)	2.304	9.040	0.000	0.433	1.050	0.000
Risks	4.1	Private Firms	0.198	0.263	0.112	0.050	0.059	0.372
	4.2	Public Sector	0.582	0.235	0.000	0.383	0.215	0.000
	4.3	Relative Risk (Private/Public)	0.347	1.152	0.000	0.145	0.329	0.000
Risk-Reward Nexus	5.1	Private Firms	35.425	35.602	0.427	77.606	100.635	0.374
	5.2	Public Sector	4.273	4.509	0.000	7.976	9.078	0.000
	5.3	Relative Risk-Reward (Private/Public)	8.365	8.153	0.001	9.227	13.888	0.107
Policy instruments	6.1	License Fee Rate	0.188	0.030		0.209	0.030	
	6.2	Tax Rate on Revenues	0.269	0.100		0.296	0.100	

References for scenarios:

5. throughout-publicRD, medium-tech, adaptive policy; **2**. early-publicRD; medium-tech, static policy;

6. throughout-publicRD, high-tech, adaptive policy; **4**. early-publicRD; high-tech, static policy.

Finally, results suggest that the relative Risk-Reward Nexus between private firms and the public sector (row 5.3 in the table) are only statistically different between scenarios 5 and 2. And even in this case, the difference is of second order. Thus, by implementing adaptive taxation and licensing policies the public sector has managed to realign *relative* (private/public) risks and rewards for each combination of 'early R&D only' and 'R&D throughout' scenarios.

5 Concluding remarks

The present paper introduces an agent-based simulation framework to study the interaction between the public sector and private firms in a process of innovation diffusion through technological competition. The progressive mastery of the new technology by economic agents results from the collective exploration of a fitness landscape, in which landscape steps depend on the extent of (public and private) R&D investment. However, higher amounts of R&D investment do not guarantee an advantageous market position: landscape exploration is a risky process subject to technological lock-in.

Moreover, we restrict our attention to a single industry using a technology to produce a final good of varying quality. The dynamics of final output follows the growth of final demand. Market competition is modelled by a (tamed) replicator equation: market shares evolve according to product quality differentials.

Thus, our model exhibits the Keynesian feature by which production capacity adapts to the growth of final demand, and the Schumpeterian feature by which R&D investments do *not* automatically translate into innovation development, due to the inherent uncertainties assocaited to innovation.

The public sector directly invests in R&D, either at an early stage or throughout the innovation chain, charging a license cost to firms in order to access accumulated technological knowledge. Private firms may take advantage of the privileged landscape position reached by the public sector, acquiring the license to operate the new technology and obtaining a relatively high fitness score, product quality and market share, thus accessing innovation suruplus profits. Profits made by firms are channelled as dividends, whereas investment in R&D contributes to the development of skills of R&D workers, increasing wages.

Within this framework, we introduce a series of metrics to capture the extent of the imbalance of risks and rewards between public and private actors, studying these across alternative scenarios that are (parametrically) defined according to: (i) the degree of direct involvement of the public sector in R&D investment and (ii) the complexity of the new technology introduced.

The time evolution of key variables of the model for a typical run of our 'benchmark' parametrization suggests that when market size grows exponentially, the industry exhibits higher instability: dividends reap increasing shares of income, the average fitness of private firms surpasses the public sector, market concentration fluctuates and aggregate knowledge accumulation by private firms slows down (Mazzucato, 2013, p. 199).

The key mechanism behind this dynamics concerns the fact that latecomer firms paying the license to the public sector have a sizeable knowledge advantage: their late entry from a privileged starting position to explore the technology landscape allows them to reap higher profits with respect to the risks they incur.

From the analysis of the simulation results for the scenarios devised, it emerges that the relative risk-reward nexus (rewards/risks) increases in favour of private firms whenever the public sector directly invests in R&D throughout the innovation chain, and this increase is sharper the lower the complexity of the new technology (i.e. the ruggedness of the fitness landscape).

At the same time, in our framework workers are the ultimate source of skills and innovation development. Hence, by increasing the wage share with its direct action through R&D investment, the public sector drives the process of landscape exploration towards a situation in which the distribution of financial rewards reflects to a larger extent the distribution of contributions to the innovation process.

Finally, by implementing an adaptive rule for taxation and licensing, we quantified the increase in the tax rate on revenues and the license fee rate that allow the public sector to realign the Risk-Reward Nexus between 'early R&D only' and 'R&D throughout' investment scenarios. Thus, when public funds are consistently invested throughout the innovation chain, we show how it should be possible to benefit from the upside, so that a next round of innovative investment can be supported via a 'revolving fund' (Mazzucato and Perez, 2014). Further research on this direction should compare different innovation 'eco-systems' in relation to different risk levels and types of finance (public/private).[28]

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[28] As well as different institutional financial setups (e.g. market-based vs. credit-based) in relation to the evolution of the industry (Dosi, 1990).

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References

Arrow, K. (1962). Economic Welfare and the Allocation of Resources for Invention. In Nelson, R. N., editor, *The Rate and Direction of Inventive Activity: Economic and Social Factors*, pages 609–626. Princeton University Press.

Auerswald, P., Kauffman, S., Lobo, J., and Shell, K. (2000). The production recipes approach to modeling technological innovation: An application to learning by doing. *Journal of Economic Dynamics and Control*, 24(3):389–450.

Bass, F. M. (1963). A dynamic model of market share and sales behavior. In *Winter Conference American Marketing Association*, pages 269–275.

Brynjolfsson, E. and McAfee, A. (2012). *Race against the machine: How the Digital Revolution is Accelerating Innovation, Driving Productivity, and Irreversibly Transforming Employment and the Economy.* Brynjolfsson and McAfee.

Ciarli, T., Leoncini, R., Montresor, S., and Valente, M. (2008). Technological change and the vertical organization of industries. *Journal of Evolutionary Economics*, 18(3):367–387.

Dosi, G. (1990). Finance, Innovation and Industrial Change. *Journal of Economic Behavior and Organization*, 13:299–319.

Dosi, G., Fagiolo, G., and Roventini, A. (2010). Schumpeter meeting Keynes: A policy-friendly model of endogenous growth and business cycles. *Journal of Economic Dynamics & Control*, 34:1748–1767.

Kauffman, S. A. (1993). *The origins of order: Self organization and selection in evolution.* Oxford university press.

Klepper, S. (1996). Entry, Exit, Growth and Innovation over the Product Life Cycle. *American Economic Review*, 80(3):562–583.

Lazonick, W. and Mazzucato, M. (2013). The risk-reward nexus in the innovation-inequality relationship: who takes the risks? Who gets the rewards? *Industrial and Corporate Change*, 22(4):1093–1128.

Mazzucato, M. (2013). The entrepreneurial state: debunking private vs. public sector myths. *Anthem, London.*

Mazzucato, M. and Perez, C. (2014). Innovation as Growth Policy: the challenge for Europe. *SPRU Working Paper Series*, 2014(13).

Mazzucato, M. and Shipman, A. (2014). Accounting for productive investment and value creation. *Industrial and Corporate Change*, 23(4):1059–1085.

Metcalfe, J. S. (1981). Impulse and diffusion in the study of technical change. *Futures*, 13(5):347–359.

Metcalfe, J. S. (1998). *Evolutionary Economics and Creative Destruction.* Routledge, London.

Nelson, R. N. (1959). The Simple Economics of Basic Scientific Research. *Journal of Political Economy*, 67(3):297–306.

UN (2009). *System of National Accounts 2008, ST/ESA/STAT/SER.F/2/Rev.5.* United Nations, New York.

Valente, M. (2014). An NK-like model for complexity. *Journal of Evolutionary Economics*, 24(1):107–134.

Winter, S. G. (1984). Schumpeterian competition in alternative technological regimes. *Journal of Economic Behavior & Organization*, 5(3):287–320.