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The University and the Prince: Public funds shaping university trajectories

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Abstract

We develop an evolutionary model to analyse the role of policymaker's preferences about the amount and the direction of funding in determining the trajectories of universities. We draw a parallel between the research and the teaching environments, and the Schumpeter Mark I and Schumpeter Mark II innovative patterns, respectively. We obtain that shifting the priority from pure to utilitarian knowledge, and vice-versa, makes production and employment dynamics follow an inverted-U shape. Likewise, the complementarity between teaching and research typical of Humboldt-like organisations allows the system to experience the best performance when preferences are neither too research- nor too teaching-oriented. Moreover, a generalised increase in funds is not effective if the distribution mechanisms are untouched and prioritise university reputation. Finally, a Baumol's cost disease arises when the scientists wage rate is centralised at system level as in most European economies.

Keywords: university trajectories; government funding policy; third mission.

JEL Classification: I23 , L16 , O30.

1 Introduction

Observed as key players in the knowledge-based economy (Cobban, 2022; Collini, 2012; Geuna, 1999) and among the most important legacies of Latin civilisation (De la Croix et al., 2024; Mokyr, 2016), universities are increasingly asked to support the economic development at local, regional as well as country levels with the provision of *useful* teaching and research (Cowan et al., 2010; Uyarra, 2010; Wowk et al., 2017). Accordingly, a university organises teaching and research activities also considering the way the government distributes funds to the production and diffusion of knowledge. The current social contract is one in which the public sector has a clear expectation that, in return to public funding, scientists and universities should also focus on the industrial and economic impacts of their activities – i.e., the *third mission* (Borsato and Llerena, 2024; Martin, 2003).
However, the university has never been a passive agent in the socioeconomic environment. Since the Middle Ages, and especially in Continental Europe, university members have usually been active players in addressing the local cultural, economic, and political needs of the city to which they belonged (Bender, 1988). Likewise, the interaction with the socioeconomic environment entailed the development of traits that changed the mission of a university with respect to the production and dissemination of knowledge.

The analysis of a university behaviour and related funding policymaking across time and space is all but an unexplored issue at the frontier of economics. For instance, Del Rey (2001) elaborates a game with two universities that operate in the same jurisdiction and compete for students and funds for teaching and research. Conversely, Gumport and Snydman (2002) and Ramirez and Christensen (2013) adopt a neo-institutional perspective, according to which formal organisations determine the evolution of university as locus of knowledge production. Seemingly, a growing bulk of research points out the complex relationship between the several activities that range from teaching and research to the public engagement (Bianchini et al., 2016; Drucker and Goldstein, 2007), highlighting how much the private side of the economy draws on public research when it comes to undertake innovative search (Arora et al., 2015; Narin et al., 1997). Nonetheless, the existent literature lacks a deeper understanding of the multiple and multifaceted trajectories which a university could follow when interacting with the policymaker. Most research does not consider the endogenous trade-offs and complementarities that may emerge between teaching and research activities and funding policymaking. In other terms, although the literature has explored analogous research questions in a limited fashion, this article constitutes the first endeavour to model the scientific and pedagogical trajectories of universities as intrinsic outcomes, or emergent properties, shaped by the micro-dynamic that involves the *amount* and the *direction* of public funding.

Therefore, we observe the university as an evolutionary entity that, far from a rational utility maximiser, adopts simple heuristics and operating rules to get oriented in an ever-changing environment in the pursuit of manageable processes and viable outcomes (Geuna, 1999; Martin, 2012). Aiming at exploring the conditions that shape the emergence and survival of a university as an evolutionary organisation, we take some distance from the works that mostly deal with the optimal formal structure of an academic institution and on static roles for governments. Moreover, we consider in this paper a university as any organisation that performs either research or teaching or both, hence – e.g., a typical Max Planck Institute is considered as a university in this framework.

We develop an agent-based model (Dosi and Roventini, 2019; Delli Gatti et al., 2018; LeBaron and Tesfatsion, 2008) in which the university is the microeconomic unit of analysis whose development trajectories arise out of the interplay with the public sector in the type of knowledge being produced, in the commitment to research and teaching, and in the third mission. In line with Anderson (1972), Dosi and Roventini (2019), and Solow (2008), we assume away any form of isomorphism between micro and macro, as opposed to neoclassical contributions on the study of higher education (Del Rey, 2001). We believe this approach suits for the purpose at hand for the user knows by construction the micro data generating process and can focus on macro variables as emerging properties of the evolutionary system (Dosi et al., 2018).

In addition, the analysis of the relationship between universities and the public sector in teaching, research, and third mission is not circumscribed to what has been since the XX century. In fact, since the advent of modern science, research funding had been tied to the expectation of returns in the form of newly developed or improved weapons, more accurate instrumentations, better medicine, and wide technical progress (Martin, 2003). Likewise, the kind of public sector that a university had to deal with was not always the national government like the present-day's. It often was a Prince or a King which was also required to be the *guardian angel* of the university's alleged intellectual freedom (Nybom, 2003). Then, conceiving the public sector as a national government of a Prince or any other public institution does not represent a major methodological issue for our purpose.

The definition of a university along the three dimensions of knowledge, commitment and third mission, makes the research activity characterised by a Schumpeter Mark I innovative pattern whereas the teaching activity displays some features typical of a Schumpeter Mark II (Malerba and Orsenigo, 1996, 1995). For what concerns to the direction of public funding as example of a Prince's preferences, we obtain that shifting the priority from pure to utilitarian knowledge, or vice-versa, renders production and employment dynamics follow an inverted-U shape. An even allocation of funds in both types of knowledge is likely a first-best choice. Indeed, increasing concentration - i.e., similar to a monopolistic - tendencies in the research sector result detrimental for a creative-destruction dynamic is at work. The lack of strict cumulativeness diminishes the pool of common knowledge useful to introduce novelties in the system as long as the environment gets concentrated.

Seemingly, the complementarity between teaching and research typical of any Humboldt-like organisation allows the academic aggregate system to experience the best teaching performance when preferences are neither too research nor too teaching oriented. *Teaching-cum-research* settings as in the USA perform better than *limit* arrangements (Dosi et al., 2006; Mowery and Sampat, 2004). Moreover, a generalised increase in funding is not effective if the distributive mechanisms are untouched and prioritise reputation, unless they target small institutes and sustain competition in the research domain. In this regard, the typical postwar US policymaking might prove effective in preserving university capabilities in incrementing the quantity and quality of research (Mowery and Rosenberg, 1999). Finally, we also have some evidence of the Baumol's cost disease when a system-level wage rate combines with the emergence of technological advantages.

The manuscript is organised as follows: Section II discusses the relevant literature; Section III traces the historical roots of Western universities; Section IV details the theoretical model; Section V concerns to the benchmark scenarios; Section VI analyses the effect of the amount and direction of public funds along with the role of demand, and draws some policy implications; last Section concludes. The Appendix provides further information.

2 Relation with the literature

This article contributes to three main streams of research. First and foremost, we refer to the evolutionary (Cobban, 2022; Geuna, 1999; Geuna and Martin, 2003; Martin, 2012, 2003) and neo-institutional (Collini, 2012; Gumport and Snydman, 2002; Ramirez and Christensen, 2013) literature that observes a university as a complex entity that keeps on developing new traits in order to deal with an ever-changing institutional environment. Universities are recognised to exert a crucial role in shaping societies and economies as a *locus* of knowledge creation and innovation (Etzo et al., 2024; Marrocu and Paci, 2013). Likewise, an increasing body of research points to the complexity of the several activities performed therein, ranging from the usual teaching and research functions to the third mission, i.e., public engagement with some focus on the industrial applications of knowledge (Borsato and Llerena, 2024; Bianchini et al., 2016; Drucker and Goldstein, 2007; Rolfo and Finardi, 2014; Uyarra, 2010). Indeed, empirical evidence increasingly highlights that firms draw heavily on the research that comes out of universities as source of knowledge to back their innovative search (Arora et al., 2015; Arundel and Geuna, 2004; Bianchini and Llerena, 2016; Bianchini et al., 2019; Narin et al., 1997).

Importantly, we relate to the literature that enhances our understanding of the impacts of science policies on economic dynamics. The role of governments in providing financial support for research has been a central topic of economic analysis since the late 1950s. Neoclassical arguments, as put forth by Nelson (1959) and Arrow (1962), highlight the challenges associated with the appropriation of benefits from research, leading to a market failure wherein private firms underinvest in innovative search. This has led to a general appeal for public funding. Conversely, there is a substantial body of literature on innovation and technical change (Dosi and Nelson, 2010; Mazzucato, 2016; Metcalfe, 1995; Rosenberg, 1982). That posits that direct and indirect innovation policies necessitate and entail an active role for national governments in shaping technological landscapes and search regimes. The evolutionary theory does not only regard governments as a solution to a market failure in and of itself, but rather as a source of enhancement of competitive performance to the promotion of structural change (Borsato and Lorentz, 2023a; Metcalfe, 1995). In this respect, scientific knowledge is not a costless good that is available to any individual or entity. Rather, it is embodied in specific researchers and institutional networks, and investments are required to master it (Rosenberg, 2010).

Several works elaborate upon the relationship between university decision-making and funding dynamics in scientific policies. The consequences of European Commission's science policies on the transnational publication system is investigated by Leydesdorff (1992). Interestingly, our contribution makes a reverse analysis since, rather than following the conventional approach of examining the publication system, we study the impact of funding dynamics on research and teaching trajectories. In a similar vein, Wowk et al. (2017) posit that academia should engage more closely with government in order to address societal needs. Yet, their perspective differs from ours for they employ a mixed-methods approach to develop recommendations as to enhance the impact of scientific research on societal issue. Additionally, their work is less about the influence of public funds on university trajectories than on the interconnections between academia and policy.
Somewhat in contrast to the literature on the economics of innovation that used to neglect the role of teaching, Hicks (2012) emphasises the importance of the educational mission of universities and the impact of funding allocation. However, her performance-based analysis is primarily focussed on the influence of research, whilst our framework provides a comprehensive understanding of the joint impact of research and teaching on funding dynamics. Likewise, Auranen and Nieminen (2010) concentrate on the distribution of funding for university research at country level, also examining the proportion of resources allocated to teaching and research. To this respect, we propose that the trajectories of research and teaching at university impact on the distribution of resources.

Secondly, we contribute to the stream of Schumpeterian literature that focusses on industrial dynamics and technological regimes (Malerba, 2007; Malerba and Orsenigo, 1995, 1996; Nelson and Winter, 1982).[1] The prevailing view is that the history of a number of industries is characterised by a succession of ages, each associated with a specific dominant technology. The advent of a novelty with an unconventional design encourages a competitive environment which, in turn, leads to the displacement of users of previous technologies. Moreover, the patterns of innovative activities among technological classes and industries are determined by technological regimes (Malerba and Orsenigo, 1995, 1996), which are defined by the conditions of opportunity, appropriability, and cumulativeness in the knowledge space. Technical progress is linked to discrepancies in the competitive standing and financial size of innovators, as well as their relative stability in the ranking.
All of these supply-side determinants are specific to individual industries. Seemingly,

[1] Discussing all the relevant literature may divert our focus. The interested reader could refer to Almudi et al. (2012, 2020, 2013), Dosi (1988, 1982), and Winter (1984) too.

our work characterises the research sector with a typical Schumpeter Mark I process. The dynamic displays several waves of leap-frogging monopoly in which some university becomes the temporary market leader. Though the assimilation of knowledge limits the university absorptive capacity, any university becomes competitive and has the opportunity to challenge the current leadership. Conversely, the teaching sector is better described by a Schumpeter Mark II pattern. Learning-by-doing shapes a university productivity and triggers the accumulation of absolute technological advantages such that a fistful of universities are permanent leaders.
Yet, we share with Borsato and Lorentz (2023a), Lorentz et al. (2016), Malerba (2007), and Malerba et al. (2007) and show that demand-side dynamics, here represented by Prince's preferences and funding policies, also matter. Technology-related factors, while essential to engender any dynamics, must interact with other determinants on the demand side to generate that specific market structure.

Thirdly, we *methodologically* join the stream of literature above since we develop an agent-based model (ABM) in line with Borsato and Lorentz (2023a,b), Caiani et al. (2016), Ciarli et al. (2010), Dawid and Delli Gatti (2018), Delli Gatti et al. (2018), Dosi and Roventini (2019), Fagiolo and Roventini (2017), LeBaron and Tesfatsion (2008), Llerena and Lorentz (2004) and Tesfatsion (2006). This body of research considers any economy as a complex evolving system - i.e., and ecology with several heterogeneous agents whose out-of-equilibrium interactions engender some aggregate order, even if the system structure is in an ongoing and permanent change (Dosi and Roventini, 2019). As in Anderson (1972), our theoretical setting assumes any isomorphism between micro and macro away. As opposed to standard neoclassical contributions on the study of higher education (Del Rey, 2001; El Ouardighi et al., 2013), we benefit from a setting which is *complex*, *adaptive*, and *structural* (Tesfatsion, 2006). It is complex for it involves interacting units. It is adaptive because it experiences environmental change and also structural because it builds upon a representation of what agents do. The implementation of an ABM is particularly suitable to the purpose at hand since the user knows by construction the micro data generating process and can explore the features of aggregate variables as properties emerging out of evolutionary dynamics (Dosi et al., 2018). In this respect, our work also relates to Hassanpour (2017), which develops a simple ABM in which individual applications and spending decisions of research grants by researchers are analysed. Yet, that framework does not consider the trade-offs and complementarities between teaching and research activities and related impacts on funding policies.

In light of the aforementioned works, which explore analogous research questions in a limited fashion, this paper constitutes the first endeavour to model the scientific and pedagogical trajectories of universities, including teaching, research, and the third mission, as intrinsic outcomes shaped by the evolutionary micro-dynamics that influence, and are influenced by, the government funding policy. To this aim, the next Section draws on and extends Borsato and Llerena (2024), Geuna (1999) and Martin (2012) to trace the historical roots of Western universities from the origins of these organisations to current developments.

3 The historical roots of Western universities

Universities appeared as organised institutions in Europe during the XI century and were considered among the most original outcomes of Western Latin civilisation (Mokyr, 2016; De la Croix et al., 2024). European universities had followed two different trajectories that impacted on the relationship between academic realities, politics and related funding dynamics since their very beginning. If Oxford's and Cambridge's universities represented the archetype of the anti-urban Anglo-Saxon context, universities in continental Europe were intertwined with the activities of the cities to which they belonged (Bender, 1988). Observed as active players in addressing the local cultural, economic, and political needs, universities constituted the *locus* to improve skills and expertise in environments from law to medicine (Cobban, 2022; Etzkowitz and Leydesdorff, 1997, 2000; Geuna, 1999). On the one hand, universities were strongly committed to teaching to lawyers, public servants and priests the "*pure* or '*immaculate*' conception" of knowledge (Martin, 2012, pp. 545-546, emphasis in original). On the other hand, they were not involved in research activities but only in a re-interpretation of existing knowledge. These functions identified the double orientations of medieval universities with respect to the '*pursuit of truth*' (*bios theoretikos*) in the studies of canon law and theology, and to the promotion of useful knowledge (*bios praktikos*) typical of law and medicine.

This distinction remained until the XVIII century when academic organisations emerged with specific room for research besides teaching and scholarship. Examples in this direction were the Cardinal Newman's and the Humboldt's models. On one side of the spectrum, Cardinal Newman's model was regarded as the typical university focussed on teaching activities. In his essay on *The Idea of a University* (Newman, 1893), Newman provided specific teaching methods based on conservative Catholic doctrine for which "knowledge is sufficiently ineffable that it can only be conveyed within a tradition that is maintained through personal contact between master and student" (Moore, 2012, p. 2). This ivory tower of independent scholars which taught students with liberal education and upright moral character made teaching the cornerstone of the academic life, leaving research to be performed elsewhere (Martin, 2012).

On the other side, the Humboldt's model is still largely believed as the benchmark of what a university should be. Humboldt developed his conception during his mandate as Undersecretary of Prussia (Nybom, 2003; Readings, 1996). This model assumes the complementarity between teaching and research within the same organisation as pivotal to the training of bureaucratic and professional elites with humanistic education. The government as represented by the Prince or the King should assure conspicuous public funds and a consistent level of autonomy to scholars. Moreover, the Humboldt's model represents a clear-cut distinction with the ivory tower *à la* Cardinal Newman. In fact, the direct link with societal needs is consubstantial and the results of research are transferred to (potential) users at the end of the project (Geuna, 1999; Martin, 2003). The figure of university professor gives a social status which implies an engagement in society. For instance, Strasbourg became one of the first European cities with a modern electrical lighting because of knowledge transfers in electrical engineering coordinated by the Nobelist Karl Ferdinand Braun, which was also professor in Strasbourg at the time (Russer, 2012). This model proved very successful in that it was soon adopted outside Prussia in most Western countries, e.g., in North America. In particular, the Humboldtian architecture envisaged a social contract with the aim of building a national culture and identity. Culture thus became a distinct public good. The *University of Culture* (Cowan et al., 2010; Readings, 1996) acquired a political value because it contributed to the training of leaders and the promotion of social cohesion.

Alongside this organisational model, others similar academies have arisen in Western countries since the XIX century. For instance, the progressive industrialisation of the USA increased the need to trained workers and engineers. The Morrill Act of 1862 was an important milestone in laying the foundation of land-grant colleges, which were established with the primary purpose of teaching subjects related to agriculture and mechanical arts, but not excluding other scientific and classical subjects, as well as military tactics. This aimed at encouraging practical education for the industrial classes in various trades and occupations (Morrill-Act, 1862). At the same time, the Humboldt model was not adopted in France in which most research activities are still performed by CNRS laboratories (Brickman, 1977; Chesnais, 1993). Founded in 1939, CNRS has aimed at revolutionising the French academic system with a focus on the relationship between science and technology for the concrete application of academic knowledge to economic reality (Belot, 2015).

Tab. 1 and Fig. 1 help us summarise the overall discussion. If we considered a university as any organisation in which either teaching or research or both activities are carried out, then we may also categorise a university along three *abstract* dimensions. The first considers the type of knowledge to be produced, be it of a pure or a more utilitarian nature - e.g., in Max Planck Institutes or in land-grant colleges, respectively. The second dimension concerns to the commitment to teaching or research, with universities *à la* Cardinal Newman that are outright focussed on teaching as opposed to a CNRS lab which is research-oriented. Finally, we have the so-called third-mission - i.e., the character of the *social contract*. On the one hand, the contract as in Bush (1945) report engenders a high degree of autonomy of science also in the way decisions of how to spend public funds are made by the scientific community. On the other hand, we find the *revised* social contract that established since the 1990s (Martin, 2003). This contract *narrows* the scope of universities and has a clear expectation that, in return to public funding, scientists and universities should be focussed more on the industrial and economic impacts in their activities (Borsato and Llerena, 2024). We position the Humboldtian university at the centre of the cube as the archetype of an organisation in which the alleged autonomy of its constituent elements allows for the pursuit of the widest ensemble of activities.

Then it becomes interesting to understand whether the scientific and pedagogic

Axis	Dimension	Description
x	Knowledge	What kind of knowledge does a university want to convey? - Pure knowledge - Utilitarian knowledge - Both
y	Commitment	What activities does a university undertake? - Teaching - Research - Both
z	Third mission	What is the social contract? - Solutions - No expected returns - Both

Table 1 University activities: a summary

trajectories of universities were the emergent properties of any evolutionary micro-dynamics as - e.g., originated in funding decisions. The next Section tries to elaborate upon this issue within an evolutionary theoretical setting.

4 An evolutionary model of university trajectories

We analyse the behaviour of universities as the result of the interplay between multiple and often conflicting goals pursued by their members with the ensemble of constraints and opportunities that external conditions pose on top of it. Far from rational utility maximisers, university decision makers adopt simple heuristics and operating rules to get oriented in an ever-changing environment in the pursuit of manageable processes and viable outcomes (Geuna, 1999). For the purpose at hand, we consider the *university* as the microeconomic unit of analysis whose development trajectories arise out of the interplay between the three dimensions as in Tab. 1 and Fig. 1: type of knowledge (x axis), commitment to teaching and research (y axis), and third mission (z axis). As above, any organisation that performs either teaching or research or both is considered as a university. The i-th university engages in teaching (T) and research (R) in different degrees and proportion with respect to competitors and across time.[2] Moreover, when carrying out "innovative search", the i-th university allocates productive resources to pure and utilitarian knowledge, with the possibility of specialising according to some path dependency. The engagement in teaching and research in terms of knowledge production is affected by government or Prince commitment and interests in the provision of *solutions* to well-established societal challenges, or a broader rise and spread of knowledge without immediate *expected returns*.

[2]In what follows *research*, *knowledge*, and *science* are used interchangeably. Moreover, when the focus is on knowledge *per se*, we distinguish between *pure* and *utilitarian*, whereas about the third mission, we make a distinction between *solutions* and $non-solutions$ oriented. Nonetheless, we are aware that defining sharp boundaries is not such an easy task in reality (Rosenberg and Nelson, 1994).

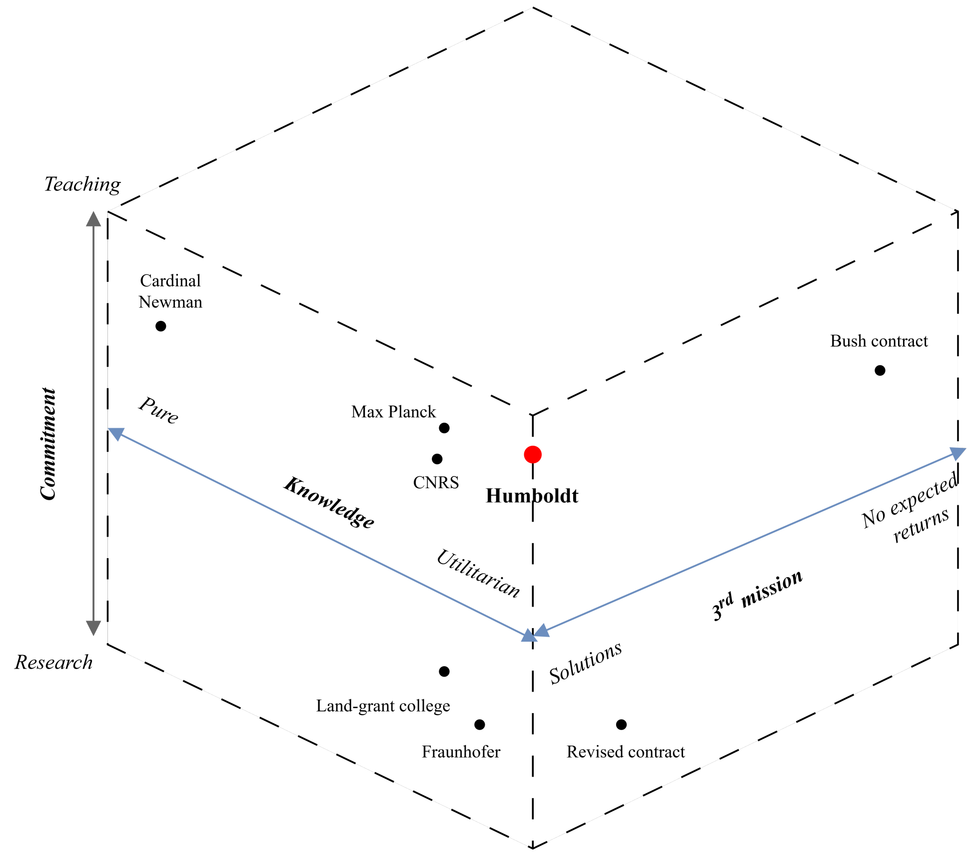

Fig. 1 University along multiple dimensions

4.1 Research production functions

Without loss of generality, we measure the production of, respectively, pure and utilitarian knowledge, with and without expected returns, with the number of papers or books published during the production cycle at time t. The writing of a document that consists of a further contribution to the literature requires two means of production: labour in the form of scientists time and capital in terms of books. Yet, though the combination of scientists and books are *necessary* to ensure the delivery of new knowledge, in no way it is a *sufficient* condition to guarantee the emergence of a contribution to the literature. The arrival of new knowledge is to a certain extent *stochastic* and aside from actual effort. We formalise it in Eq. (1), in which the probability of the arrival of contributions depends positively on the amount of researchers time and books available at university:

$$Prob\left[R_{ijt}^{P,v}\right] = 1 - \exp\left(-\epsilon_0 \cdot \min\left[A_{ijt}^{R} \cdot L_{ijt}^{R,v}; C^{R} \cdot K_{ijt}\right]\right) \quad (1)$$

in which $R^{P,v}_{ijt}$ is the potential amount of new knowledge, A^R_{ijt} is researchers productivity, $L^{R,v}_{ijt}$ is labour time as teachers-researchers [3], C^R is the fixed capital-output ratio, K_{ijt} is the capital stock in terms of books – e.g., a library – and ϵ_0 is a parameter; j refers to pure ($j = p$) or utilitarian ($j = u$) knowledge, and v refers to solution-oriented ($v = S$) or non-solution oriented ($v = NS$) research. If successful, the quantity contribution to the literature is determined by potential production:

$$R^v_{ijt} = \min\left[A^R_{ijt} \cdot L^{R,v}_{ijt}; C^R \cdot K_{ijt}\right] \tag{2}$$

We assume that the arrival of new knowledge does not consist only in *quantities* of new books or manuscripts. Since we have potentially four different production functions as a result of the combination between types of knowledge and its contribution to the third mission, each piece of new knowledge is characterised by a quality index. The outcome of any research endeavour is a new capital vintage that piles up to the university past stock of knowledge with a quality indicator. This index determines the embodied productivity of a new vintage and follows the dynamic as in Eq. (3):

$$a^v_{ijt} = (1 - \delta_{1jt}) \cdot a^v_{ijt-1} + \epsilon^v_{ijt} \tag{3}$$

in which δ_{1jt} is a simple linear function of the aggregate growth rate of knowledge $\left(\frac{\Delta R_{jt-1}}{R_{jt-1}}\right)$ and ϵ^v_{ijt} is drawn from a Beta(2,5) distribution with support $[\epsilon_1;\ \epsilon_2] = [-0.5; 2]$. The rationale behind this specification is twofold. On one side, we assume that the quality of past knowledge depreciates with the arrival of new knowledge and when research stagnates at university level – e.g., $\epsilon^v_{ijt} = 0$. On the other side, we choose a Beta(2,5) distribution for the probability to draw a research output of remarkable quality is far lower than drawing a contribution of average quality. We allow some negative draws since research often results in failure. This formulation allows for the technological opportunities as potential research outcome to endogenously improve in time. The productivity of a group of scientists in pursuing research is a weighted average between two components:[4]

$$A^R_{ijt} = \frac{\Delta K_{ijt}}{K_{ijt}} \cdot \bar{a}_{ijt} + \left(1 - \frac{\Delta K_{ijt}}{K_{ijt}}\right) \cdot A^R_{ijt-1} \tag{4}$$

[3] We do not differentiate between classes or types of workers. Scientists teach and undertake research in both pure and utilitarian knowledge. What matters is their different productivity across activities as well as the time devoted to each.

[4] For simplicity, researchers productivity does not change if their activity is committed to targeted or non-targeted research: only the type of knowledge matters.

in which $\frac{\Delta K_{ijt}}{K_{ijt}}$ is the growth rate of the corresponding stock of knowledge at university level, whereas $\bar{a}_{ijt}$ corresponds to the average quality of in-house research. Eq. (4) entails an *absorptive − capacity* mechanism. The efficiency of scientists in a university stays the same if the university does not invest in new knowledge. Moreover, scientists suffer from *obsolescence* the greater the arrival of new knowledge in the system, which reduces labour productivity unless the university fuels absorptive capacity. What allows scientists to increase productivity and keep abreast of new literature is the first element on the right-hand-side. The greater the quality of research at university, the greater the capacity of scientists thereof to master knowledge from outside, and the greater their research productivity.[5] Since the in-house stock of knowledge is a stock of vintages, the average quality of science has to be weighted by the several vintages:

$$\bar{a}_{ijt} = \frac{R^v_{ijt}}{\sum_t^\tau R^v_{ijt}} \cdot a^v_{ijt} + \left(1 - \frac{R^v_{ijt}}{\sum_t^\tau R^v_{ijt}}\right) \cdot \bar{a}_{ijt-1} \tag{5}$$

Capital corresponds to the stock of knowledge accumulated by a university over time, that is knowledge from inside and outside. This stock does not measure *quantity* knowledge only, it also accounts for the *quality* of past production to define the resources available at any time step. Moreover, capital depreciates with the arrival of new knowledge and with the increase in its average quality:

$$K_{ijt} = \left[\sum_{t=0}^{\tau} \left(a^v_{ijt} \cdot R^v_{ijt}\right) + \phi_{ijt} \cdot \sum_{t}^{\tau} \sum_{-i} \left(a^v_{-ijt} \cdot R^v_{-ijt}\right)\right] \cdot \delta_{ijt} \tag{6}$$

in which ϕ_{ijt} defines the university capability to master and exploit the knowledge produced elsewhere in the system, and δ_{ijt} refers to depreciation. Absorptive capacity follows a logistic schedule that is bounded between 0 and 1 such that the benefit from outside knowledge as *input* is equal to its value as previously an *output* at most; additionally, absorptive capacity is a positive function of the previous capital stock accumulated by a university:

$$\phi_{ijt} = 1 - \exp\left[-\phi_0 \cdot K_{ijt-1}\right] \tag{7}$$

[5] See also Kaur et al. (2015) for an empirical assessment of the relationship between research quality and quantity.

in which ϕ_0 is a positive parameter. For what concerns to depreciation, we make it depend on the average growth of research as well as its average quality growth:

$$\delta_{ijt} = \exp\left[-\delta_0 \cdot \left(\frac{\Delta R_{jt-1}}{R_{jt-1}} + \frac{\Delta \bar{a}_{jt-1}}{\bar{a}_{jt-1}}\right)\right] \tag{8}$$

with δ_0 as parameter.

4.2 Teaching production functions

Universities also perform teaching with the employment of the same scholars that undertake research. Teaching is the amount of time provided in pure and utilitarian knowledge. The corresponding production functions mimic Eq. (2):

$$T_{ijt}^{P,v} = \min\left[A_{ijt}^T \cdot L_{ijt}^{T,v}; C^T \cdot K_{ijt}\right] \tag{9}$$

in which $T_{ijt}^{P,v}$ defines potential teaching, A_{ijt}^T the productivity of scholars' time ($L_{ijt}^{T,v}$) and C^T is the fixed capital-output ratio. We assume that labour-productivity growth is determined by learning by doing that takes into account the fact that productivity improves the more scholars keep on performing this task.[6] Furthermore, we also consider a complementarity between research and teaching, such that contributing to the production of new knowledge or just keeping it updated allows to ameliorate teaching quality. These assumptions are represented in Eq. (10):

$$A_{ijt}^T = \left[1 + \lambda \cdot \left(\frac{\Delta T_{ijt-1}}{T_{ijt-1}} + \frac{\Delta A_{ijt-1}^R}{A_{ijt-1}^R}\right)\right] \cdot A_{ijt-1}^T \tag{10}$$

in which λ is a coefficient.

4.3 Funding

The Prince - i.e., the State - funds universities for both teaching and research.[7] Provided an aggregate amount of public funds F_t, the government allocates it according to three policy parameters. The first, γ^T, splits funds between research and teaching; the second coefficient, γ^j, determines what goes to utilitarian and what to pure knowledge; the third parameter, γ^v, defines government preferences for solutions and

[6] Murnane and Phillips (1981) argues that the relationship between teaching experience and related performance could be explained via learning by doing along with the teachers' academic excellence and influence in the job market for the selection of teachers.

[7] For the sake of simplicity, we do not enter the debate on public v. private funded higher education here, and we adopt a scheme corresponding to a large share of universities in Europe.

non-solutions-oriented activities. We gather in the following array of equations the eight sources of funds:

$$\begin{cases} F_{u,t}^{T,S} = \gamma^T \cdot \gamma^j \cdot \gamma^v \cdot F_t \\ F_{p,t}^{T,S} = \gamma^T \cdot \left(1-\gamma^j\right) \cdot \gamma^v \cdot F_t \\ F_{u,t}^{T,NS} = \gamma^T \cdot \gamma^j \cdot (1-\gamma^v) \cdot F_t \\ F_{p,t}^{T,NS} = \gamma^T \cdot \left(1-\gamma^j\right) \cdot (1-\gamma^v) \cdot F_t \\ F_{u,t}^{R,S} = \left(1-\gamma^T\right) \cdot \gamma^j \cdot \gamma^v \cdot F_t \\ F_{p,t}^{R,S} = \left(1-\gamma^T\right) \cdot \left(1-\gamma^j\right) \cdot \gamma^v \cdot F_t \\ F_{u,t}^{R,NS} = \left(1-\gamma^T\right) \cdot \gamma^j \cdot (1-\gamma^v) \cdot F_t \\ F_{p,t}^{R,NS} = \left(1-\gamma^T\right) \cdot \left(1-\gamma^j\right) \cdot (1-\gamma^v) \cdot F_t \end{cases} \tag{11}$$

Therefore, funding is classified according to teaching v. research distribution (T, R), targets (S, NS), and type of knowledge (u, p). Aggregate funds grow at rate g^F. This rate considers an exogenous component that refers to policymaking and an endogenous component about aggregate productivity dynamics in both teaching $(\frac{\Delta A_{t-1}^T}{A_{t-1}^T})$ and research $(\frac{\Delta A_{t-1}^R}{A_{t-1}^R})$. The aggregate growth rate results from the weighted average between the exogenous and endogenous elements:

$$g^F = \theta_0 \cdot g^{ex} + (1-\theta_0) \cdot \left[\omega_1 \cdot \frac{\Delta A_{t-1}^R}{A_{t-1}^R} + (1-\omega_1) \cdot \frac{\Delta A_{t-1}^T}{A_{t-1}^T}\right] \tag{12}$$

in which θ_0 and ω_1 are parameters whereas g^{ex} is the exogenous growth rate.

4.4 Reputation and fund-distribution dynamics

We distribute public funds to universities according to a share reflecting their fitness. The shares dynamic accounts for the relative *reputation* of institutions such that a university share rises (lowers) as long as its reputation is higher (lower) than average. Reputation defines a university efficiency or excellency in the provision of research and teaching.[8] We distinguish between targeted and non-targeted research. In the former case, the university reputation $(E_{ijt}^{R,v})$ is determined by its researchers productivity relative to market average $(A_{jt}^{R,v})$. Conversely, solution-oriented research conditions university reputation to its ability to satisfy the research demand $(R_{ijt-1}^{D,v})$ for solutions. We represent both mechanisms in Eq. (13), in which θ_1 is a parameter

[8]Seemingly, Garcia and Sanz-Menéndez (2005) consider research quality as a distinguishing element of scientific reputation. In this respect, they measure the competition for research funding using data from research-proposal applications and awards as opposed to bibliometric techniques that also include citations. See also Whitley and Gläser (2014) on within-university principal-agent issues when competition for funds is based on reputation.

that takes positive value when research is targeted and zero otherwise:

$$E_{ijt}^{R,v} = \left(\frac{A_{ijt}^{R,v}}{A_{jt}^{R}} \right) \cdot \left(1 - \theta_1 \cdot \frac{R_{ijt-1}^{D,v} - R_{ijt-1}^{v}}{R_{ijt-1}^{D,v}} \right) \tag{13}$$

Teaching reputation ($E_{ijt}^{T,v}$) is also determined by the ability of the university to satisfy the demand ($T_{ijt-1}^{D,v}$) for frontier and applied science, irrespectively of any target:

$$E_{ijt}^{T,v} = \left(\frac{A_{ijt}^{T,v}}{A_{jt}^{T,v}} \right) \cdot \left(1 - \theta_1 \cdot \frac{T_{ijt-1}^{D,v} - T_{ijt-1}^{v}}{T_{ijt-1}^{D,v}} \right) \tag{14}$$

The share of funds allocated to each university respectively for research ($s_{ijt}^{R,v}$) and teaching ($s_{ijt}^{T,v}$) follow a replicator dynamic as usual in evolutionary economics (Metcalfe, 1994):

$$s_{ijt}^{R,v} = s_{ijt-1}^{R,v} \cdot \left[1 + \sigma \cdot \left(\frac{E_{ijt}^{R,v}}{E_{jt}^{R,v}} - 1 \right) \right] \tag{15}$$

$$s_{ijt}^{T,v} = s_{ijt-1}^{T,v} \cdot \left[1 + \sigma \cdot \left(\frac{E_{ijt}^{T,v}}{E_{jt}^{T,v}} - 1 \right) \right] \tag{16}$$

in which σ is a parameter while $E_{jt}^{T,v}$ and $E_{jt}^{R,v}$ are market-average reputations.

4.5 Labour market

Labour supply is fully elastic, hence the supply of scholars' time does not constrain university demand. For both teaching and solutions-oriented research, universities form expectations based on past demand. They apply an adaptive rule to keep some spare capacity in order to meet unexpected peaks in demand. Moreover, since public funds arrive at institutions *by activity*, it might be the case that a university cannot fully satisfy its labour demand in – e.g., solutions-oriented teaching, even if it has some extra capacity potentially available out of – e.g., solutions-oriented pure research. To avoid this mismatch, universities pool all funds in excess in order to hire extra labour time. Then, universities allocate this excess supply of scholars according to each relative market requirements. If, again, some form of extra labour is available once all the labour demand for solutions-oriented activities is met, then the remaining workforce is distributed to non-targeted research.

With respect to solutions-oriented research, universities plan their excess capacity as in Eq. (17):

$$R_{ijt}^{d,S} = R_{ijt-1}^{d,S} + \iota \cdot \left[R_{ijt-1}^{D,S} - R_{ijt-1}^{S}\right] \cdot \left(1 + u^R\right) \tag{17}$$

in which $R_{ijt}^{d,S}$ is desired research capacity while ι and u^R are coefficients. Desired labour demand ($L_{ijt}^{dR,S}$) is determined accordingly:

$$L_{ijt}^{dR,S} = \frac{R_{ijt}^{d,S}}{A_{ijt}^{R}} \tag{18}$$

The actual number of scientists' time ($L_{ijt}^{R,S}$) devoted to solutions-oriented research becomes:

$$L_{ijt}^{R,S} = \min\left[L_{ijt}^{dR,S}; \frac{F_{ijt}^{R,S}}{w_t}\right] + EL_{ijt}^{R,S} \tag{19}$$

in which w_t is the wage rate and $EL_{ijt}^{R,S}$ is any extra labour. Conversely, when research is not targeted, the labour force is constrained by the availability of funds plus a share η of the remaining labour (NEL_{it}) once all solution-oriented labour demand is met:

$$L^{R,NS} = \frac{F_{ijt}^{R,NS}}{w_t} + \eta \cdot NEL_{it} \tag{20}$$

The dynamics of the teaching labour markets is analogous to solutions-oriented research. Desired teaching demand ($T_{ijt}^{d,v}$) is represented in Eq. (21):

$$T_{ijt}^{d,v} = T_{ijt-1}^{d,v} + \iota \cdot \left[T_{ijt-1}^{D,v} - T_{ijt-1}^{P,v}\right] \cdot \left(1 + u^T\right) \tag{21}$$

in which u^T is a parameter. Likewise, desired teaching labour demand ($L_{ijt}^{dT,v}$) accounts for teaching productivity:

$$L_{ijt}^{dT,v} = \frac{T_{ijt}^{d,v}}{A_{ijt}^{T}} \tag{22}$$

The actual teaching labour force results from the difference between that desired and that allowed by funds to pay for, plus any form of extra workforce available to meet labour demand:

$$L_{ijt}^{T,v} = \min\left[L_{ijt}^{dT,v}; \frac{F_{ijt}^{T,v}}{w_t}\right] + EL_{ijt}^{T,v} \tag{23}$$

Provided any funding that allows to hire excess labour force with respect to any single activity for which labour demand is already met, we define excess labour as:

$$EL_{it} = \max\left[0, \sum_i \sum_j \left(\frac{F_{ijt}}{w_t} - L_{ijt}^{d,v}\right)\right] \tag{24}$$

By definition, the *labour requirement* - i.e., all the labour needed in order to meet the unsatisfied labour demand is:

$$LR_{it} = \max\left[0, \sum_i \sum_j \left(L_{ijt}^{d,v} - \frac{F_{ijt}}{w_t}\right)\right] \tag{25}$$

For each university, excess labour will be proportional to its labour requirement:

$$EL_{ijt} = \left(\frac{L_{ijt}^{d} - \frac{F_{ijt}}{w_t}}{LR_{it}}\right) \cdot EL_{it} \tag{26}$$

What remains, if any, out of EL_{it} is spread to non-solutions-oriented research. Therefore, we define the net excess labour (NEL_{it}) as:

$$NEL_{it} = EL_{it} - LR_{it} \tag{27}$$

Finally, the wage rate holds at system level regardless of the activity undertaken; moreover, it grows based on the aggregate growth rate of productivity in both research $\left(\frac{\Delta A_{t-1}^R}{A_{t-1}^R}\right)$ and teaching $\left(\frac{\Delta A_{t-1}^T}{A_{t-1}^T}\right)$:

$$w_t = w_{t-1} \cdot \left[1 + \omega_0 \cdot \left(\omega_1 \cdot \frac{\Delta A^R_{t-1}}{A^R_{t-1}} + (1-\omega_1) \cdot \frac{\Delta A^T_{t-1}}{A^T_{t-1}}\right)\right] \tag{28}$$

in which ω_0 is a parameter. [9]

4.6 Demand

Demand grows exogenously as set by public policy. On the research side, the government demands research contributions only when directed to some solutions. Eq. (29) sets research demand as:

$$R^{D,S}_t = \left(1 + g^R\right) \cdot R^{D,S}_{t-1} \tag{29}$$

in which g^R is the exogenous growth rate. This amount is split between pure (R^D_{pt}) and utilitarian (R^D_{ut}) knowledge by γ^j:

$$R^{D,S}_{pt} = \gamma^j \cdot R^{D,S}_t \tag{30}$$

$$R^{D,S}_{ut} = \left(1 - \gamma^j\right) \cdot R^{D,S}_t \tag{31}$$

Likewise, teaching demand (T^D_t) grows at an exogenous rate g^T:[10]

$$T^D_t = \left(1 + g^T\right) \cdot T^D_{t-1} \tag{32}$$

γ^v divides teaching demand for targeted and non-targeted knowledge:

$$T^{D,S}_t = \gamma^v \cdot T^D_t \tag{33}$$

[9] A wage rate at system level is not too a demanding assumption (Bianchini et al., 2016; Geuna, 1999) since in most European universities governments set uniform wages that hold across national boundaries and depend only on seniority. We account for seniority by indexing the growth factor with the average productivity growth in both teaching and research. Moreover, this dynamic strengthens a selection mechanism across institutions for if $\omega_1 = 1$, all the university benefits from focussing on teaching only reduce, and conversely when $\omega_1 = 0$. Then the dynamics of the wage rate puts a premium on extreme specialisation patterns in either teaching or research.

[10] We may also think of exogenous growth in teaching as the result of demographic dynamics or about the huge increase in enrolments over population after WWII.

$$T_t^{D,NS} = (1 - \gamma^v) \cdot T_t^D \tag{34}$$

Seemingly, pure $\left(T_{pt}^{D,v}\right)$ and utilitarian $(T_{ut}^{D,v})$ teaching demand are defined as:

$$T_{pt}^{D,v} = \gamma^j \cdot \left(T_t^{D,S} + T_t^{D,NS}\right) \tag{35}$$

$$T_{ut}^{D,v} = \left(1 - \gamma^j\right) \cdot \left(T_t^{D,S} + T_t^{D,NS}\right) \tag{36}$$

Research $\left(R_{ijt}^{D,S}\right)$ and teaching demand $(T_{ijt}^{D,v})$ are allocated to universities *via* market shares. The actual output of teaching (T_{ijt}^v) will be:

$$T_{ijt}^v = \min\left[T_{ijt}^{D,v}; T_{ijt}^{P,v}\right] \tag{37}$$

5 Baseline scenario: results

We perform the model with computer simulations as for most of the models incorporating evolutionary features (Caiani et al., 2016; Delli Gatti et al., 2018). Tab. A1 gathers baseline parameter values. The benchmark scenario is performed along 2500 period simulations across 50 Monte Carlo runs, which is a logical time span more than sufficient to reach some stability in the dynamics of the model. The artificial system counts a hundred of universities and a public sector in a closed economy. We set initial conditions such that universities start as perfectly homogeneous: the heterogeneity emerges when the model unfolds as outcome of interactions and different decision rules. Moreover, the government let funding grow at 5% per period and represents the only buyer for the output of research and teaching activities. In other terms, we depict a monopsonistic economy. However, the growth in teaching demand can be supposed of as originating from exogenous population dynamics. Likewise, we do not believe that research demand as coming out of policymaking concerns is a strong hypothesis. The Prince also has no marked preferences for targeted, or non-targeted activities to particular solutions. Therefore, public funds are evenly spread between teaching and research, pure and utilitarian knowledge, and targeted and non-targeted endeavours.[11]

We remind that universities potentially compete in eight different markets from a

[11] For an empirical assessment on whether and to what extent government funding affects the external funding options available to universities, see Muscio et al. (2013).

Market	University activity	Examples
Market I	Targeted utilitarian research	Land-grant colleges (US), National Board for Industrial and Technical Development (SWE), Fraunhofer (GER)
Market II	Targeted pure research	Strategic Research Foundation (SWE)
Market III	Non-targeted utilitarian research	CNRS (FR), Research Council for Engineering Sciences (SWE)
Market IV	Non-targeted pure research	Max Planck Institutes (GER), CNRS (FR)
Market V	Targeted utilitarian teaching	French *HEC* and *Polytechniques*, any *Humboldt* university
Market VI	Targeted pure teaching	French *EHESS*, any *Humboldt* university
Market VII	Non-targeted utilitarian teaching	French *Ecole Normale*, any *Humboldt* university
Market VIII	Non-targeted pure teaching	*Any Humboldt University*, Cardinal Newman's (UK)

Table 2 Markets with real-world examples

theoretical perspective. Finding real-world examples for all of them may not be an easy task but we tried some approximations in Tab. 2. For instance, the Fraunhofer Institutes in Germany and the Swedish National Board for Industrial and Technical Development (NUTEK) aim at connecting and integrating academic research with industry (Benner and Sandström, 2000). Conversely, French CNRS is involved in funding all types of academic research (Brickman, 1977), while any university that adopts an organisational model *à la* Humboldt teaches pure and utilitarian knowledge (Nybom, 2003).

5.1 Aggregate and market dynamics

Tab. 3 reports some average statistics about production, employment, market structure, productivity and research quality by market.[12] Research and teaching outputs present an expected dynamic for they grow over time as to keep the pace of exogenous demand (Freeman, 1986). For what concerns to solutions-oriented research (Markets I-II), output tripled on average from the first bunch of periods to the last one. Seemingly for teaching (Markets V to VIII), which displays the same average dynamic. On the one hand, these average values are slightly greater than targeted-research output. On the other hand, the same average dynamic is expected because of policymaking in spreading evenly both funds and demand across markets. Furthermore, we notice that non-targeted research produces more than other markets. The reason lies in the greater labour force available and the employment dynamic. Indeed, the labour-market reallocation of excess labour allows universities to push research capacity ahead such that the probability of further contributions to the literature enhances.

For what concerns to labour productivity, some interesting dynamics arise. Both research and teaching productivities soar on average. Nevertheless, respective dynamics differ. On the one hand, researchers productivity grows more than teaching productivity at the early university life. Subsequently, researchers productivity reaches a plateau whose improvements occur but at negligible rates. This pattern matches some empirical evidence according to which there is at least a turning point in researchers career, a point in which scholars start relying on elder literature and where their productivity increases at a slower pace, after having substantially raised before (Gingras et al., 2008). This dynamic is most explained by the average pattern

[12] As usual in ABMs, a slot of initial period simulations is removed as it is considered a training period for the model. Given the overall dynamics, we believe that a hundred of periods is sufficient.

Period	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
				Production				
100-500	8.046	8.045	16.413	16.416	7.554	7.554	7.554	7.554
500-1000	10.071	10.074	27.853	27.857	12.032	12.032	12.032	12.032
1000-1500	14.708	14.708	40.193	40.192	16.007	16.007	16.007	16.007
1500-2000	19.680	19.680	52.419	52.419	21.982	21.982	21.982	21.982
2000-2500	24.655	24.655	64.610	64.609	26.957	26.957	26.957	26.957
				Employment				
100-500	4.605	4.605	12.912	12.912	4.883	4.872	4.883	4.872
500-1000	5.802	5.808	23.640	23.640	6.483	6.447	6.483	6.447
1000-1500	10.239	10.245	35.803	35.803	9.671	9.625	9.671	9.625
1500-2000	15.174	15.173	47.980	47.980	13.109	13.064	13.109	13.064
2000-2500	20.143	20.143	60.160	60.160	16.565	16.519	16.565	16.519
				Inverse Herfindahl index				
100-500	82.518	82.692	1.436	1.411	1.004	1.004	1.004	1.004
500-1000	14.287	14.287	1.235	1.249	1.000	1.000	1.000	1.000
1000-1500	1.882	1.882	1.256	1.248	1.000	1.000	1.000	1.000
1500-2000	1.731	1.731	1.253	1.288	1.000	1.000	1.000	1.000
2000-2500	1.471	1.471	1.238	1.156	1.000	1.000	1.000	1.000
	Productivity				**Quality**			
	Utilitarian research	**Pure research**	**Utilitarian teaching**	**Pure teaching**	**Targeted utilitarian**	**Non-targeted utilitarian**	**Targeted pure**	**Non-targeted pure**
100-500	3.448	3.446	1.507	1.511	3.824	3.818	3.700	3.696
500-1000	4.196	4.194	2.121	2.140	4.311	4.314	4.253	4.255
1000-1500	4.425	4.424	4.441	4.487	4.449	4.439	4.401	4.406
1500-2000	4.438	4.437	4.391	4.440	4.485	4.483	4.443	4.443
2000-2500	4.455	4.454	5.855	5.906	4.484	4.498	4.454	4.457

Table 3 Monte Carlo baseline averages for key statistics

Note: Averages are computed over 50 Monte Carlo simulations across reference periods. All values are in log terms but for the inverse Herfindahl index. We recall the content of Tab. 2: Market I (targeted utilitarian research); Market II (targeted pure research); Market III (non-targeted utilitarian research); Market IV (non-targeted pure research); Market V (targeted utilitarian teaching); Market VII (targeted pure teaching); Market VII (non-targeted utilitarian teaching); Market VIII (non-targeted pure teaching).

of research quality (cf. Fig. 2). After an initial sharp growth in quality, the accumulation of knowledge makes the contribution of also high-quality research smaller relative to the *mare magnum* of research ever produced. The arrival of high-quality books, some likely failures, and depreciation then result in volatility and small growth (Fig. 3). Conversely, teaching productivity keeps on increasing as a matter of learning by doing. This behaviour is the outcome of the arrival of new methods, which endogenously emerge as teachers continuously perform this task.[13]

As last indicator, we discuss the inverse Herfindahl index of the market shares which conveys information on the average number of universities actually *active* in each market. Overall, we highlight a trend toward concentration as typical of any replicator dynamic. The tendency is very pronounced for teaching, which arrives at a monopolistic structure at earliest periods. Competitive market structures, conversely, hold for targeted research, which displays fierce competition until $t = 500$, then shifts toward oligopolistic structures in the subsequent 500 periods, to conclude to a duopoly at the end of the simulation. Markets for non-targeted research show instead a tendency to oligopoly since the onset.
Yet, the averages hide qualitatively different dynamics that only a closer inspection of simulations could reveal. Fig. 4 and Fig. 5 report the results of a single, representative simulation about the several universities market shares across time. We argued that research markets seem to be characterised by a greater competitive structure than teaching markets. Though true this assertion is incomplete. Sustained competition holds at most for a fifth of simulation periods for the markets of solutions-oriented research. Afterwards, and for all other research markets, we observe the usual pattern

[13]Though not shown here, the average coefficients of variation of productivity reach very higher values for teaching than for research, and this difference enhances across time. This is a first indicator that few universities accumulate absolute technological advantages in teaching. Results are available on request.

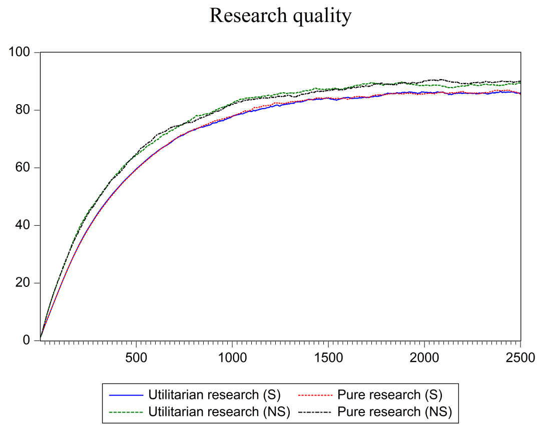

Fig. 2 Average research quality from a representative MC simulation

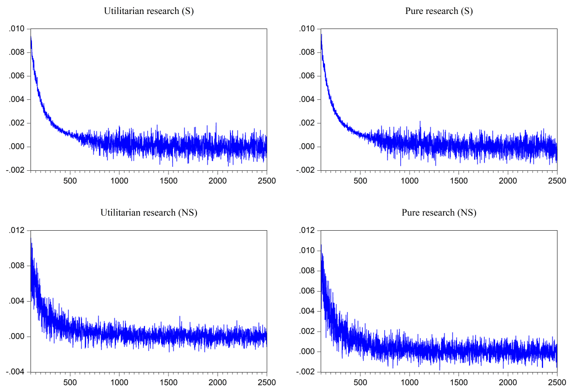

Fig. 3 Average quality growth from a representative MC simulation

of Schumpeterian competition marked by *leap frogging* (Aghion et al., 2005). In other terms, the dynamic depicts several waves of oligopoly and quasi-monopoly in which some university becomes the temporary market leader. Indeed, the knowledge produced by a university through research becomes public. The university absorptive capacity limits the *assimilation* of knowledge but, as time runs, any large university becomes competitive and has the opportunity to jump ahead and challenge the leadership. Moreover, the leaders change continuously, hence there is not the usual cumulativeness in the knowledge space such that a university can benefit from perpetual absolute advantages. Overall, this dynamic mimics the so-called Schumpeter Mark I pattern (Malerba and Orsenigo, 1996, 1995).
In contrast, a handful of periods is sufficient to experience the typical setting à la Schumpeter Mark II for what regards teaching. The learning-by-doing schedule

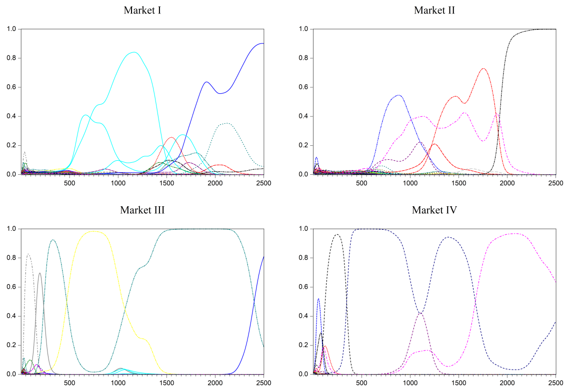

Fig. 4 Universities market shares from a representative MC simulation (Markets I to IV)

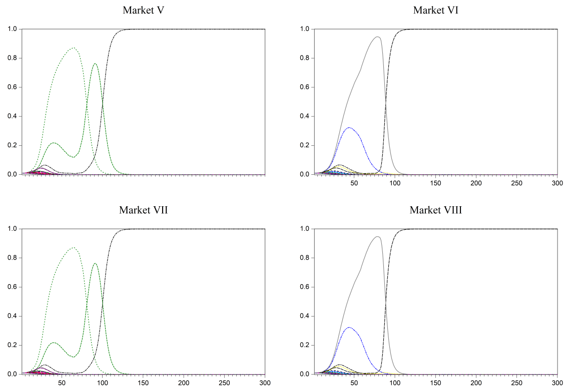

Fig. 5 Universities market shares from a representative MC simulation (Markets V to VIII)

shaping a university teaching productivity fuels an accumulation mechanism such that two universities are leaders of utilitarian and pure markets for teaching, respectively, regardless their target orientation. In addition to this, we suggest that the reinforcement mechanism typical of any Schumpeter Mark II behaviour is further strengthened by a cost disease à la Baumol (1967). Indeed, the wage rate is uniform across institutions and grows following aggregate productivity growth. This means that universities with below-average productivity growth suffer from an increase in labour cost which is only partially offset by productivity improvements. This further complicates their ability to satisfy demand. The reduced reputation eases the emergence of a market leader.[14]

[14] Labour-productivity dynamic also explains why monopoly happens before in utilitarian teaching markets than elsewhere: levels are usually greater in pure teaching markets on average. This factor may have delayed the emergence of monopoly.

5.2 Locating universities in the cube

Fig. 6 portrays the position of universities in the cube as outcome of their evolution across six sampled periods. Coordinates are determined as follows. The x axis measures the share of utilitarian knowledge produced in total research; the y axis refers to the share of labour time committed to research; the z axis denotes the share of mission-oriented funds that a university obtains from the Prince out of total funding. As the dynamic of the model begins, we notice that universities are of similar small size and tend to perform more research than teaching. Universities are equally distributed in the production of pure and utilitarian knowledge, presenting the traits of CNRS institutes. Yet, from the point of view of the third mission, there are no clear patterns of specialisation and we find examples of land-grant colleges, Max Planck Institutes and more Humboldt-like universities. Dynamics start changing in the first half of the simulations. On the one hand, we notice a trend toward concentration. Most universities stay small and specialise in solutions-oriented utilitarian research (cf. Gamson (1966)). In other words, applied mission-oriented government programs become vital for the survival of these little land-grant colleges. On the other hand, few of leading institutes emerge as research centres, in which the balanced production of both pure and utilitarian knowledge absorbs most labour force, setting teaching as residual activity. Nevertheless, it is worth noting at both bottom corners the presence of two Max Planck Institutes with average magnitude which build some advantage in the production of pure or utilitarian knowledge, respectively.

Overall, the location of universities stabilises for most period simulations but in the last fifth of simulations a form of discontinuity arises. Even if most universities keep on surviving as providers of mission-oriented knowledge, the market structure become slightly more competitive. Universities still tend to focus most on research but their labour force is uniformly spread between targeted and non-targeted research programs. From what said, it is interesting to analyse what the impact could be of a change in government preferences in the allocation of funds and demand. We describe these experiments in the next Section.

6 Mapping trajectories: some experiments

We exploit the potential of the model to analyse the role of Prince's preferences in determining the university evolution and patterns of specialisation across time. Seemingly, we focus on the role of demand as engine of dynamics and performance in the several markets of interest. We map the results in Tab. 4 to Tab. 9 and Fig. 7 to Fig. 12.

6.1 Prince's preferences: some unexpected inverted-U shape

We study the preferences of the public sector with three parameters. First, changes in γ^j denote increasing preferences and priorities for utilitarian knowledge, in which the maximum value is obtained when the parameter is equal to 1 (Tab. 4, Fig. 7).

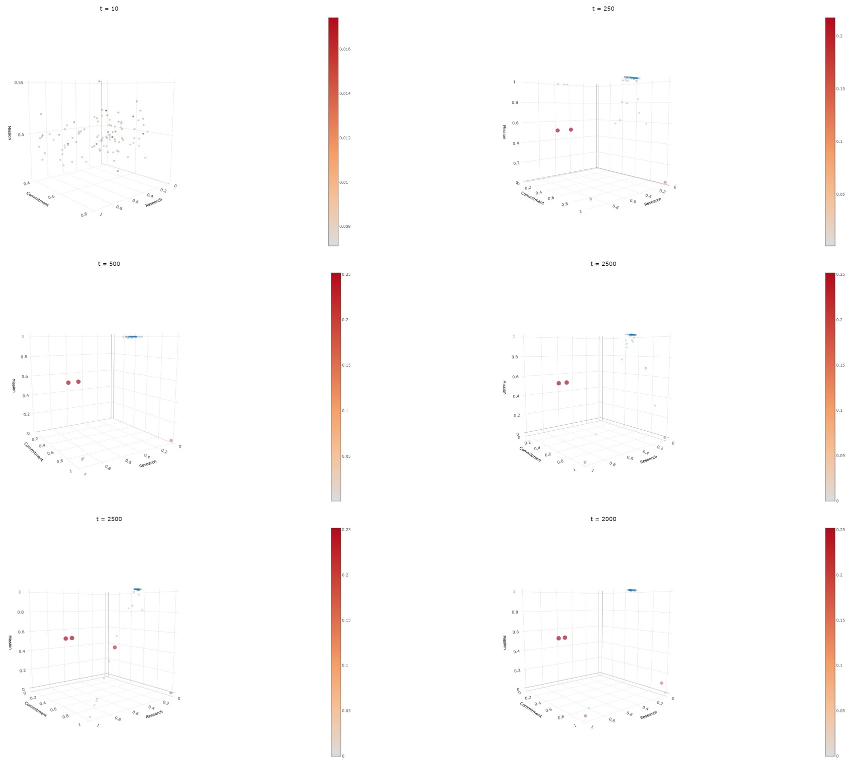

Fig. 6 Locating universities in the cube

Note: The colour scale and the point size denote the employment share in aggregate

Secondly, we test the effect on favouring preferences for teaching activities at the expense of research in the allocation of public funds. This policy choice concerns to γ^T, whose unit value regards highest interest for teaching services (Tab. 5, Fig. 8). Finally, we analyse what dynamic emerges when all public policy is committed to funding mission-oriented programs, as summarised by γ^v, in which again the unit value identifies outright priority to solutions (Tab. 6, Fig. 9).

We argue that shifting the priority from pure to utilitarian knowledge leads production and employment dynamics to follow an inverted-U shaped pattern. Although Markets I-II reach their maxima when interest is fully concentrated in either pure or utilitarian knowledge, as somehow expected, an even allocation of funds in both types of knowledge is likely a first-best choice. Indeed, production and employment levels are at their peak in the baseline scenario. Taking γ^j to the upper and lower bounds fuels market concentration as witnessed by the reduced inverse Herfindahl index of research markets. Therefore, the aggressive Schumpeterian competition of the baseline, with about one fifth of universities with strictly positive market shares, narrows to a duopoly in non-targeted research markets. Likewise, targeted research markets become a quasi-monopoly when the highest priority is set to either pure or utilitarian knowledge. Increasing monopolistic tendencies in a typical Schumpeterian Mark I setting then result detrimental. The evident *lack* of strict cumulativeness lessens the pool of common knowledge out of which a university can draw to introduce further knowledge as long as the market concentrates. Even if the quality of each research endeavour remained unchanged, productivity improvement would impoverish to a certain extent. The more so when research quality also follows an inverted-U shape as it happens to be. Therefore, it comes as no surprise that the reduced productivity with respect to the benchmark setting negatively affects all production and employment patterns along with a concentrated market structure. In contrast, changes in γ^j do not affect the teaching market structure, in which permanent monopoly still holds regardless the scenarios. Yet, the inverted-U shape dynamic takes place as well. We recall that part of productivity dynamics is determined by research performance. Then, creative accumulation in the knowledge space is weakened by the decreased research learning process.

Fig. 7 portrays the university location in the cube. As time goes by, universities shift from a continuum of research institutes of small size with no preferences for target research when all preferences are for pure knowledge, to a spared distribution of research institutes which draw most funding to carry out mission-oriented research without marked preferences. Interestingly, strong preferences for utilitarian knowledge polarise universities at the two bounds of research. Most institutes are of tiny magnitude and perform utilitarian research, while the others focus most on basic research. Furthermore, two institutions on the utilitarian side are of greater magnitude than average, as the duopolistic market structure suggests above. To sum up on this issue, we underline the strong complementarity between pure and utilitarian forms of knowledge, whose actual examples are found in the US postwar academic system (Mowery, 1995). The entrance of the federal government as key manoeuvrer of the national research enterprise allowed funds for basic and applied research to move in parallel. For examples, in the case of National Institute of Health (NIH) investments, increasing funds for basic academic research were coupled with strong incentives to combine university, medical schools, and firms applied efforts to carry out drug experiments and clinical trials.

We tell a slightly different discourse with respect to teaching preferences (Tab. 5, Fig. 8). Moving γ^T to its left or right boundaries causes a shift toward a research and teaching *economy*, respectively. The competitive and monopolistic structures still characterise the research and teaching related markets, respectively. This feature allows universities to benefit again from high productivity standards as result of good research performance, despite levels are somehow smaller than benchmark values. Although production and employment present the usual inverted-U shaped pattern in the research sub-economy, we do not experience the same dynamics in the teaching markets. The high complementarity between teaching and research activities typical of any Humboldt-like institution allows the academic aggregate system to experience

γ^j	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
				Production				
0	8.724***	36.460***	40.633***	39.392***	17.504***	16.616***	17.504***	16.616***
0.2	15.050***	16.109***	41.426***	41.096***	17.505***	17.505***	17.505***	17.505***
0.5	23.964	23.964	66.620	66.626	26.266	26.266	26.266	26.266
0.7	16.003***	15.351***	41.187***	41.397***	17.505***	17.505***	17.505***	17.505***
1	35.714***	8.715***	39.045***	40.082***	16.916***	17.505***	16.916***	17.505***
				Employment				
0	4.605***	41.935***	36.407***	35.898***	10.067***	4.822***	10.067***	4.822***
0.2	10.874***	11.831***	37.190***	36.888***	10.089***	10.346***	10.089***	10.346***
0.5	19.455	19.468	62.198	62.198	15.493	15.507	15.493	15.507
0.7	11.725***	11.082***	36.959***	37.160***	10.439***	10.226***	10.439***	10.226***
1	33.441***	4.605***	35.320***	35.830***	4.753***	10.072***	4.753***	10.072***
				Inverse Herfindahl index				
0	1.164***	11.145***	1.164***	1.489***	1	1.001	1	1.001
0.2	22.892***	15.029***	1.233	1.291	1	1	1	1
0.5	17.756	17.805	1.275	1.319	1.001	1.001	1.001	1.001
0.7	15.818***	20.631***	1.267	1.161***	1.003***	1	1.003***	1
1	10.985***	1.169***	1.495***	1.169***	1.001	1	1	1
	Productivity				Quality			
	Utilitarian research	Pure research	Utilitarian teaching	Pure teaching	Targeted utilitarian	Non-targeted utilitarian	Targeted pure	Non-targeted pure
0	4.143***	3.518***	8.445***	172.498***	3.143***	3.121***	4.273***	-0.002***
0.2	4.212***	4.216***	3.713***	3.473***	4.334***	4.271***	4.327***	4.273***
0.5	4.274	4.274	4.654	4.634	4.358	4.312	4.362	4.312
0.7	4.214***	4.214***	3.397***	3.595***	4.338***	4.270***	4.334***	4.268***
1	3.383***	4.111***	71.849***	3.741***	4.323***	4.271***	3.032***	2.985***

Table 4 Experiments on the preferences for utilitarian knowledge

Note: Mean values over 25 replications for key indicators at aggregate level over the last 2400 simulation steps. Baseline values are for $\gamma^j = 0.5$. All values are in log terms except for the inverse Herfindahl index. We recall the content of Tab. 2: Market I (targeted utilitarian research); Market II (targeted pure research); Market III (non-targeted utilitarian research); Market IV (non-targeted pure research); Market V (targeted utilitarian teaching); Market VI (targeted pure teaching); Market VII (non-targeted utilitarian teaching); Market VIII (non-targeted pure teaching). Statistical significance from the benchmark values is computed with a t-test: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

the best teaching performance when preferences are neither too research nor too teaching oriented. In other words, $teaching - cum - research$ settings with at least some minimum levels of both activities let the aggregate system perform better than compared to limit arrangements. The leaders in the teaching markets are also great research performers (cf. Fig. 8). Their ongoing introduction of new pieces of knowledge increases the knowledge pool from which the other institutes can draw to further contribute to the literature.
These results confirm the potential explanation for the US leadership in scientific productivity that resides in the excellence of its research universities (Dosi et al., 2006; Mowery and Sampat, 2004). Although Humboldt-like environments first emerged in Europe, US universities have proven more successful in adopting this organisational model that exploits the strong complementarities between research and teaching. Conversely, in France and Germany research performers are most found in non-university institutions such as CNRS and Max Planck Institutes (Chesnais, 1993; Keck, 1993). Splitting the two functions does look neither good for research nor for teaching, as also showed by the relative size of universities in Fig. 8.

Finally, when the Prince's preferences are directed toward missions or solutions, we do not notice improved performance in the several markets (Tab. 6, Fig. 9). Most likely an inverted-U shape dynamic still arises and characterises the patterns of employment and production. Once again, radical policy choices drives research markets toward concentration, at the detriment of productivity gains. This outcome is somehow contrasting with what expected from the empirical performance of the US university system. Though involved in both basic and applied research, American universities have long been characterised by some forms of third mission (Mowery and Rosenberg, 1999; Rosenberg and Nelson, 1994). The allocation of public funding

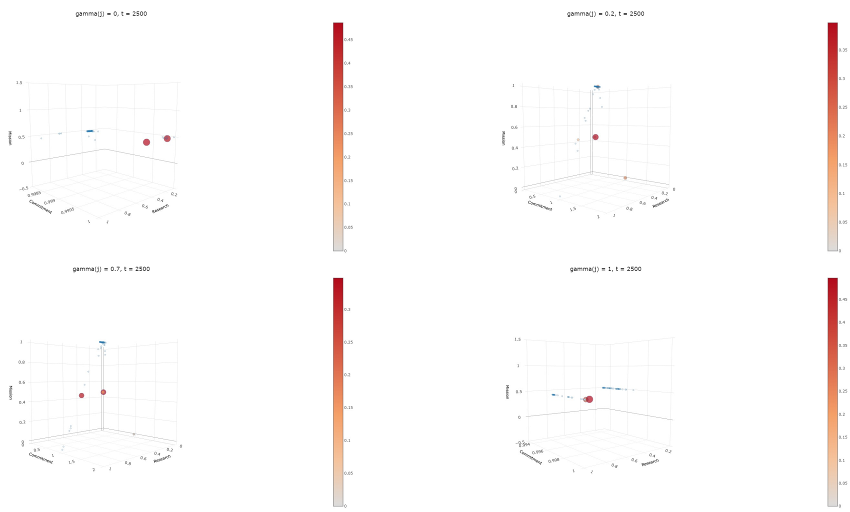

Fig. 7 Impact of preferences for utilitarian knowledge
Note: The colour scale and the point size denote the employment share in aggregate

by mission proved very impactful on economic growth all along the XX century. Yet again, broad-spectrum and non-targeted science and technology policies are useful to preserve the variety in the knowledge space, while incrementing the available trajectories for future developments (Borsato and Lorentz, 2023a). Thus, the likelihood of knowledge bottleneck diminishes. To conclude this first battery of experiments, we show in Fig. 9 that for average preferences for solutions, universities are larger in magnitude on average and distributed in the continuum of the research space.

6.2 The role of funding and demand growth

This second battery of experiments investigates the dynamics of the model for different growth rates of public funds and demand. Notably, the growth rate of public funds (Eq. (12)) has two components, one of which is exogenous and dependent on policymaking. Seemingly, the growth rates of demand concern to teaching (Eq. (32)) regardless orientation, and to mission-oriented research (Eq. (29)). We might understand teaching growth as the result of exogenous demographic dynamics like the arrival of the baby-boom generation soon after WWII. Instead, the growth in mission-oriented research demand is interpretable as the establishment of national priorities in health and defence that characterised the postwar US economy, the research initiatives at the Atomic Energy Commission (CEA) in France or at the Swedish National Board for Industrial and Technical Development (NUTEK).

We discuss the impact of exogenous growth in public funds in Tab. 7 and Fig. 10. Raising funding exogenously is beneficial to any teaching market. The performance in

γ^T	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
				Production				
0	15.742***	15.742***	40.511***	40.512***	38.011***	38.144***	38.011***	38.144***
0.2	15.742***	15.742***	39.913***	39.905***	44.220***	44.240***	44.220***	44.240***
0.5	23.964	23.964	66.626	66.620	26.266	26.266	26.266	26.266
0.7	15.742***	15.743***	39.291***	39.293***	43.557***	43.584***	43.557***	43.584***
1	18.031***	18.390***	20.40***	21.437***	23.720***	24.526***	23.720***	24.526***
				Employment				
0	11.459***	11.459***	36.243***	36.244***	22.558***	22.667***	22.558***	22.677***
0.2	11.451***	11.457***	35.639***	35.638***	33.544***	33.545***	33.544***	33.545***
0.5	19.468	19.455	62.198	62.198	15.507	15.493	15.507	15.493
0.7	11.455***	11.450***	35.019***	35.019***	35.121***	35.121***	35.121***	35.121***
1	17.241***	16.764***	19.622***	19.622***	34.277***	34.274***	34.277***	34.274***
				Inverse Herfindahl index				
0	17.427	17.567	1.294	1.280	1.001	1.003***	1.002	1.003***
0.2	17.347*	17.192*	1.193***	1.235	1.011***	1.014***	1.011***	1.014***
0.5	17.805	17.756	1.319	1.275	1.001	1.001	1.001	1.001
0.7	17.357*	17.259*	1.175***	1.236	1.001	1.001	1.001	1.001
1	16.247***	16.798***	1.683***	1.602***	1.001	1.001	1.001	1.001
		Productivity				**Quality**		
	Utilitarian research	**Pure research**	**Utilitarian teaching**	**Pure teaching**	**Targeted utilitarian**	**Non-targeted utilitarian**	**Targeted pure**	**Non-targeted pure**
0	4.224***	4.224***	11.069***	11.124***	4.293***	4.343***	4.291***	4.347***
0.2	4.227***	4.224***	15.716***	15.642***	4.292***	4.355	4.294***	4.350***
0.5	4.274	4.274	4.634	4.654	4.312	4.358	4.312	4.362
0.7	4.225***	4.225***	11.948***	12.452***	4.295***	4.361	4.292***	4.358
1	4.474***	4.630***	121.464***	106.447***	3.972***	4.027***	4.033***	4.081***

Table 5 Experiments on the preferences for teaching

Note: Mean values over 25 replications for key indicators at aggregate level over the last 2400 simulation steps. Baseline values are for $\gamma^T = 0.5$. All values are in log terms except for the inverse Herfindahl index. We recall the content of Tab. 2: Market I (targeted utilitarian research); Market II (targeted pure research); Market III (non-targeted utilitarian research); Market IV (non-targeted pure research); Market V (targeted utilitarian teaching); Market VI (targeted pure teaching); Market VII (non-targeted utilitarian teaching); Market VIII (non-targeted pure teaching). Statistical significance from the benchmark values is computed with a t-test: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

γ^v	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
				Production				
0	33.596***	33.762***	38.206***	38.511***	0.000***	0.000***	41.806***	0.000***
0.2	15.738***	15.738***	39.724***	39.718***	43.946***	43.981***	44.020***	44.009***
0.5	23.964	23.964	66.626	66.260	26.266	26.266	26.266	26.266
0.7	15.742***	15.742***	39.640***	39.643***	43.940***	43.962***	43.895***	43.938***
1	15.742***	15.741***	40.986***	40.980***	0.000***	45.259***	0.000***	0.000***
				Employment				
0	32.134***	31.038***	34.770***	34.971***	4.605***	4.605***	34.570***	4.605***
0.2	11.450***	11.456***	35.445***	35.444***	33.792***	33.792***	35.174***	35.173***
0.5	19.468	19.455	62.198	62.198	15.507	15.493	15.507	15.493
0.7	11.454***	11.449***	35.375***	35.375***	34.976***	34.975***	34.131***	34.131***
1	11.465***	11.469***	36.754***	36.754***	4.605***	36.346***	4.605***	4.605***
				Inverse Herfindahl index				
0	13.059***	12.723***	1.485***	1.313	1.012***	1.074***	1.012***	1.074***
0.2	17.098***	16.950***	1.199***	1.214	1.001	1.001	1.001	1.001
0.5	17.805	17.756	1.319	1.275	1.001	1.001	1.001	1.001
0.7	17.342*	17.282*	1.203***	1.241	1.004***	1.001	1.004***	1.001
1	17.335*	17.537	1.317	1.343	1.048***	1.007***	1.048***	1.007***
		Productivity				**Quality**		
	Utilitarian research	**Pure research**	**Utilitarian teaching**	**Pure teaching**	**Targeted utilitarian**	**Non-targeted utilitarian**	**Targeted pure**	**Non-targeted pure**
0	4.888***	4.676***	158.336***	49.578***	3.167***	3.199***	3.701***	3.376***
0.2	4.223***	4.220***	13.504***	12.616***	4.294***	4.355	4.298*	4.348**
0.5	4.274	4.274	4.634	4.645	4.312	4.358	4.312	4.362
0.7	4.226***	4.225***	13.356***	14.314***	4.297***	4.363	4.295**	4.361
1	4.212***	4.210***	1.526***	8.883***	4.272***	4.352	4.279***	4.341***

Table 6 Experiments on the preferences for solutions

Note: Mean values over 25 replications for key indicator at aggregate level over last 2400 simulation steps. Baseline values are for $\gamma^v = 0.5$. All values are in log terms but the inverse Herfindahl index. We recall the content of Tab. 2: Market I (targeted utilitarian research); Market II (targeted pure research); Market III (non-targeted utilitarian research); Market IV (non-targeted pure research); Market V (targeted utilitarian teaching); Market VII (targeted pure teaching); Market VII (non-targeted utilitarian teaching); Market VIII (non-targeted pure teaching). Statistical significance from the benchmark values is computed with a t-test: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

terms of production and employment considerably improves with respect to the baseline as long as the exogenous growth rate goes up. For instance, doubling the growth rate from 5% to 10% result in a tripled output for teaching. Corresponding rises in teaching productivity and employment go hand in hand with output performance. Specifically, employment in most teaching markets pass from a log-level of 15 units to a log-value of 65. As expected, we observe no impact on the market structure at all.

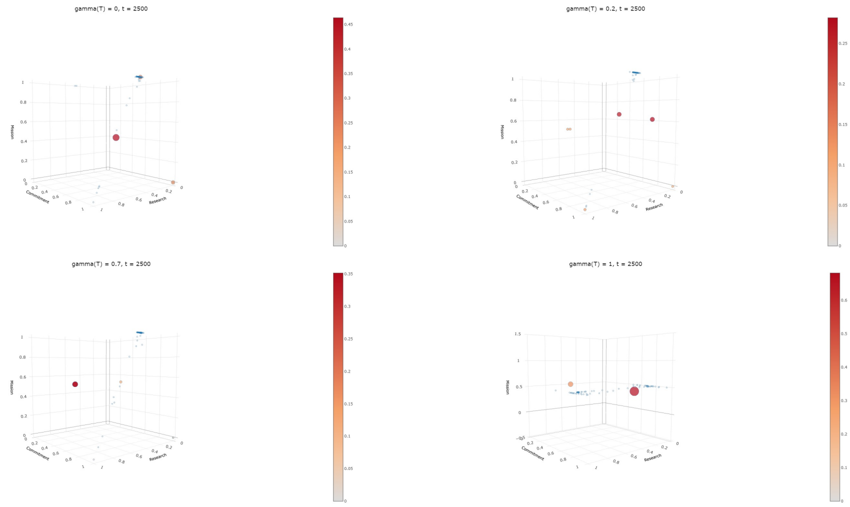

Fig. 8 Impact of preferences for teaching
Note: The colour scale and the point size denote the employment share in aggregate

The learning-by-doing mechanism that shapes teaching productivity always acts as a powerful catalyst for absolute advantages. Such a behaviour does not reverse even if the corresponding performance in the research-related markets does not fare as good as in the baseline. Alike previous experiments, the baseline parameter values are local first bests in order to maximise performance in the research markets. Indeed, the increase in public funding carries some general negative effects that reduce both production and employment levels, as outcome of an increased market concentration. The quality of research and, hence, productivity also suffer from this dynamic.
We advance the hypothesis that such an outcome is determined by a Baumol's cost disease that we have already envisaged. The system-level wage rate (Eq. (28)) takes into account both research and teaching productivity growth. Since the latter hikes considerably, it becomes a burden to research performers. The monopolistic structure typical of any market makes most universities specialise as research producers. However, they keep on facing increasing unit labour costs that curb their hiring capabilities. Therefore, the average university size decreases and this explains the worsened research performance in the several respects.

The inspection of Fig. 10 reveals further detail. As long as exogenous growth soars, universities specialise. Leaders in the teaching markets do not look very involved in the research enterprise and they are on average much bigger than research counterparts. They assume the typical traits of French *Grandes Ecoles*. Conversely, research performers are usually very small institutes whose research endeavour spans in the continuum from basic to applied science. Two examples stand: the first is a research institute that evenly performs targeted and non-targeted research and whose size is

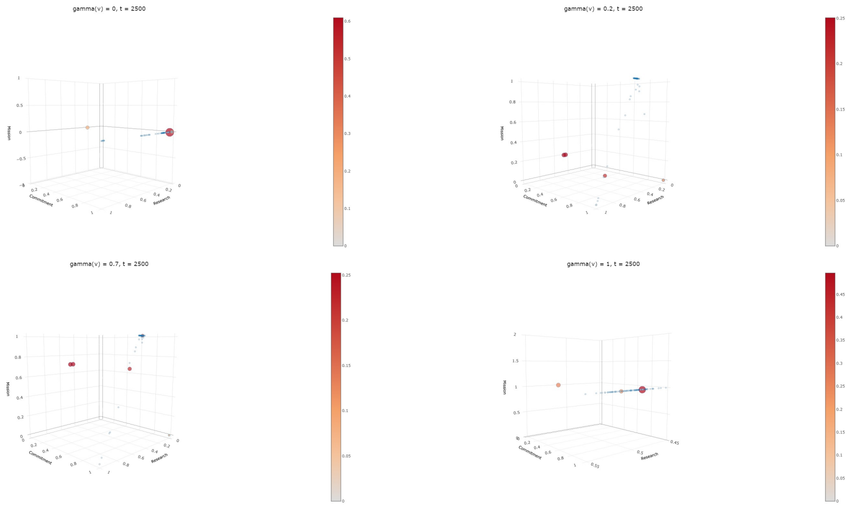

Fig. 9 Impact of preferences for solutions
Note: The colour scale and the point size denote the employment share in aggregate

not much smaller than teaching leaders; the second points to a below-average Max Planck Institute which is focussed on the pursuit of non-targeted basic research.

We suggest similar interpretations out of Tab. 8 and Fig. 11. The higher demographic pressure with progressive increases from 1% to 10% growth has strong and positive impacts on the overall performance of teaching-related markets, even though the rise in aggregate employment and production levels is somehow smaller than what occurred with an exogenous increase in public funds. The Baumol's cost disease still affects the research performance, although the teaching growth is not effective in changing the market structure of research activities. In fact, the similar average market dynamics help hide some trajectories at microeconomic level.
All the experiments so far have qualitatively changed the trajectories of universities and the corresponding position in the cube with respect to the benchmark scenario. Fig. 11 shows this is not always the case. Different growth rates for teaching demand are associated with a uniform location of universities that bears resemblance with benchmark simulations. On one side, we have the two leaders of teaching markets which together employ half of the aggregate labour force. Moreover, we notice a third large institute which is specialised in projects evenly spread between pure and utilitarian, targeted and non-targeted research. This third university employs another fourth of the available workforce. On the other side, the last labour quarter is allocated to a constellation of universities that are involved in both mission-oriented and non-mission-oriented endeavours at varying degrees. Therefore, teaching demand seems ineffective in changing the qualitative development trajectory of a university

g^{ex}	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
				Production				
0.01	14.112***	14.164***	15.276***	15.281***	20.166***	20.250***	20.166***	20.250***
0.03	15.755***	15.756***	27.756***	27.750***	32.295***	32.260***	32.295***	32.260***
0.05	23.964	23.964	66.266	66.620	26.266	26.266	26.266	26.266
0.07	15.725***	15.724***	51.635***	51.638***	55.682***	55.690***	55.682***	55.690***
0.1	15.699***	15.698***	69.474***	69.473***	73.212***	73.204***	73.212***	73.204***
				Employment				
0.01	9.278***	9.298***	10.522***	10.486***	9.868***	9.853***	9.868***	9.853***
0.03	11.174***	11.179***	23.182***	23.182***	22.328***	22.327***	22.328***	22.327***
0.05	19.468	19.455	62.198	62.198	15.507	15.493	15.507	15.493
0.07	11.678***	11.673***	47.616***	47.615***	46.926***	46.926***	46.926***	46.926***
0.1	11.933***	11.935***	65.748***	65.752***	65.071***	65.071***	65.071***	65.071***
				Inverse Herfindahl index				
0.01	15.774***	15.559***	1.196***	1.202	1.001	1.001	1.001	1.001
0.03	14.928***	14.962***	1.135***	1.125***	1.001	1.000	1.001	1.000
0.05	17.805	17.456	1.319	1.275	1.001	1.001	1.001	1.001
0.07	17.152**	17.160**	1.218***	1.324	1.002	1.006***	1.002	1.006***
0.1	16.313***	16.466***	1.315	1.434***	1.000	1.001	1.000	1.001
		Productivity				**Quality**		
	Utilitarian research	**Pure research**	**Utilitarian teaching**	**Pure teaching**	**Targeted utilitarian**	**Non-targeted utilitarian**	**Targeted pure**	**Non-targeted pure**
0.01	4.772***	4.853***	36.746***	36.837***	5.069***	5.016***	5.059***	5.006***
0.03	4.503***	4.500***	9.611***	9.594***	4.694***	4.646***	4.702***	4.646***
0.05	4.274	4.274	4.634	4.654	4.312	4.358	4.312	4.362
0.07	3.982***	3.981***	16.003***	16.177***	4.091***	4.024***	4.093***	4.027***
0.1	3.694***	3.692***	19.682***	20.929***	3.787***	3.728***	3.797***	3.724***

Table 7 Experiments on the exogenous growth of public funds

Note: Mean values over 25 replications for key indicators at aggregate level over last 2400 simulation steps. Baseline values are for $g^{ex} = 0.5$. All values are in log terms except for the inverse Herfindahl index. We recall the content of Tab. 2: Market I (targeted utilitarian research); Market II (targeted pure research); Market III (non-targeted utilitarian research); Market IV (non-targeted pure research); Market V (targeted utilitarian teaching); Market VI (targeted pure teaching); Market VII (non-targeted utilitarian teaching); Market VIII (non-targeted pure teaching). Statistical significance from the benchmark values is computed with a t-test: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

g^{T}	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
				Production				
0.01	23.964	23.964	66.626	66.260	26.266	26.266	26.266	26.266
0.03	15.741***	15.742***	40.500***	40.508***	42.732***	42.734***	42.732***	42.734***
0.05	15.743***	15.743***	39.867***	39.856***	43.940***	43.929***	43.940***	43.929***
0.07	15.742***	15.742***	39.832***	39.830***	44.000***	43.998***	44.000***	43.998***
0.1	15.742***	15.742***	39.682***	39.673***	43.975***	43.966***	43.975***	43.966***
				Employment				
0.01	19.468	19.455	62.198	62.198	15.507	15.493	15.507	15.493
0.03	11.454***	11.454***	36.255***	36.255***	28.166***	28.195***	28.166***	28.195***
0.05	11.451***	11.457***	35.593***	35.589***	34.806***	34.806***	34.806***	34.806***
0.07	11.457***	11.451***	35.561***	35.559***	34.835***	34.835***	34.835***	34.835***
0.1	11.448***	11.455***	35.402***	35.401***	34.673***	34.673***	34.673***	34.673***
				Inverse Herfindahl index				
0.01	17.845	17.756	1.319	1.275	1.001	1.001	1.001	1.001
0.03	17.828	17.719	1.325	1.286	1.002	1.000	1.002	1.000
0.05	17.722	17.478	1.221***	1.269	1.000	1.001	1.000	1.001
0.07	17.515	17.398	1.148***	1.254	1.001	1.001	1.001	1.001
0.1	17.074***	17.284*	1.208***	1.199*	1.002	1.001	1.002	1.001
		Productivity				**Quality**		
	Utilitarian research	**Pure research**	**Utilitarian teaching**	**Pure teaching**	**Targeted utilitarian**	**Non-targeted utilitarian**	**Targeted pure**	**Non-targeted pure**
0.01	4.274	4.274	4.634	4.654	4.312	4.358	4.312	4.362
0.03	4.231***	4.231***	10.683***	10.648***	4.295***	4.346	4.294***	4.353
0.05	4.224***	4.221***	10.712***	10.720***	4.292***	4.355	4.295***	4.349**
0.07	4.221***	4.220***	11.155***	11.644***	4.291***	4.360	4.289***	4.356
0.1	4.225***	4.223***	13.622***	13.058***	4.291***	4.365	4.302	4.356

Table 8 Experiments on the growth rate of teaching demand

Note: Mean values over 25 replications for key indicators at aggregate level over last 2400 simulation steps. Baseline values are for $g^{T} = 0.01$. All values are in log terms except for the inverse Herfindahl index. We recall the content of Tab. 2: Market I (targeted utilitarian research); Market II (targeted pure research); Market III (non-targeted utilitarian research); Market IV (non-targeted pure research); Market V (targeted utilitarian teaching); Market VI (targeted pure teaching); Market VII (non-targeted utilitarian teaching); Market VIII (non-targeted pure teaching). Statistical significance from the benchmark values is computed with a t-test: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

across time.

The last set of results is in Tab. 9 and Fig. 12 and regards an increase in government demand for solutions-oriented research. All markets benefit from this engine but the two markets of non-targeted research. Universities drive their labour force to the pursuit of targeted research with aggregate improvements in production and

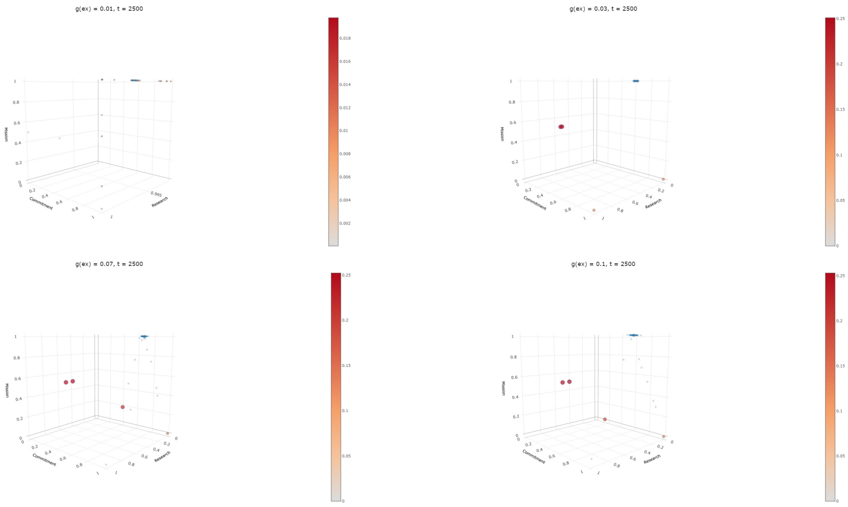

Fig. 10 Impact of exogenous funding growth
Note: The colour scale and the point size denote the employment share in aggregate

employment levels. Nonetheless, some universities start accumulating absolute technological advantages that contribute to reducing the competitive pressure in all the corresponding markets. The concentration of the market has, as expected, a negative effect in research quality and productivity dynamics. A diminished number of universities active in the research enterprise lessens the pool of common knowledge out of which researchers can draw to introduce further knowledge. Such negative outcomes are yet not present in teaching markets. The increase in productivity *via* learning by doing helps top institutions to keep on the pace set by aggregate demand such that they could afford higher employment levels.
Interesting becomes the allocation of universities in the cube. Apart from the usual leaders in the teaching markets, universities follow two distinct and established trajectories. On the one hand, universities either conduct pure research or utilitarian research *in toto*. On the other hand, they are homogeneously distributed in the target they commit to.

6.3 Summing up and policy implications

This subsection summarises main results and draws some implications for policy. We shall keep in mind that the general behaviour of the model characterises the research sector as a Schumpeter Mark I environments – i.e., a *locus* where some forms of creative destruction (Schumpeter, 1934) rules. This means that the arrival of innovations – i.e., the further contribution to the literature – is the result of intensive endeavour by small institutions that become leaders of the market. Yet, since knowledge is progressively mastered by other teams, leadership is a transitory phenomenon and others may *leap-frog* the previous monopolists. In addition to this, on average there

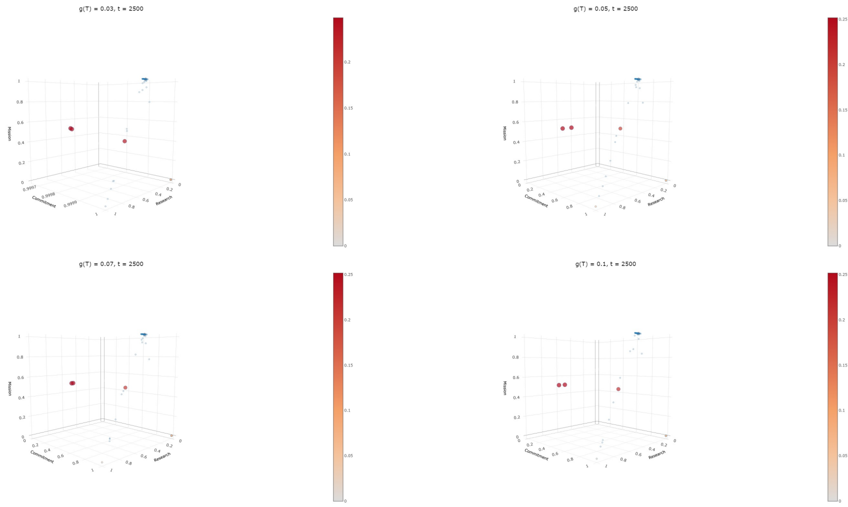

Fig. 11 Impact of teaching growth

Note: The colour scale and the point size denote the employment share in aggregate

is a competitive structure in which about one fifth of the agents might share the leadership of one market. In contrast, a creative accumulation (Schumpeter, 1942) dynamic à la Schumpeter Mark II is at work when dealing with teaching. In this case, productivity is shaped by forms of learning by doing that create and sustain the accumulation of clear technological advantages such that an incumbent's reputation as *top* university represents an insurmountable hurdle for potential *new entrants*. Therefore, we should understand the results as follows.

Firstly, pushing government's preferences to the (theoretical) boundaries produce overall negative consequences. In most cases, the Humboldt model in which a university commits to a *balance* between teaching and research allows to maximise performance, both in *quantity* – e.g., production and employment – and (research) *quality*. In other words, the relationship between preferences for – e.g., teaching and research or between pure and utilitarian knowledge - and performance does usually result in an inverted-U shape. The Humboldtian organisational model seems efficient. Secondly, we claim that any policymaking which, willing or not, boils down to reduced competition in the research market and allocates most resources to top institutes, then it curtails the overall quality of research. Universities find an impoverished pool of common knowledge to draw upon, and the likelihood of further discoveries falls. Thirdly, a system-level wage rate that is based on aggregate research and teaching growth might entail a vicious cycle *à la* Baumol (1967). On the one hand, the monopolists' accumulation of technological advantages in the markets for teaching forces other universities to become dedicated research institutes. On the other hand, they contribute to increasing unit labour costs. This second effect makes harder any hiring

g	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
				Production				
0.01	23.964	23.964	66.626	66.260	26.266	26.266	26.266	26.266
0.03	38.103^{***}	38.098^{***}	36.614^{***}	38.006^{***}	43.563^{***}	43.565^{***}	43.563^{***}	43.565^{***}
0.05	37.878^{***}	37.872^{***}	10.026^{***}	10.033^{***}	42.801^{***}	42.086^{***}	42.801^{***}	42.086^{***}
0.07	37.937^{***}	37.911^{***}	8.987^{***}	9.014^{***}	42.105^{***}	43.311^{***}	42.105^{***}	43.311^{***}
0.1	38.420^{***}	38.431^{***}	8.613^{***}	8.549^{***}	43.793^{***}	42.660^{***}	43.793^{***}	42.660^{***}
				Employment				
0.01	19.468	19.455	62.198	62.198	15.507	15.493	15.507	15.493
0.03	33.870^{***}	33.830^{***}	32.365^{***}	33.772^{***}	34.641^{***}	34.641^{***}	34.641^{***}	34.641^{***}
0.05	33.811^{***}	33.816^{***}	6.461^{***}	6.461^{***}	33.782^{***}	33.783^{***}	33.782^{***}	33.783^{***}
0.07	33.917^{***}	33.922^{***}	5.483^{***}	5.483^{***}	33.745^{***}	33.747^{***}	33.745^{***}	33.747^{***}
0.1	34.373^{***}	34.370^{***}	4.982^{***}	4.982^{***}	34.237^{***}	34.237^{***}	34.237^{***}	34.237^{***}
				Inverse Herfindahl index				
0.01	17.805	17.456	1.319	1.275	1.001	1.001	1.001	1.001
0.03	1.920^{***}	1.880^{***}	1.202^{***}	1.175^{**}	1.001	1.002^{**}	1.001	1.002^{**}
0.05	1.392^{***}	1.358^{***}	1.132^{***}	1.144^{***}	1.001	1.003^{***}	1.001	1.003^{***}
0.07	1.397^{***}	1.355^{***}	1.191^{***}	1.263	1.002	1.001	1.002	1.001
0.1	1.240^{***}	1.305^{***}	1.170^{***}	1.181^{*}	1.000	1.002^{**}	1.000	1.002^{**}
		Productivity				**Quality**		
	Utilitarian research	**Pure research**	**Utilitarian teaching**	**Pure teaching**	**Targeted utilitarian**	**Non-targeted utilitarian**	**Targeted pure**	**Non-targeted pure**
0.01	4.274	4.274	4.634	4.654	4.312	4.358	4.312	4.362
0.03	4.201^{***}	4.216^{***}	108.927^{***}	128.833^{***}	4.294^{***}	4.314^{***}	4.281^{***}	4.301^{***}
0.05	3.518^{***}	3.610^{***}	22.114^{***}	230.327^{***}	4.133^{***}	-4.357^{***}	4.059^{***}	4.035^{***}
0.07	3.455^{***}	3.611^{***}	282.409^{***}	232.546^{***}	4.013^{***}	3.997^{***}	4.151^{***}	4.142^{***}
0.1	3.692^{***}	3.611^{***}	18.525^{***}	282.579^{***}	4.201^{***}	4.186^{***}	4.105^{***}	4.081^{***}

Table 9 Experiments on the growth rate of solutions-oriented research demand

Note: Mean values over 25 replications for key indicators at aggregate level over last 2400 simulation steps. Baseline values are for $g^R = 0.01$. All values are in log terms except for the inverse Herfindahl index. We recall the content of Tab. 2: Market I (targeted utilitarian research); Market II (targeted pure research); Market III (non-targeted utilitarian research); Market IV (non-targeted pure research); Market V (targeted utilitarian teaching); Market VI (targeted pure teaching); Market VII (non-targeted utilitarian teaching); Market VIII (non-targeted pure teaching). Statistical significance from the benchmark values is computed with a t-test: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

procedure in the research markets since universities have lower shares of public funds to spend on the research enterprise. The aggregate research quality is hampered and so is productivity.

A generalised increase in funding, i.e., a pure *quantity* measure, does not appear really effective if the distributive mechanisms are untouched and prioritise reputation, unless they target small institutes and sustain competition in the research markets. In this regard, the policymaking at work in the US postwar (Mowery and Rosenberg, 1999) where the federal administrations did not concentrate the resources to large incumbents only might prove effective to preserve universities capabilities in incrementing the quantity and quality of research. At the same time, none of our experiments is helpful in triggering competition in the teaching markets. The learning-by-doing driven labour productivity is a powerful selection mechanism that neither preferences nor *quantity* policies could turn off.

7 Conclusions

The role of the university in the society, its evolution across time and space, its mechanisms of coordination and interaction with other socioeconomic entities have long been at the core of economic analysis. A large array of approaches has been adopted for the historical analysis of university roots (Bender, 1988; Collini, 2012; Readings, 1996), to understand the optimal formal structure of an academic institution (Del Rey, 2001), and to analyse the complex relationships between the several functions that the university performs, from teaching and research to the third mission (Bianchini et al., 2016; Drucker and Goldstein, 2007; Leydesdorff, 1992).

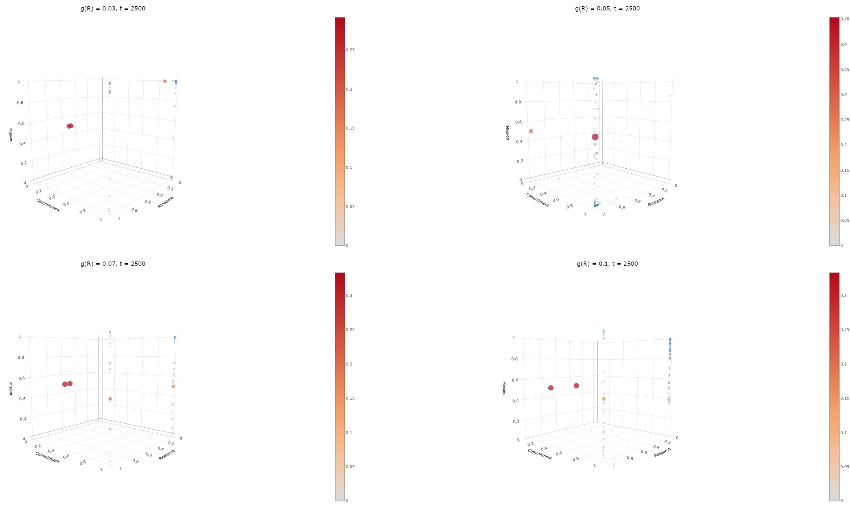

Fig. 12 Impact of demand for solutions-oriented research

Note: The colour scale and the point size denote the employment share in aggregate

We entered this broad literature by considering the university as an evolutionary agent which keeps on developing new traits while dealing with the surrounding environment (Geuna, 1999; Martin, 2012). Our aim was to understand whether and to what extent the scientific and pedagogic trajectories of universities were the emergent properties of evolutionary micro-dynamics. In particular, we have focussed on the complementarities and potential trade-offs that may arise when the university interacts with the public sector, when the latter decides the amount and the direction of research and teaching funds.

Therefore, taking some distance from the works mostly concerned to the optimal formal structure of an academic institution and on static roles for the governments, we developed an agent-based model broadly in line with Caiani et al. (2016), Ciarli et al. (2010), Delli Gatti et al. (2018), and Dosi and Roventini (2019), in which a group of universities is analysed. Three dimensions reflected the endogenous trajectory of an organisation: the choice between teaching and research, the type of knowledge being produced, and the commitment to any third mission. As opposed to the utility-maximisation framework, we assumed that university decision-makers tend to employ relatively straightforward heuristics and operational rules in order to navigate in an ever-changing environment.

The characterisation of universities along these dimensions gave rise to an innovative pattern of research that may be regarded as Schumpeter Mark I – i.e., *creative destruction* (Schumpeter, 1934). In contrast, the teaching sector presents some features typical of a Schumpeter Mark II pattern – i.e., *creative accumulation* (Schumpeter, 1942).

In terms of the direction of public funding, which can be seen as an illustration of a Prince's preferences, the results show that when the priority shifts, whether upwards or downwards, from pure to utilitarian knowledge, or in the opposite direction, this has the effect of producing an inverted-U shape in the dynamics of production and employment. An even distribution of funds across both types of knowledge is likely to represent the optimal solution. In other words, the Humboldt university model, which entails a commitment to achieve a balance between pure and utilitarian knowledge, enables the highest performance to be attained in terms of both quantity and quality in the context of research. Indeed, an increase in permanent-monopoly tendencies in the research environment has a detrimental effect on the creative-destruction dynamic. The absence of strict cumulativeness reduces the pool of common knowledge that can be used to introduce further knowledge in the system, particularly in concentrated market structures.

It also appears that the complementarity between teaching and research, again a typical feature of Humboldt-like organisations, allows the aggregate academic system to experience top teaching performance when public preferences are neither excessively research-oriented nor excessively teaching-oriented. These results confirm the potential explanation for the US leadership in scientific productivity that resides in the excellence of its research universities (Dosi et al., 2006; Mowery and Sampat, 2004). Although Humboldt-like environments first emerged in Europe, US universities have proven more successful in adopting this organisational model that exploits the strong complementarities between research and teaching.
Furthermore, an increase in funding or in the demand for mission-oriented research do not seem effective solutions if the distributive mechanisms of public funds remain unchanged and prioritise reputation, unless they target smaller institutes and sustain competition. In this regard, the postwar US policymaking, when the federal administrations did not concentrate the resources to large incumbents only may be observed as a helpful policy in preserving university capabilities in incrementing the quantity and quality of research (Mowery and Rosenberg, 1999). Yet again, broad-spectrum and non-targeted science and technology policies are useful to preserve the variety in the knowledge space, while increasing the available trajectories for future developments (Borsato and Lorentz, 2023a).
Finally, a system-level wage rate based on aggregate productivity growth may potentially result in a vicious cycle, as postulated by Baumol (1967). The consolidation of technological advantages by monopolists in the teaching markets forces universities to orient themselves as dedicated research institutes. Moreover, a generalised increase in unit labour costs emerges. This second effect renders the hiring process in the research markets more challenging, given that universities have reduced access to public funding for research activities. The overall quality of research is diminished, as is productivity.

To conclude, this article shed some light on the complex effects that the amount and direction of public funds engender on university trajectories. However, the theoretical setting had some limitations. More generally, the Humboldt model has more than any other comparable vision represented the idea of university as an autonomous world with its own logics and system of norms (Östling, 2018). Yet, industry is increasingly involved in the financing of university activities (Borsato and Llerena, 2024; Gulbrandsen and Smeby, 2005; Muscio et al., 2013). What are the impacts on university trajectories out of private funding? What is the impact on teaching performance? Also, teaching effectiveness as opposed to what we identified with teaching productivity gained some momentum in the recent past (Noser et al., 1996; Volkwein and Carbone, 1994): what are the consequences on teaching effectiveness from academic organisations that specialise on the production of pure *vis-à-vis* utilitarian knowledge? The labour supply was fully elastic: what happens to the market structures in case of labour shortage? Do concentration tendencies reinforce or loosen? Furthermore, we have allocated funds *via* reputation: what happens if (selection) mechanisms changed and were counteracted by some policy that aims at helping small institutes survive? On the more empirical side, are our results empirically well-founded when it comes to deal with Baumol's cost disease? These questions open avenues for future research.

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Appendix A

T	Time	2500
N	University	100
MC	Monte Carlo runs	50
C^R	Capital-labour ratio in research	1
C^T	Capital-labour ratio in teaching	1
g^{ex}	Exogenous growth component in public funding	0.05
g^R	Growth rate for solution-oriented research demand	0.01
g^T	Growth rate of teaching demand	0.01
u^R	Desired share of research idle capacity	0.1
u^T	Desired share of teaching idle capacity	0.1
γ^j	Preferences for utilitarian knowledge	0.5
γ^T	Preferences for teaching	0.5
γ^v	Preferences for solutions	0.5
δ_0	Parameter in capital-depreciation schedule	0.1
ϵ_0	Probability sensitivity to research capacity	0.3
ϵ_1	Support of Beta distribution	-0.5
ϵ_2	Support of Beta distribution	2
η	Share of net excess labour to non-solution-oriented research	0.5
θ_0	Weight in the aggregate growth rate of public funds	0.5
θ_1	Reputation sensitivity to demand fulfilment	0.05
ι	Parameter in desired teaching and research capacity	0.25
λ	Parameter in teaching productivity	0.3
ϕ_0	Sensitivity of university capability to stock of knowledge	0.001
σ	Sensitivity of market share to reputation	0.2
ω_0	Parameter in the wage equation	0.7
ω_1	Parameter in the wage equation	0.5

Table A1 Parameter list

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