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RESEARCH PAPER

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 on the amount and direction of funding in determining university trajectories. Results are four. First, the policies that maximise performance in certain dimensions do not require that funds targeted at those dimensions are maximised, due to the complementarities between research and teaching. In most cases, the Humboldt model in which a university commits to a balance between teaching and research tends to generate more robust performance patterns. Second, any policymaking that boils down to reduced competition in the research market and allocates most resources to top institutes might curtail research quality. Third, 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. Finally, we have some evidence of the Baumol's cost disease when a system-level wage rate combines with the emergence of technological advantages. At the best of our knowledge, this article constitutes the first endeavour to model the scientific and pedagogical trajectories of universities as emergent properties of the micro-dynamic that involves the *amount* and the *direction* of public funding, which is our way to formalise the third mission.

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1 Introduction

Observed as key players in the knowledge-based economy (Cobban 2022; Collini 2012; Cowan et al. 2010; Geuna 1999, 2001) and among the most enduring institutions of Western civilisation (David 2008; Mokyr 2016), universities are increasingly expected to support economic development at local, regional, and national levels through the provision of *useful* teaching and research (Uyarra 2010; Wowk et al. 2017). In exchange for public funding, higher education institutions are now required to contribute to innovation, social welfare, and entrepreneurial capabilities through knowledge transfer and engagement activities, commonly referred to as the *third mission* (Compagnucci and Spigarelli 2020; Martin 2003).

The analysis of university behaviour and funding policymaking has gained increasing attention in economics (Geuna 2001; Carayol and Maublanc 2025). Existing research highlights the interaction between teaching, research, and engagement activities (Benneworth et al. 2016). However, the literature still lacks a formal understanding of the endogenous trade-offs and complementarities that may arise between university activities and funding regimes.

In this paper, we model the university as an evolutionary organisation that adopts simple heuristics rather than acting as a rational maximiser (Geuna 1999; Martin 2012). We develop an agent-based model (ABM) (Delli Gatti et al. 2018; Dosi and Roventini 2019) in which universities interact with the public sector and shape their development paths in response to both the *amount* and the *direction* of public funding. Scientific and pedagogical trajectories emerge as intrinsic outcomes of these micro-dynamics. To the best of our knowledge, this is the first attempt to model scientific and pedagogical university trajectories as emergent properties shaped by the micro-dynamics of public funding allocation, both in its amount and its direction. The model is not designed to replicate specific national systems nor to evaluate short-run policy effectiveness, but to explore structural mechanisms linking funding regimes and university trajectories.

The main results of the paper can be summarised in four points. First, policies that aim to maximise performance in specific dimensions do not require maximising funds allocated to those dimensions, due to complementarities between research and teaching. Second, policymaking that reduces competition in the research domain by concentrating resources on top institutes may ultimately curtail overall research quality. Third, a generalised increase in funding is ineffective if distributive mechanisms remain unchanged and continue to prioritise reputation, unless resources are directed toward smaller institutes to sustain competitive dynamics. Fourth, we observe dynamics consistent with Baumol's cost disease when system-level wages interact with emerging technological advantages.

Some caveats are in order. First, we adopt a broad definition of university, encompassing organisations that perform research, teaching, or both, including publicly funded research institutes closely connected to higher education systems. Second, we define a trajectory as the dynamic path that a university follows over time as a result of internal heuristics and external funding pressures. Third, we model the third mission in a stylised manner, focusing on government demand for knowledge rather than on its institutional and historical heterogeneity. Finally, we abstract from disciplinary specialisation and represent knowledge in simplified categories. These simplifications allow us to isolate the structural mechanisms at the core of the model. Despite these simplifications, the framework allows us to examine how economic and political forces shape university trajectories and to highlight potential unintended consequences of funding reorientation (Geuna 2001).

The manuscript is organised as follows. Section 2 discusses the historical background and relevant literature. Section 3 presents the theoretical model. Section 4 introduces the benchmark scenario. Sections 5 and 6 analyse the effects of the direction and the amount of public funding. The final Section discusses policy implications and concludes. The Appendix and the online Supplementary Material provide additional sensitivity analyses and further details on the emergence of new organisations.

2 The Evolution of Western Universities: Historical Roots and Literature on Funding Policymaking

2.1 A Short Recap of the Historical Development of Western Universities

Universities emerged in medieval Europe as teaching-oriented institutions embedded in broader political and social structures (David 2008; Mokyr 2016). Research activities were largely absent, and knowledge transmission prevailed over knowledge production.

From the eighteenth century onwards, alternative models emerged. Cardinal Newman's ideal-type emphasised teaching as the core university mission, whereas the Humboldtian model institutionalised the complementarity between research and teaching within the same organisation, supported by public funding and academic autonomy (Martin 2012; Geuna 1999). The Humboldtian configuration became highly influential across Western countries and shaped the modern university system. However, institutional diversity persisted, as exemplified by the French system, where research activities have historically been concentrated in specialised public research organisations.

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 (Fig. 1). The first dimension concerns the type of knowledge produced, spanning from pure to utilitarian research. The second dimension refers to the relative commitment between teaching and research activities. The third dimension captures the nature of the social contract, ranging from autonomy-oriented funding to mission-oriented, solutions-driven allocation. Together, these three axes define the conceptual space within which university trajectories unfold. In the post-WWII period, a social contract emerged in which governments granted substantial autonomy to the scientific community in allocating public funds, largely through peer-reviewed

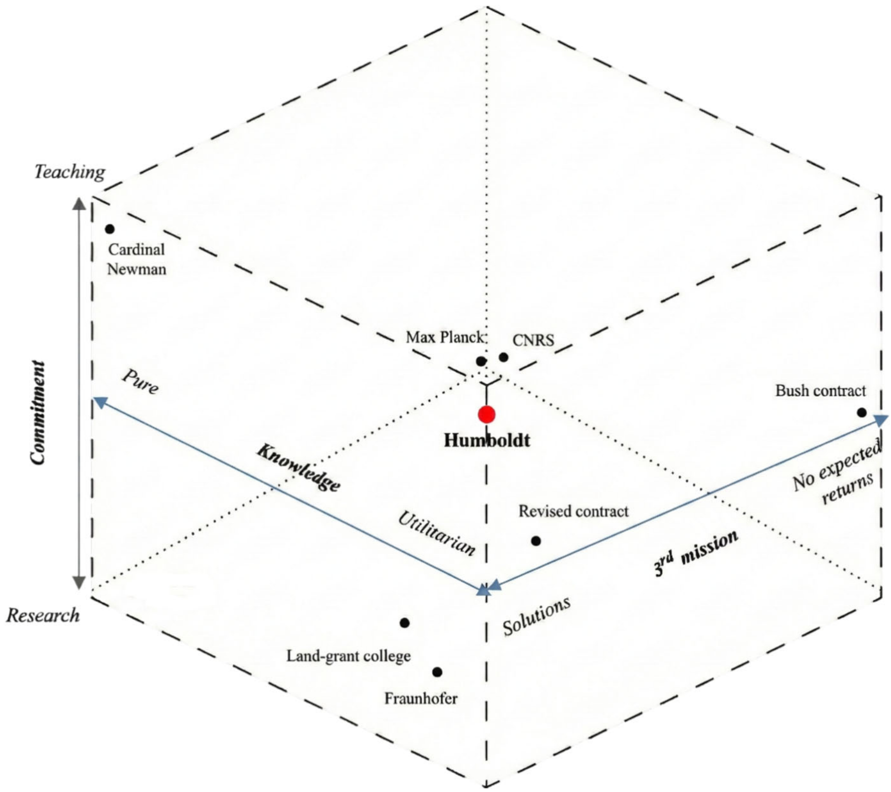

Fig. 1 University along multiple dimensions. Note: This cube and the overall paper focus on the university and higher education systems largely at work in European and North-American countries. The *x* axis concerns the kind of knowledge produced and it spans along a continuum between pure and utilitarian knowledge. The *y* axis refers to the relative commitment between teaching and research. The third axis, *z*, is about the social contract which goes from "science for the sake of science" (no expected returns) to solutions-oriented activities

and block funding mechanisms (Dasgupta and David 1994; Geuna 2001; Stephan 2013). From the 1980s onwards, this contract progressively shifted: universities were increasingly expected to contribute directly to national economic performance, and competitive allocation mechanisms gained prominence (Martin 2003).[1]

This historical recap frames the literature to which we contribute, namely the research on how public funding shapes university organisation and development trajectories in research and teaching activities. The next subsection reviews this literature in greater detail.

[1] 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.

2.2 Relation with the Literature

This article contributes to three main strands of literature. First, it builds on the evolutionary and neo-institutional approaches that conceptualise universities as adaptive organisations evolving within changing institutional environments (Geuna 1999; Martin 2003; Ramirez and Christensen 2013). These perspectives emphasise the dynamic interplay between organisational routines, institutional pressures, and societal expectations.

Second, we relate to the literature on the third mission and university-industry interactions, which documents the growing relevance of knowledge transfer and the role of universities as engines of innovation and regional development (Foray and Lissoni 2010; Bianchini et al. 2016; Arora et al. 2015). Empirical evidence consistently shows that firms rely extensively on academic research as an input into their innovative activities.

Third, we contribute to the literature analysing public funding mechanisms and their impact on university behaviour. Existing studies have examined competitive funding, performance-based allocation, and mission-oriented policies (Aghion et al. 2009; Geuna 2001; Martin 2003; Steinmueller 2010; Schot and Steinmueller 2018). However, all these contributions rarely explore the endogenous dynamic interactions between funding rules, organisational adaptation, and system-level outcomes. Our framework addresses this gap by modelling how different funding regimes shape long-run university trajectories.

Several contributions analyse the co-evolution of universities, industries, and institutions (Almudi et al. 2012; Fatas-Villafranca et al. 2008, 2009). These studies primarily examine how university systems support industrial leadership and technological catch-up. By contrast, our paper shifts the analytical focus to the university itself. Rather than treating universities as background suppliers of knowledge and human capital, we model them as evolutionary agents whose research and teaching trajectories emerge from their interaction with the public funder. In doing so, we extend the co-evolutionary perspective to the micro-dynamics of university decision-making and funding allocation.

We also relate to the literature on science and innovation policy, which emphasises the role of governments in shaping technological trajectories and research incentives (Arrow 1962; Nelson 1959; Dosi 2023). While this literature highlights the importance of funding design and policy direction, it rarely models how allocation rules interact with internal university dynamics. We show that maximising performance in research and teaching does not necessarily require maximising targeted funds, due to complementarities between university activities.

A further stream of research examines the evolving social contract and the expansion of universities' third mission activities (Carayol and Maublanc 2025; Ejermo and Sofer 2024; Hoppmann 2021). These studies explore how funding sources and organisational capabilities shape engagement with industry and society. Our contribution differs in that we focus on how funding allocation rules influence the joint evolution of research and teaching trajectories, highlighting potential unintended consequences of extreme funding strategies.

Finally, some contributions emphasise the role of teaching and performance-based funding (Hicks 2012; Borah et al. 2023; Auranen and Nieminen 2010). While these studies examine how funding affects research or teaching outputs separately, our framework models their joint dynamics and the feedback effects between resource allocation and university trajectories.

Taken together, these strands of literature highlight important aspects of university evolution and funding design. Our evolutionary framework integrates these perspectives by modelling research and teaching trajectories as emergent outcomes of the evolutionary interaction between universities and public funding regimes. The next Section develops this research task.

3 An Evolutionary Model of University Trajectories

We model universities as heterogeneous agents operating within a dynamic funding environment. The university is the microeconomic unit of analysis, and its development trajectory evolves along the three conceptual dimensions introduced in Fig. 1: type of knowledge (x axis), commitment to teaching and research (y axis), and orientation of the third mission (z axis). Each university i allocates resources between teaching (T) and research (R), and within research between *pure* and *utilitarian* knowledge. These allocation decisions evolve over time and may exhibit path dependence. The distribution of activities is influenced by the funding regime adopted by the public authority, which can prioritise *solution-oriented* knowledge addressing specific societal challenges or adopt a *non-solutions-oriented* approach that supports broader knowledge accumulation. Formalising this setting under out-of-equilibrium conditions, aggregate outcomes emerge from the interaction of individual allocation rules and funding mechanisms. This approach allows us to make the micro-level decision rules explicit and to analyse how different funding regimes shape system-level trajectories.

3.1 Research Production Functions

Research output is measured by the number of publications produced in period t, distinguishing between pure ($j = p$) and utilitarian ($j = u$) knowledge, and between solutions-oriented ($v = S$) and non-solutions-oriented ($v = NS$) research. The production of research requires labour input in the form of scientists' time and capital in the form of accumulated knowledge (proxied by books and past research). However, the generation of new knowledge is stochastic. The probability that university i produces research of type (j, v) in period t is given by:

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

where $R_{ijt}^{P,v}$ is the potential research output, A_{ijt}^{R} denotes research productivity, $L_{ijt}^{R,v}$ labour allocated to research of type (j, v), K_{ijt} the knowledge stock, C^{R} the capital-output ratio, and ϵ_0 a parameter. The function implies complementarity between labour and capital. Conditional on success, output equals the minimum between effective labour input and capital constraints:

$$R_{ijt}^{v} = R_{ijt}^{P,v} = \min\left[A_{ijt}^{R} \cdot L_{ijt}^{R,v}; C^{R} \cdot K_{ijt}\right] \tag{2}$$

We assume that the arrival of new knowledge does not consist only in *quantities* of new books. Each research output is characterised not only by quantity but also by a quality index, a_{ijt}^{v}. The arrival of new knowledge generates a new capital vintage that adds to the existing stock of knowledge at the university. Research quality evolves according to:

$$a_{ijt}^{v} = \left(1 - \delta_{1jt}\right) \cdot a_{ijt-1}^{v} + \epsilon_{ijt}^{v} \tag{3}$$

where δ_{1jt} depends on the aggregate growth rate of knowledge and captures obsolescence effects, while ϵ_{ijt}^{v} is drawn from a Beta(2,5) distribution with support [−0.5, 2]. This specification reflects two features. First, quality depreciates when the overall knowledge frontier advances, implying that stagnation reduces the relative value of existing knowledge. Second, the asymmetric Beta distribution ensures that high-quality breakthroughs are relatively rare compared to average contributions, while allowing for negative draws to capture unsuccessful research outcomes. The average research quality $\bar{a}_{ijt}$ at university i is the weighted-average of all research ever produced at university i up to time $t = \tau$ (regardless of it mission orientation v), in which weights are the research quantities R_{ijt}^{v}:

$$\bar{a}_{ijt} = \sum_{v}\left(\frac{R_{ijt}^{v}}{\sum_{t=0}^{t=\tau} R_{ijt}^{v}}\right) \cdot a_{ijt}^{v} + \left[1 - \sum_{v}\left(\frac{R_{ijt}^{v}}{\sum_{t=0}^{t=\tau} R_{ijt}^{v}}\right)\right] \cdot \bar{a}_{ijt-1} \tag{4}$$

The productivity of a group of scientists in pursuing research is determined by $\bar{a}_{ijt}$ and it is a weighted average between two components:

$$A_{ijt}^{R} = \frac{\Delta K_{ijt}}{K_{ijt}} \cdot \bar{a}_{ijt} + \left(1 - \frac{\Delta K_{ijt}}{K_{ijt}}\right) \cdot A_{ijt-1}^{R} \tag{5}$$

in which $\frac{\Delta K_{ijt}}{K_{ijt}}$ is the growth rate of the corresponding stock of knowledge at university level. Research productivity changes only with respect to the type of knowledge j, namely we assume that, for any given j, research productivity is the same between solutions-oriented and non-solutions-oriented research activity. Equation (5) captures the dynamics of absorptive capacity (Cohen and Levinthal 1990). Research productivity increases when the university expands its knowledge stock, as measured by the growth rate $\frac{\Delta K_{ijt}}{K_{ijt}}$, and when the average quality of its research is high. The first term on the right-hand side reflects the idea that productivity improvements require active knowledge accumulation. If the university does not invest in new knowledge, productivity converges to its past level. The second term introduces path dependence, as past productivity continues to influence current performance. At the same time, rapid expansion of knowledge at the system level may generate obsolescence effects. Scientists must continuously update their competencies in order to remain at the frontier. Thus, productivity growth depends not only on effort, but also on the university's ability to renew and internalise high-quality knowledge.

Capital, as in Eq. (6), corresponds to the stock of knowledge accumulated by a university over time, both internally and from other universities in the system. Importantly, capital is not measured solely in quantitative terms. It is defined as a quality-weighted sum of all past research outputs, so that higher-quality contributions expand the effective knowledge base more strongly than average ones. The first term in Eq. (6) captures internally produced knowledge, while the second term incorporates external knowledge generated by other universities (indexed by $-i$). The variable ϕ_{ijt} measures the university's ability to absorb and exploit external knowledge, thereby introducing inter-university spillovers into the system. Finally, the entire stock is multiplied by a depreciation factor δ_{ijt}, which captures the erosion of knowledge value as new and higher-quality research emerges in the system:

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

Absorptive capacity, ϕ_{ijt}, determines the extent to which a university can benefit from knowledge produced elsewhere in the system. We model it as a bounded and increasing function of past accumulated knowledge:

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

This specification ensures that absorptive capacity lies between 0 and 1. The parameter ϕ_0 regulates the speed at which the university approaches its absorptive frontier.[2] We assume that the rate of depreciation depends on aggregate growth in both research quantity and average research quality:

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

where δ_0 is a parameter. When aggregate research expands rapidly, either in volume or in quality, the effective value of previously accumulated knowledge declines more quickly. This formulation introduces a competitive dynamic at the system level: universities must continuously update their knowledge base in order to maintain their productive capacity. At the same time, the exponential specification ensures that depreciation remains bounded and prevents excessive volatility in capital dynamics.

[2] This formulation captures cumulative learning effects: universities with a larger knowledge base are better able to understand, evaluate, and exploit external research. At the same time, the bounded nature of the function prevents unlimited spillover effects and ensures diminishing returns to knowledge accumulation.

3.2 Teaching Production Functions

Teaching production mirrors the structure of research production. Teaching output is determined by the allocation of scholars' time and by the available stock of knowledge, distinguishing between pure and utilitarian domains.

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

where $T_{ijt}^{P,v}$ denotes teaching capacity, A_{ijt}^{T} teaching productivity, $L_{ijt}^{T,v}$ labour allocated to teaching, and C^{T} the capital-output ratio. As above, labour and capital are perfect complements. Teaching productivity evolves through two channels. First, we assume learning-by-doing: productivity increases when teaching activity expands, i.e., when $\frac{\Delta T_{ijt-1}}{T_{ijt-1}} > 0$ (Murnane and Phillips 1981). Second, we introduce complementarity between research and teaching. Improvements in research productivity spill over into teaching performance, capturing the idea that active engagement in knowledge production enhances pedagogical quality:

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

in which λ is a parameter.

3.3 Reputation and Funding Distribution

Public funds are allocated to universities according to their relative fitness, which we proxy through reputation ($E_{ijt}^{R,v}$). Reputation reflects a university's performance in research and teaching and determines its share of public resources (Garcia and Sanz-Menéndez 2005; Geuna 2001). We distinguish between solutions-oriented and non-solutions-oriented regimes. In a non-solutions-oriented setting, research reputation depends on research productivity relative to the system average (A_{jt}^{R}). In a solutions-oriented regime, reputation additionally depends on the university's ability to satisfy externally defined research demand ($R_{ijt-1}^{D,v}$):

$$E_{ijt}^{R,v} = \left(\frac{A_{ijt}^{R}}{A_{jt}^{R}}\right) \cdot \left(1 - \theta_1 \cdot \frac{R_{ijt-1}^{D,v} - R_{ijt-1}^{v}}{R_{ijt-1}^{D,v}}\right) \tag{11}$$

When $\theta_1 = 0$, reputation depends exclusively on relative research productivity. When $\theta_1 > 0$, failure to meet externally defined demand reduces reputation, introducing mission-oriented selectivity into the funding process.

Teaching reputation ($E_{ijt}^{T,v}$) follows an analogous structure. It depends on relative teaching productivity and, when mission-oriented criteria are active, on the university's ability to satisfy teaching demand ($T_{ijt-1}^{D,v}$):

$$E_{ijt}^{T,v} = \left(\frac{A_{ijt}^{T}}{A_{jt}^{T}}\right) \cdot \left(1 - \theta_1 \cdot \frac{T_{ijt-1}^{D,v} - T_{ijt-1}^{v}}{T_{ijt-1}^{D,v}}\right) \tag{12}$$

The allocation of funds to each university for research ($s_{ijt}^{R,v}$) and for teaching ($s_{ijt}^{T,v}$) follows a replicator dynamic (Metcalfe 1994):

$$s_{ijt}^{R,v} = s_{ijt-1}^{R,v} \cdot \left[1 + \sigma \cdot \left(\frac{E_{ijt}^{R,v}}{E_{jt}^{R,v}} - 1\right)\right] \tag{13}$$

$$s_{ijt}^{T,v} = s_{ijt-1}^{T,v} \cdot \left[1 + \sigma \cdot \left(\frac{E_{ijt}^{T,v}}{E_{jt}^{T,v}} - 1\right)\right] \tag{14}$$

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

3.4 Funding, Labour Markets and Demand

The Prince finances universities for both research and teaching.[3] Given an aggregate funding level F_t, the government allocates resources according to three policy parameters. The parameter γ^j determines the allocation between pure and utilitarian knowledge, γ^T splits funds between research and teaching, and γ^v captures the degree of mission orientation by allocating funds between solutions-oriented and non-solutions-oriented activities.

Aggregate funding evolves at rate g^F. This rate combines an exogenous policy-driven component, g^{ex}, with an endogenous component reflecting system-wide productivity growth in research (A_{t-1}^R) and teaching (A_{t-1}^T). The overall growth rate is given by:

$$g^F = \theta_0 \cdot g^{ex} + (1 - \theta_0) \cdot \left[\omega_1 \cdot \frac{\Delta A_{t-1}^R}{A_{t-1}^R} + (1 - \omega_1) \cdot \frac{\Delta A_{t-1}^T}{A_{t-1}^T}\right] \tag{15}$$

where θ_0 and ω_1 are parameters. This specification introduces feedback from university performance to aggregate funding dynamics: when productivity increases at the system level, public funding expands more rapidly.

[3] For simplicity, we abstract from mixed public-private funding schemes and adopt a structure representative of many European higher education systems. Moreover, in the interest of synthesis, the full description of the equations is in the online Supplementary Material.

Labour supply is assumed to be fully elastic. Universities are therefore not constrained by aggregate labour availability. For teaching and solutions-oriented research, universities form adaptive expectations based on past demand and maintain spare capacity to accommodate unexpected demand shocks. Because public funds are allocated by activity, mismatches may arise between labour demand across different tasks. To mitigate such imbalances, universities pool excess funds and reallocate labour across activities according to relative demand conditions. If residual labour capacity remains after satisfying solutions-oriented activities, it is allocated to non-solutions-oriented research.

The wage rate w_t is uniform across activities at the system level (Bianchini et al. 2016; Geuna 1999). Wage growth depends on aggregate productivity growth in research and teaching:

$$w_t = w_{t-1} \cdot \left[1 + \omega_0 \cdot \left(\omega_1 \cdot \frac{\Delta A^R_{t-1}}{A^R_{t-1}} + (1 - \omega_1) \cdot \frac{\Delta A^T_{t-1}}{A^T_{t-1}} \right) \right] \tag{16}$$

in which ω_0 is a parameter; this mechanism links labour costs to system-wide performance and introduces the possibility of cost pressures when productivity rises unevenly across activities.

Demand evolves exogenously as determined by public policy. On the research side, the government expresses demand only for solutions-oriented research. Research demand ($R_t^{D,S}$) grows at rate g^R and is split between pure and utilitarian knowledge according to γ^j. Similarly, teaching demand (T_t^D) grows at rate g^T and is distributed between solutions-oriented and non-solutions-oriented activities through γ^v.[4]

Actual teaching output (T^v_{ijt}) is constrained by both demand and production capacity:

$$T^v_{ijt} = \min\left[T^{D,v}_{ijt} ; T^{P,v}_{ijt} \right] \tag{17}$$

4 Baseline Scenario: Results

We simulate the model over 2500 periods and 50 Monte Carlo runs. Baseline parameter values are reported in Table 9. The time horizon is sufficient for the system to converge to stable dynamic patterns. The artificial system counts a hundred of universities and a public sector. Universities start as perfectly homogeneous: the heterogeneity emerges when the model unfolds as outcome of interactions and different decision rules. Public

[4] We should consider funding and demand as following different dynamics. The government funds research and teaching regardless of the type of knowledge being produced. However, the demand concerns to the third mission. It is worth noting that solutions-oriented knowledge can be both basic and applied. For instance, US government agencies has funded a lot of research on science-based disciplines which were mission-oriented since the postwar period. Funded research was not applied in character only (Mowery and Rosenberg 1999). Quite the opposite, basic research was not financed less than applied research for several decades. That basic research was nonetheless mission-oriented too (Borsato and Llerena 2025, 2026).

funds are evenly spread between teaching and research, pure and utilitarian knowledge, and solutions-oriented and non-solutions-oriented endeavour: as in Eq. (A1) in the online Supplementary Material, the even allocation means that $\gamma^j = \gamma^T = \gamma^v = 0.5$.

The model is not calibrated to reproduce empirical magnitudes. Numerical results should therefore be interpreted as analytical outcomes rather than forecasts. What matters is the relative ordering of scenarios and the internal coherence of the mechanisms generating these differences. Universities potentially compete in eight markets (M_j^v), reflecting the 2 × 2 structure of research and teaching across knowledge type and mission orientation. Aggregate statistics are reported by Market (see Table 1) and by type of activity.

Table 2 and 10 report Monte Carlo average growth statistics for production, employment, and the inverse Herfindahl index by Market, as well as productivity and research quality by type of activity and knowledge. Aggregate production corresponds to the sum of research outputs (Eq. (2)) or teaching outputs (Eq. (17)) across universities. Employment aggregates labour allocations across institutions. Market structure is measured by the inverse Herfindahl index ($invHH_{jt}^v$), computed from the funding shares in Eqs. (13) and (14). This index ranges from one (monopoly) to N (equal distribution across universities). Research productivity and teaching productivity are weighted averages of Eqs. (5) and (10), respectively, with market shares as weights. Research quality is the weighted average of Eq. (4). In the benchmark scenario, both research and teaching outputs grow over time, reflecting the expansion of exogenous demand and the

Table 1 Simulated markets and real-world examples

Market	University activity	Examples
Market I ($M_u^{R,S}$)	Solutions-oriented utilitarian research	Land-grant colleges (US), National Board for Industrial and Technical Development (SWE), Fraunhofer (GER)
Market II ($M_p^{R,S}$)	Solutions-oriented pure research	Strategic Research Foundation (SWE)
Market III ($M_u^{R,NS}$)	Non-solutions-oriented utilitarian research	CNRS (FR), Research Council for Engineering Sciences (SWE)
Market IV ($M_p^{R,NS}$)	Non-solutions-oriented pure research	Max Planck Institutes (GER), CNRS (FR)
Market V ($M_u^{T,S}$)	Solutions-oriented utilitarian teaching	French *HEC* and *Polytechniques*, any *Humboldt* university
Market VI ($M_p^{T,S}$)	Solutions-oriented pure teaching	French *EHESS*, any *Humboldt* university
Market VII ($M_u^{T,NS}$)	Non-solutions-oriented utilitarian teaching	French *Ecole Normale*, any *Humboldt* university
Market VIII ($M_p^{T,NS}$)	Non-solutions-oriented pure teaching	*Any Humboldt University*, Cardinal Newman's (UK)

funding allocation rules. Differences across markets emerge endogenously from labour reallocation and the replicator dynamics governing funding shares (Eqs. (13)–(14)). Non-solutions-oriented research displays higher output levels, primarily due to labour reallocation toward activities not directly constrained by demand. This mechanism increases effective research capacity and raises the probability of additional contributions to knowledge (Eq. (1)). 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.

Research and teaching productivity both increase on average, but follow different dynamic patterns. Research productivity initially grows due to improvements in average research quality (Eqs. (3)–(5)), but eventually stabilises as knowledge accumulation reduces the marginal contribution of new outputs. Teaching productivity, by contrast, grows persistently through the cumulative learning-by-doing mechanism embedded in Eq. (10). This closed feedback structure generates sustained improvements as long as teaching activity expands.

The inverse Herfindahl index highlights the emergence of market concentration through the replicator dynamics (Eqs. (13)–(14)). Teaching markets converge rapidly toward monopolistic structures, whereas research markets display persistent leadership turnover. The divergence stems from the different feedback mechanisms embedded in the model. Teaching productivity evolves through a closed cumulative process driven by learning-by-doing (Eq. (10)). Productivity gains depend primarily on internal past activity, generating a strong self-reinforcing dynamic: early advantages translate into higher productivity, stronger reputation, expanding funding shares, and further opportunities to accumulate experience. This cumulative causation progressively locks the teaching market into a concentrated structure consistent with a Schumpeter Mark II regime.[5] Research markets, by contrast, follow a different trajectory. Research productivity (Eq. (5)) depends not only on internal effort but also on absorptive capacity and the quasi-public nature of knowledge (Eqs. (6)–(7)). Advances by leading universities expand the common knowledge frontier, which lagging institutions can partially assimilate. This mechanism counteracts permanent incumbency advantages and allows recurrent leap-frogging in market leadership. As a result, research markets display waves of temporary dominance rather than stable monopoly, consistent with a Schumpeter Mark I regime.[6] Importantly, these regimes are not imposed ex ante through behavioural assumptions, but arise from the structural asymmetry between cumulative internal learning and quasi-public knowledge spillovers (see the dynamics of the market shares in Fig. 2).

To assess the robustness of the cumulative mechanism in teaching markets, we conduct a sensitivity analysis on the parameter λ, which governs the strength of complementarity between research and teaching (Eq. (10)). Results are reported in Table S4 and Fig. S4 in the online Supplementary Material. For $\lambda > 0$, the qualitative structure of the teaching market remains unchanged. The learning-by-doing mechanism continues to generate cumulative productivity advantages for early leading universities,

[5] Under the Mark II regime, innovative activities are significantly more cumulative and largely driven by a few incumbent agents that emerge as serial innovators (Malerba and Orsenigo 1995, 1996; Dosi 2023).

[6] The Mark I regime is characterised by recurrent entry, leap-frogging, and relatively low cumulative persistence of leadership at the organisational level (Malerba and Orsenigo 1996; Dosi 2023).

ultimately driving the system toward a concentrated Mark II configuration. Lower values of λ delay the emergence of dominance but do not alter its long-run existence. Only when $\lambda = 0$ does the cumulative mechanism disappear. In that case, teaching productivity no longer benefits from past activity, and the market remains structurally competitive. While variations in λ affect the timing and speed of concentration, they do not modify the underlying feedback logic embedded in Eq. (10). This confirms that concentration in teaching markets is a structural outcome of cumulative productivity dynamics rather than a parameter-specific artefact. We also suggest that the reinforcement mechanism typical of any Schumpeter Mark II behaviour is further strengthened by a cost disease (Baumol 1967). Indeed, the wage rate (see Eq. (16)) 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 (see Sect. S1.3 in the online Supplementary Material). The reduced reputation fosters the emergence of a market leader.

To summarise, Fig. 4 illustrates the distribution of universities across the three structural dimensions of the model, type of knowledge, commitment to research versus teaching, and mission orientation, at selected simulation periods. Over most of the simulation horizon, the distribution stabilises around persistent configurations shaped by the cumulative and competitive mechanisms described above. In later periods, slight discontinuities emerge, reflecting shifts in market concentration and resource allocation. While the majority of universities remain active in solutions-oriented knowledge provision, the internal composition of activities adjusts endogenously in response to evolving funding shares and productivity dynamics. The benchmark thus provides a coherent baseline against which to evaluate policy changes. We now turn to experiments that modify government preferences in the direction (parameters γ^j, γ^T, γ^v) and the amount (parameters g^{ex}, g^T, g^R) of public funds. We describe these experiments in the next Sections.

5 On Prince's Preferences

We exploit the model to examine how alternative configurations of Prince's preferences shape university evolution and patterns of specialisation. Our analysis does not follow a comparative statics logic typical of policy evaluation exercises in agent-based macroeconomics (Dawid and Delli Gatti 2018). Rather than measuring deviations from a normative benchmark, we explore how different institutional parametrisations generate distinct structural outcomes. Results are reported in Tables 3, 4 and 5, while the distribution of universities across activities under each configuration is illustrated in Figs. S1–S3 in the online Supplementary Material,[7] To facilitate comparability across configurations characterised by different dynamic regimes, outcomes are presented in log-differences. This approach is consistent with institutional comparative exercises

[7] The Supplementary Material also provides additional details on the implementation of the experiments and further robustness checks. Additionally, whenever a Figure in the main manuscript is indexed by an *S* it means the Figure is in the online Supplementary Material.

Table 2 Monte Carlo baseline: average growth for key statistics

Period	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
	$M_u^{R,S}$	$M_p^{R,S}$	$M_u^{R,NS}$	$M_p^{R,NS}$	$M_u^{T,S}$	$M_p^{T,S}$	$M_u^{T,NS}$	$M_p^{T,NS}$
Production (growth rates)								
t	R_u^S	R_p^S	R_u^{NS}	R_p^{NS}	T_u^S	T_p^S	T_u^{NS}	T_p^{NS}
100–500	0.004	0.004	0.026	0.026	0.010	0.010	0.010	0.010
500–1000	0.007	0.007	0.025	0.025	0.010	0.010	0.010	0.010
1000–1500	0.010	0.010	0.024	0.024	0.010	0.010	0.010	0.010
1500–2000	0.010	0.010	0.024	0.024	0.010	0.010	0.010	0.010
2000–2500	0.010	0.010	0.024	0.024	0.010	0.010	0.010	0.010
Employment (growth rates)								
t	$L_u^{R,S}$	$L_p^{R,S}$	$L_u^{R,NS}$	$L_p^{R,NS}$	$L_u^{T,S}$	$L_p^{T,S}$	$L_u^{T,NS}$	$L_p^{T,NS}$
100–500	0.000	0.000	0.022	0.022	0.001	0.001	0.001	0.001
500–1000	0.006	0.006	0.024	0.024	0.005	0.005	0.005	0.005
1000–1500	0.010	0.010	0.024	0.024	0.007	0.007	0.007	0.007
1500–2000	0.010	0.010	0.024	0.024	0.007	0.007	0.007	0.007
2000–2500	0.010	0.010	0.024	0.024	0.007	0.007	0.007	0.007

Table 2 (continued)

Period	Market I $M_u^{R,S}$	Market II $M_p^{R,S}$	Market III $M_u^{R,NS}$	Market IV $M_p^{R,NS}$	Market V $M_u^{T,S}$	Market VI $M_p^{T,S}$	Market VII $M_u^{T,NS}$	Market VIII $M_p^{T,NS}$
Inverse Herfindahl index (levels)								
t	$invHH_u^{R,S}$	$invHH_p^{R,S}$	$invHH_u^{R,NS}$	$invHH_p^{R,NS}$	$invHH_u^{T,S}$	$invHH_p^{T,S}$	$invHH_u^{T,NS}$	$invHH_p^{T,NS}$
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 (growth rates)				Quality (growth rates)			
	Utilitarian research	Pure research	Utilitarian teaching	Pure teaching	Solutions-oriented utilitarian	Non-targeted utilitarian	Solutions-oriented pure	Non-solutions-oriented pure
t	A_u^R	A_p^R	A_u^T	A_p^T	$\bar{a}_u^S$	$\bar{a}_u^{NS}$	$\bar{a}_p^S$	$\bar{a}_p^{NS}$
100–500	0.004	0.004	0.002	0.002	0.003	0.003	0.003	0.003
500–1000	0.001	0.001	0.001	0.002	5.30×10^{-4}	5.00×10^{-4}	5.40×10^{-4}	4.70×10^{-4}
1000–1500	1.90×10^{-4}	1.90×10^{-4}	0.002	0.002	1.60×10^{-4}	1.10×10^{-4}	1.60×10^{-4}	1.10×10^{-4}

Table 2 (continued)

Period	Market I $M_u^{R,S}$	Market II $M_p^{R,S}$	Market III $M_u^{R,NS}$	Market IV $M_p^{R,NS}$	Market V $M_u^{T,S}$	Market VI $M_p^{T,S}$	Market VII $M_u^{T,NS}$	Market VIII $M_p^{T,NS}$
1500–2000	6.00×10^{-5}	6.00×10^{-5}	0.003	0.003	5.00×10^{-5}	3.00×10^{-5}	3.00×10^{-5}	8.00×10^{-5}
2000–2500	2.00×10^{-5}	2.00×10^{-5}	0.003	0.003	1.00×10^{-6}	1.00×10^{-5}	2.00×10^{-5}	4.00×10^{-5}

The table provides average growth statistics across 50 Monte Carlo runs for key variables of interest. The average growth rate of a variable X is defined as $\bar{GR}_x = [log X(T) - log X(0)]/(T+1)$, in which $T = 500$. We removed a hundred of periods to wash the warm-up simulation phase away, i.e., the first time window is $T = 400$. We recall the content of Table 1: Market I (solutions-oriented utilitarian research); Market II (solutions-oriented pure research); Market III (non-solutions-oriented utilitarian research); Market IV (non-solutions-soriented pure research); Market V (solutions-oriented utilitarian teaching); Market VI (solutions-oriented pure teaching); Market VII (non-solutions-oriented utilitarian teaching); Market VIII (non-solutions-oriented pure teaching). Variables are defined as follows. *Production*, when referring to research Markets, is the aggregation across universities of the research outputs in Eq. (2); conversely, it is the aggregation of teaching outputs computed in Eq. (17) when dealing with teaching Markets. *Employment* is the aggregation of employment levels across universities as described in Section S1.2 of the online Supplementary Material. The *Inverse Herfindahl index*, which is the only variable represented in *levels* and not in *growth* terms, is the inverse of the weighted-average market share of each Market (with market shares as weights) and determines the number of universities with production levels significantly larger than zero, thus ranging from one (monopoly) to N, i.e., the total number of universities. Research *Productivity* is the weighted-average of Eq. (5) across universities (weights are market shares); likewise, teaching productivity is the weighted-average of Eq. (10). Productivity measures do not change across Markets but with respect to the type of knowledge produced ($j = u, p$). Research *Quality* is the weighted average of Eq. (4) across universities (weights are market shares). Research quality does not change by Market but only by type of knowledge produced ($j = u$, p) and between solution-oriented v. non-solution oriented ($v = S, NS$) research. See Sect. 3.1 for further information on productivity and quality dynamics

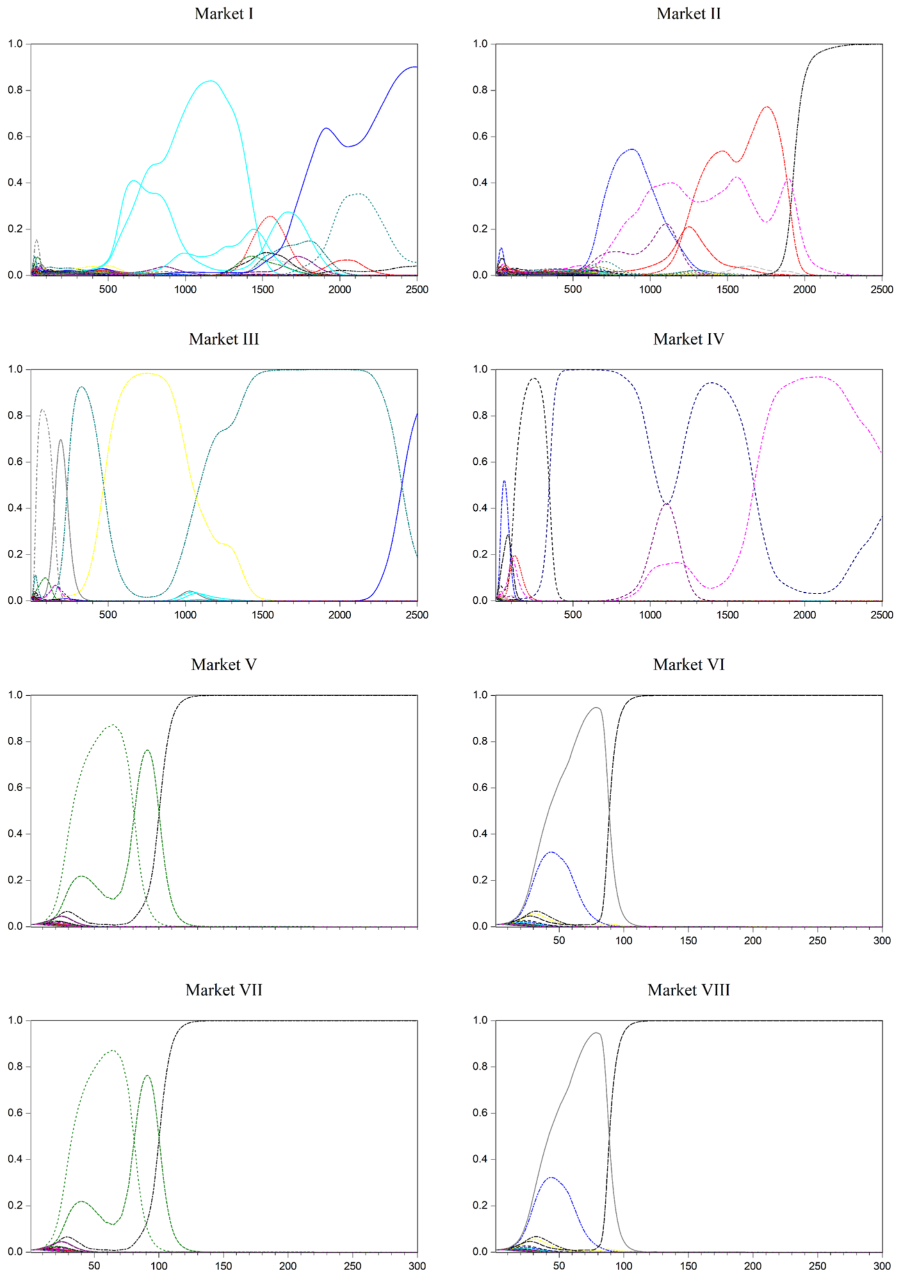

Fig. 2 Universities' market shares. *Note*: the Figure represents the evolution of universities' market shares as described in Eqs. (13) and (14). We recall the content of Table 1: Market I (solutions-oriented utilitarian research); Market II (solutions-oriented pure research); Market III (non-solutions-oriented utilitarian research); Market IV (non-solutions-oriented pure research); Market V (solutions-oriented utilitarian teaching); Market VI (solutions-oriented pure teaching); Market VII (non-solutions-oriented utilitarian teaching); Market VIII (non-solutions-oriented pure teaching). Plots refer to a representative MC simulation

and parameter-space explorations common in evolutionary modelling (Ciarli et al. 2019), where the focus lies on emergent structural patterns rather than on estimating the magnitude of policy deviations.

We study the preferences of the public sector through three policy parameters. First, changes in γ^j denote increasing priority for utilitarian knowledge, reaching its maximum when the parameter equals 1 (Table 3, Fig. S1). Secondly, γ^T reallocates public funds between research and teaching, with a unit value indicating full priority to teaching activities (Table 4, Fig. S2). Finally, γ^v captures the orientation toward mission-driven programs, where a unit value corresponds to full priority to solutions-oriented activities (Table 5, Fig. S3).

Since all tables report log-differences between average experimental values and the corresponding baseline averages for key variables, a negative value indicates lower average growth relative to the baseline configuration, while positive values indicate higher average growth. Log-differences are zero under the baseline parameter setting. The only exception is the inverse Herfindahl index, which is reported in absolute values given its bounded nature between 1 and N.[8]

Shifting funding priorities across pure and utilitarian knowledge (γ^j) generates non-linear effects on aggregate production and employment. Extreme allocations toward either pure or utilitarian knowledge are associated with lower average growth relative to the baseline configuration, while intermediate allocations yield stronger aggregate performance, consistent with an inverted-U pattern (Table 3). This outcome can be traced to the interaction between funding concentration and the replicator dynamics (Eqs. (13)–(14)). As γ^j approaches its extremes, resources concentrate in a smaller subset of universities, as reflected in the inverse Herfindahl index. Fewer institutions contribute actively to research production, reducing the breadth of knowledge creation within the system. This mechanism resonates with the resource concentration dynamics discussed by Geuna (2001). In the model, stronger concentration reduces contributions to the common knowledge stock (Eq. (6)) and weakens absorptive capacity (Eq. (7)). As a result, cumulative productivity growth declines when funding becomes excessively polarised across knowledge types.

Variations in γ^j do not fundamentally alter the structural configuration of teaching markets, where concentration persists due to the cumulative learning-by-doing mechanism in Eq. (10). However, extreme reallocations indirectly affect teaching performance through their impact on research dynamics and knowledge accumulation, thereby weakening aggregate production and employment growth.

Overall, the results highlight the structural complementarity between pure and utilitarian knowledge. Intermediate allocations are associated with broader participation in knowledge production and stronger interaction across research types.[9]

We observe a distinct pattern when varying γ^T (Table 4, Fig. S2). Moving γ^T toward its lower boundary (full priority to research) or toward its upper boundary

[8] The inverse Herfindahl index being defined between 1 and N a presentation in log-differences would distort interpretation.

[9] This complementarity echoes historical patterns observed in postwar US science policy, where federal funding supported both basic and applied research in parallel (Mowery 1995).

Table 3 Experiments on the preferences for utilitarian knowledge

γ^j	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
	$M_u^{R,S}$	$M_p^{R,S}$	$M_u^{R,NS}$	$M_p^{R,NS}$	$M_u^{T,S}$	$M_p^{T,S}$	$M_u^{T,NS}$	$M_p^{T,NS}$
Production (difference from baseline)								
	R_u^S	R_p^S	R_u^{NS}	R_p^{NS}	T_u^S	T_p^S	T_u^{NS}	T_p^{NS}
0	−7.016***	20.720***	−0.660***	−1.902***	0.000	−0.888***	0.000	−0.888***
0.2	−0.690***	−0.369***	−0.133***	−0.198***	0.001	0.001	0.001	0.001
0.5	0	0	0	0	0	0	0	0
0.7	−0.263***	−0.389***	−0.106***	0.103***	0.001	0.001	0.001	0.001
1	19.974***	−7.025***	−2.248***	−1.212***	−0.588***	0.001	−0.588***	0.001
Employment (difference from baseline)								
	$L_u^{R,S}$	$L_p^{R,S}$	$L_u^{R,NS}$	$L_p^{R,NS}$	$L_u^{T,S}$	$L_p^{T,S}$	$L_u^{T,NS}$	$T_p^{T,NS}$
0	−6.863***	30.465***	−0.658***	−1.167***	−0.295***	−5.502***	−0.295***	−5.502***
0.2	−0.594***	−0.361***	−0.125***	−0.177***	−0.273***	0.022***	−0.273***	0.022***
0.5	0	0	0	0	0	0	0	0
0.7	−0.257***	−0.388***	−0.106***	0.095***	0.077***	−0.098***	0.077***	−0.098***
1	21.973***	−6.865***	−1.745***	−1.235***	−5.609***	−0.252***	−5.609***	−0.252***
Inverse Herfindahl index (levels)								

Table 3 (continued)

γ^j	Market I $M_u^{R,S}$	Market II $M_p^{R,S}$	Market III $M_u^{R,NS}$	Market IV $M_p^{R,NS}$	Market V $M_u^{T,S}$	Market VI $M_p^{T,S}$	Market VII $M_u^{T,NS}$	Market VIII $M_p^{T,NS}$
	$invHH_u^{R,S}$	$invHH_p^{R,S}$	$invHH_u^{R,NS}$	$invHH_p^{R,NS}$	$invHH_u^{T,S}$	$invHH_p^{T,S}$	$invHH_u^{T,NS}$	$invHH_p^{T,NS}$
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	17.769	17.640	1.277	1.264	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 (difference from baseline)				Quality (difference from baseline)			
	Utilitarian research	Pure research	Utilitarian teaching	Pure teaching	Solutions-oriented utilitarian	Non-solutions-oriented utilitarian	Solutions-oriented pure	Non-solutions-oriented pure
	A_u^R	A_p^R	A_u^T	A_p^T	$\bar{a}_u^S$	$\bar{a}_u^{NS}$	$\bar{a}_p^S$	$\bar{a}_p^{NS}$
0	−0.071***	−0.695***	4.976***	168.996***	−1.131***	−1.210***	−0.002	−4.333***
0.2	−0.002	0.003	−0.244***	−0.029***	0.060***	−0.060***	−0.052***	−0.058***
0.5	0	0	0	0	0	0	0	0

Table 3 (continued)

γ^j	Market I $M_u^{R,S}$	Market II $M_p^{R,S}$	Market III $M_u^{R,NS}$	Market IV $M_p^{R,NS}$	Market V $M_u^{T,S}$	Market VI $M_p^{T,S}$	Market VII $M_u^{T,NS}$	Market VIII $M_p^{T,NS}$
0.7	0.000	0.001	−0.072***	−0.093***	−0.064***	−0.061***	−0.059***	−0.063***
1	−0.831***	−0.102***	68.380***	−0.239***	−0.049***	−0.060***	−1.243***	−1.346***

The table displays the log-difference between the experiment and the baseline scenario for key variables of interest across 50 Monte Carlo runs. Therefore, the average baseline values are set as equal to 0. The exception is represented by the Inverse Herfindahl index, whose representations in *levels* conveys greater information than in *differences*. We removed a hundred of periods to wash the warm-up simulation phase away. We recall the content of Table 1: Market I (solutions-oriented utilitarian research); Market II (solutions-oriented pure research); Market III (non-solutions-oriented utilitarian research); Market IV (non-solutions-oriented pure research); Market V (solutions-oriented utilitarian teaching); Market VI (solutions-oriented pure teaching); Market VII (non-solutions-oriented utilitarian teaching); Market VIII (non-solutions-oriented pure teaching). Variables are defined as follows. *Production*, when referring to research Markets, is the aggregation across universities of the research outputs in Eq. (2); conversely, it is the aggregation of teaching outputs computed in Eq. (17) when dealing with teaching Markets. *Employment* is the aggregation of employment levels across universities as described in Sect. S1.2 of the online Supplementary Material. The *Inverse Herfindahl index* is the inverse of the weighted-average market share of each Market (with market shares as weights) and determines the number of universities with production levels significantly larger than zero, thus ranging from one (monopoly) to N, i.e., the total number of universities. Research *Productivity* is the weighted-average of Eq. (5) across universities (weights are market shares); likewise, teaching productivity is the weighted-average of Eq. (10). Productivity measures do not change across Markets but with respect to the type of knowledge produced ($j = u, p$). Research *Quality* is the weighted average of Eq. (4) across universities (weights are market shares). Research quality does not change by Market but only by type of knowledge produced ($j = u, p$) and between solution-oriented v. non-solution oriented ($v = S, NS$) research. See Sect. 3.1 for further information on productivity and quality dynamics. Baseline values are for $\gamma^j = 0.5$: please refer to Table 10 for baseline log averages

Statistical significance from the benchmark values is computed with a t-test: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

(full priority to teaching) reorients the system toward a teaching-dominant configuration. In both cases, research growth does not improve and may weaken relative to intermediate allocations. Market structures remain qualitatively unchanged: research markets continue to exhibit leadership turnover, whereas teaching markets converge toward monopolistic structures due to the cumulative learning-by-doing mechanism in Eq. (10). Extreme prioritisation of teaching reinforces internal cumulative dynamics within leading universities. As teaching productivity evolves through idiosyncratic experience accumulation, institutions that receive larger funding shares strengthen their position over time.

However, unlike research, teaching productivity does not depend on spillovers from a common knowledge stock. Consequently, concentration in teaching markets does not generate system-wide feedback effects. This asymmetry between private cumulative gains and limited inter-university spillovers is consistent with the resource concentration mechanisms discussed by Geuna (2001). In the model, amplified teaching advantages remain largely confined within dominant institutions and do not propagate through network-wide productivity dynamics. Moreover, extreme teaching-oriented allocations reduce the scale of research activity and thereby weaken the complementarities embedded in Eqs. (10) and (5). When research effort contracts, the contribution of research-driven productivity improvements to teaching also diminishes, moderating long-run aggregate growth.

These dynamics provide a structural interpretation of institutional configurations historically associated with different national systems. Empirical studies emphasise the role of research-intensive universities in sustaining scientific leadership in the United States (Borsato and Llerena 2025, 2026; Dosi et al. 2006; Mowery and Sampat 2004; Rodríguez-Navarro and Narin 2018). While Humboldt-inspired complementarities between research and teaching originated in Europe, institutional arrangements that maintain strong integration between the two functions are associated, within the model, with more sustained productivity dynamics. Conversely, systems where research and teaching are institutionally separated, such as those involving specialised public research organisations (e.g., CNRS or Max Planck Institutes), exhibit different structural trade-offs (Chesnais 1993; Keck 1993). Within our framework, separating these functions reduces the strength of complementarities and alters long-run growth patterns without necessarily improving aggregate outcomes.

We finally consider variations in γ^v, which reallocate public funds between solutions-oriented and non-solutions-oriented activities (Table 5, Fig. S3). Increasing γ^v strengthens the weight of demand satisfaction in the reputation mechanism (Eqs. (11)–(12)), thereby intensifying selection pressures in mission-oriented markets. As γ^v approaches its upper bound, universities compete more aggressively to satisfy publicly defined research and teaching demand. This strengthens short-run alignment with policy targets but also increases concentration through the replicator dynamics (Eqs. (13)–(14)). Fewer universities remain active contributors in mission-oriented markets, while non-solutions-oriented activities contract. This shift modifies the composition of the knowledge stock (Eq. (6)). When a larger share of resources is tied to targeted demand, exploratory research activities diminish. Although targeted production may initially expand, the reduced diversity of knowledge accumulation weakens absorptive capacity (Eq. (7)) over time. Consequently, aggregate productivity growth

Table 4 Experiments on the preferences for teaching

γ^T	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
	$M_u^{R,S}$	$M_p^{R,S}$	$M_u^{R,NS}$	$M_p^{R,NS}$	$M_u^{T,S}$	$M_p^{T,S}$	$M_u^{T,NS}$	$M_p^{T,NS}$
Production (difference from baseline)								
	R_u^S	R_p^S	R_u^{NS}	R_p^{NS}	T_u^S	T_p^S	T_u^{NS}	T_p^{NS}
0	0.002	0.002	−0.782***	−0.782***	20.507***	20.640***	20.507***	20.640***
0.2	0.002	0.002	−1.380***	−1.389***	26.716***	26.736***	26.716***	26.736***
0.5	0	0	0	0	0	0	0	0
0.7	0.002	0.003	−2.002***	−2.001***	26.053***	26.080***	26.053***	26.080***
1	2.291***	2.650***	−20.893***	−19.857***	6.216***	7.022***	6.216***	7.022***
Employment (difference from baseline)								
	$L_u^{R,S}$	$L_p^{R,S}$	$L_u^{R,NS}$	$L_p^{R,NS}$	$L_u^{T,S}$	$L_p^{T,S}$	$L_u^{T,NS}$	$T_p^{T,NS}$
0	−0.009	−0.011*	−0.822***	−0.821***	12.196***	12.343***	12.196***	12.353***
0.2	−0.017***	−0.013***	−1.426***	−1.427***	23.182***	23.221***	23.182***	23.221***
0.5	0	0	0	0	0	0	0	0
0.7	−0.013***	−0.020***	−2.046***	−2.046***	24.759***	24.797***	24.759***	24.797***
1	5.773***	5.294***	−17.443***	−17.443***	23.915***	23.950***	23.915***	23.950***
Inverse Herfindahl index (levels)								
	$invHH_u^{R,S}$	$invHH_p^{R,S}$	$invHH_u^{R,NS}$	$invHH_p^{R,NS}$	$invHH_u^{T,S}$	$invHH_p^{T,S}$	$invHH_u^{T,NS}$	$invHH_p^{T,NS}$
0	17.427	17.567	1.294	1.280	1.001	1.003***	1.002	1.003***

Table 4 (continued)

γ^T	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
	$M_u^{R,S}$	$M_p^{R,S}$	$M_u^{R,NS}$	$M_p^{R,NS}$	$M_u^{T,S}$	$M_p^{T,S}$	$M_u^{T,NS}$	$M_p^{T,NS}$
0.2	17.347*	17.192*	1.193***	1.235	1.011***	1.014***	1.011***	1.014***
0.5	17.769	17.640	1.277	1.264	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 (difference from baseline)				Quality (difference from baseline)			
	Utilitarian research	Pure research	Utilitarian teaching	Pure teaching	Solutions-oriented utilitarian	Non-solutions-oriented utilitarian	Solutions-oriented pure	Non-solutions-oriented pure
	A_u^R	A_p^R	A_u^T	A_p^T	$\bar{a}_u^S$	$\bar{a}_u^{NS}$	$\bar{a}_p^S$	$\bar{a}_p^{NS}$
0	−0.010***	−0.011***	7.600***	7.622***	−0.019***	−0.012***	−0.016***	−0.016***
0.2	−0.013***	−0.011***	12.247***	12.140***	−0.018***	−0.024***	−0.019***	−0.019***
0.5	0	0	0	0	0	0	0	0

Table 4 (continued)

γ^T	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
	$M_u^{R,S}$	$M_p^{R,S}$	$M_u^{R,NS}$	$M_p^{R,NS}$	$M_u^{T,S}$	$M_p^{T,S}$	$M_u^{T,NS}$	$M_p^{T,NS}$
0.7	−0.011***	−0.012***	8.479***	8.950***	−0.021***	−0.030***	−0.017**	−0.027***
1	−0.260***	−0.417***	118.995***	102.945***	−0.302***	−0.304***	−0.242***	−0.250***

The table displays the log-difference between the experiment and the baseline scenario for key variables of interest across 50 Monte Carlo runs. Therefore, the average baseline values are set as equal to 0. The exception is represented by the Inverse Herfindahl index, whose representations in *levels* conveys greater information than in *differences*. We removed a hundred of periods to wash the warm-up simulation phase away. We recall the content of Table 1: Market I (solutions-oriented utilitarian research); Market II (solutions-oriented pure research); Market III (non-solutions-oriented utilitarian research); Market IV (non-solutions-oriented pure research); Market V (solutions-oriented utilitarian teaching); Market VI (solutions-oriented pure teaching); Market VII (non-solutions-oriented utilitarian teaching); Market VIII (non-solutions-oriented pure teaching). Variables are defined as follows. *Production*, when referring to research Markets, is the aggregation across universities of the research outputs in Eq. (2); conversely, it is the aggregation of teaching outputs computed in Eq. (17) when dealing with teaching Markets. *Employment* is the aggregation of employment levels across universities as described in Sect. S1.2 of the online Supplementary Material. The *Inverse Herfindahl index* is the inverse of the weighted-average market share of each Market (with market shares as weights) and determines the number of universities with production levels significantly larger than zero, thus ranging from one (monopoly) to N, i.e., the total number of universities. Research *Productivity* is the weighted-average of Eq. (5) across universities (weights are market shares); likewise, teaching productivity is the weighted-average of Eq. (10). Productivity measures do not change across Markets but with respect to the type of knowledge produced ($j = u, p$). Research *Quality* is the weighted average of Eq. (4) across universities (weights are market shares). Research quality does not change by Market but only by type of knowledge produced ($j = u, p$) and between solution-oriented v. non-solution oriented ($v = S, NS$) research. See Sect. 3.1 for further information on productivity and quality dynamics. Baseline values are for $\gamma^T = 0.5$: please refer to Table 10 for baseline log averages

Statistical significance from the benchmark values is computed with a t-test: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

does not monotonically increase with stronger mission orientation. Conversely, when γ^v approaches zero, demand-driven incentives weaken and universities rely predominantly on productivity-based reputation. While this configuration sustains broader participation in research markets, alignment with policy-defined societal objectives becomes less pronounced.

Overall, the simulations suggest that extreme mission-oriented allocations alter the balance between directed and exploratory knowledge production, reshaping concentration patterns and long-run growth trajectories without generating uniformly superior aggregate outcomes.

To conclude this battery of experiments, the simulations reveal strong interdependencies between teaching and research specialization. Concentration in one domain systematically reshapes labour allocation and strategic positioning in the other. When teaching markets become highly concentrated under extreme γ^T allocations, universities that lose teaching shares tend to reallocate labour toward research activities, effectively re-specializing as research-intensive institutions. This adaptive behaviour emerges endogenously from the model's feedback structure: effort is redirected toward activities where cumulative knowledge, absorptive capacity, and competitive opportunities sustain productivity growth. These dynamics are visible in Fig. 4, which shows convergence toward higher research commitment among institutions that lag in teaching markets. Extreme concentration in one activity therefore does not merely reduce output in that domain; it alters specialization trajectories across the system. The resulting configuration reflects endogenous adjustments to selective pressures rather than exogenous design. This mechanism complements the unintended-consequence dynamics discussed by Archibugi and Filippetti (2018) and Geuna (2001). In the model, policy-induced concentration propagates through labour reallocation and knowledge accumulation channels, generating cascading adjustments in specialization patterns and altering the structural configuration of the university system over time.

6 On the Role of Funding and Demand Growth

A 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 (see Eq. (15)) has two components, one of which is exogenous and dependent on policymaking. Likewise, the growth rates of demand concern to teaching (see Eq. (A13)) regardless orientation, and to solutions-oriented research (see Eq. (A16)). Teaching demand growth can be interpreted as reflecting exogenous demographic or institutional pressures, while growth in solutions-oriented research demand captures shifts in publicly defined priorities.

We discuss the impact of exogenous growth in public funds in Table 6 and Fig. S4. An increase in the exogenous component of public funding growth primarily expands teaching-related markets. The performance in terms of production and employment considerably improves with respect to the baseline as long as the exogenous growth rate goes up. Corresponding rises in teaching productivity and employment go hand in hand with output performance. As expected, we observe no impact on the market

Table 5 Experiments on the preferences for solutions

γ^v	Market I $M_u^{R,S}$	Market II $M_p^{R,S}$	Market III $M_u^{R,NS}$	Market IV $M_p^{R,NS}$	Market V $M_u^{T,S}$	Market VI $M_p^{T,S}$	Market VII $M_u^{T,NS}$	Market VIII $M_p^{T,NS}$
Production (difference from baseline)								
	R_u^S	R_p^S	R_u^{NS}	R_p^{NS}	T_u^S	T_p^S	T_u^{NS}	T_p^{NS}
0	17.856***	18.022***	−3.087***	−1.783***	−17.504***	−17.504***	24.302***	−17.504***
0.2	−0.002	−0.002	−1.569***	−1.576***	26.442***	26.477***	26.516***	26.505***
0.5	0	0	0	0	0	0	0	0
0.7	0.002	0.002	−1.653***	−1.651***	26.436***	26.458***	26.391***	26.434***
1	0.002	0.001	−0.307***	−0.314***	−17.504***	27.755***	−17.504***	−17.504***
Employment (difference from baseline)								
	$L_u^{R,S}$	$L_p^{R,S}$	$L_u^{R,NS}$	$L_p^{R,NS}$	$L_u^{T,S}$	$L_p^{T,S}$	$L_u^{T,NS}$	$T_p^{T,NS}$
0	20.666***	19.568***	−2.295***	−2.094***	−5.757***	−5.719***	24.208***	−5.719***
0.2	−0.018***	−0.014***	−1.620***	−1.621***	23.430***	23.468***	24.812***	24.849***
0.5	0	0	0	0	0	0	0	0
0.7	−0.014***	−0.021***	−1.690***	−1.690***	24.614***	24.651***	23.769***	23.807***
1	−0.003	−0.001	−0.311***	−0.311***	−5.757***	26.022***	−5.757***	−5.719***
Inverse Herfindahl index (levels)								
	$invHH_u^{R,S}$	$invHH_p^{R,S}$	$invHH_u^{R,NS}$	$invHH_p^{R,NS}$	$invHH_u^{T,S}$	$invHH_p^{T,S}$	$invHH_u^{T,NS}$	$invHH_p^{T,NS}$
0	13.059***	12.723***	1.485***	1.313	1.012***	1.074***	1.012***	1.074***

Table 5 (continued)

γ^v	Market I $M_u^{R,S}$	Market II $M_p^{R,S}$	Market III $M_u^{R,NS}$	Market IV $M_p^{R,NS}$	Market V $M_u^{T,S}$	Market VI $M_p^{T,S}$	Market VII $M_u^{T,NS}$	Market VIII $M_p^{T,NS}$
0.2	17.098***	16.950***	1.199***	1.214	1.001	1.001	1.001	1.001
0.5	17.769	17.640	1.277	1.264	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 (difference from baseline)				Quality (difference from baseline)			
	Utilitarian research	Pure research	Utilitarian teaching	Pure teaching	Solutions-oriented utilitarian	Non-solutions-oriented utilitarian	Solutions-oriented pure	Non-solutions-oriented pure
	A_u^R	A_p^R	A_u^T	A_p^T	$\bar{a}_u^S$	$\bar{a}_u^{NS}$	$\bar{a}_p^S$	$\bar{a}_p^{NS}$
0	−0.674***	−0.463***	154.867***	46.076***	−1.107***	−1.132***	−0.574***	−0.955***
0.2	−0.009***	−0.007***	10.035***	10.114***	−0.020***	−0.024***	−0.023***	0.017***
0.5	0	0	0	0	0	0	0	0

Table 5 (continued)

γ^v	Market I $M_u^{R,S}$	Market II $M_p^{R,S}$	Market III $M_u^{R,NS}$	Market IV $M_p^{R,NS}$	Market V $M_u^{T,S}$	Market VI $M_p^{T,S}$	Market VII $M_u^{T,NS}$	Market VIII $M_p^{T,NS}$
0.7	−0.012***	−0.012***	9.887***	10.812***	−0.023***	−0.032***	−0.020***	0.030***
1	−0.002	−0.003	−1.943***	5.381***	−0.002	−0.021***	0.004	−0.010***

The table displays the log-difference between the experiment and the baseline scenario for key variables of interest across 50 Monte Carlo runs. Therefore, the average baseline values are set as equal to 0. The exception is represented by the Inverse Herfindahl index, whose representations in *levels* conveys greater information than in *differences*. We removed a hundred of periods to wash the warm-up simulation phase away. We recall the content of Table 1: Market I (solutions-oriented utilitarian research); Market II (solutions-oriented pure research); Market III (non-solutions-oriented utilitarian research); Market IV (non-solutions-oriented pure research); Market V (solutions-oriented utilitarian teaching); Market VI (solutions-oriented pure teaching); Market VII (non-solutions-oriented utilitarian teaching); Market VIII (non-solutions-oriented pure teaching). Variables are defined as follows. *Production*, when referring to research Markets, is the aggregation across universities of the research outputs in Eq. (2); conversely, it is the aggregation of teaching outputs computed in Eq. (17) when dealing with teaching Markets. *Employment* is the aggregation of employment levels across universities as described in Sect. S1.2 of the online Supplementary Material. The *Inverse Herfindahl index* is the inverse of the weighted-average market share of each Market (with market shares as weights) and determines the number of universities with production levels significantly larger than zero, thus ranging from one (monopoly) to N, i.e., the total number of universities. Research *Productivity* is the weighted-average of Eq. (5) across universities (weights are market shares); likewise, teaching productivity is the weighted-average of Eq. (10). Productivity measures do not change across Markets but with respect to the type of knowledge produced ($j = u, p$). Research *Quality* is the weighted average of Eq. (4) across universities (weights are market shares). Research quality does not change by Market but only by type of knowledge produced ($j = u, p$) and between solution-oriented v. non-solution oriented ($v = S, NS$) research. See Sect. 3.1 for further information on productivity and quality dynamics. Baseline values are for $\gamma^v = 0.5$: please refer to Table 10 for baseline log averages

Statistical significance from the benchmark values is computed with a t-test: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

structure at all. 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. Under the benchmark parametrisation, research markets display higher average performance relative to scenarios with stronger exogenous funding growth. The quality of research and, hence, productivity also suffer from this dynamic.

This outcome is consistent with a Baumol-type cost mechanism already embedded in the model. The system-level wage rate (see Eq. (16)) 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. This mechanism introduces a cross-activity externality: productivity gains in teaching raise system-wide wages, thereby compressing margins for research-intensive institutions

The inspection of Fig. S4 reveals further detail. As long as exogenous growth soars, universities specialise in commitment and third mission but not in the type of knowledge. Leaders in the teaching markets do not look very involved in the research enterprise and they are on average much bigger than research counterparts. Their structural features resemble specialised teaching-oriented institutions observed in certain national systems. Conversely, research performers are usually very small institutes whose research endeavour spans in the continuum from basic to applied science.

We suggest similar interpretations out of Table 7 and Fig. S5. The higher demographic pressure with progressive increases from 1 to 10% growth has strong and positive impacts on the overall growth performance of teaching-related markets. 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 often qualitatively changed the trajectories of universities and the corresponding distribution. Figure S5 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. 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, solutions-oriented and non-solutions-oriented research. This third university employs another fourth of the available workforce.[10] Therefore, variations in teaching demand growth do not substantially alter the qualitative specialization patterns observed under the benchmark configuration.

The last set of results is in Table 8 and Fig. S6 and regards an increase in government demand for solutions-oriented research. All markets benefit from this engine but the two markets of non-solutions-oriented research. Universities drive their labour force to

[10] Related pictures are available on request.

Table 6 Experiments on the exogenous growth of public funds

g^{ex}	Market I $M_u^{R,S}$	Market II $M_p^{R,S}$	Market III $M_u^{R,NS}$	Market IV $M_p^{R,NS}$	Market V $M_u^{T,S}$	Market VI $M_p^{T,S}$	Market VII $M_u^{T,NS}$	Market VIII $M_p^{T,NS}$
Production (difference from baseline)								
	R_u^S	R_p^S	R_u^{NS}	R_p^{NS}	T_u^S	T_p^S	T_u^{NS}	T_p^{NS}
0.01	−1.628***	−1.576***	−25.017***	−25.013***	−2.662***	−2.746***	−2.662***	−2.746***
0.03	−0.035***	−0.116***	−13.537***	−13.544***	14.791***	14.756***	14.791***	14.756***
0.05	0	0	0	0	0	0	0	0
0.07	−0.015***	−0.016***	−10.342***	−10.344***	38.178***	38.186***	38.178***	38.186***
0.1	−0.041***	−0.042***	28.181***	28.179***	55.708***	55.700***	55.708***	55.700***
Employment (difference from baseline)								
	$L_u^{R,S}$	$L_p^{R,S}$	$L_u^{R,NS}$	$L_p^{R,NS}$	$L_u^{T,S}$	$L_p^{T,S}$	$L_u^{T,NS}$	$T_p^{T,NS}$
0.01	−2.190***	−2.172***	−26.543***	−26.579***	−0.494***	−0.471***	−0.494***	−0.471***
0.03	−0.294***	−0.291***	−13.883***	−13.883***	11.966***	12.003***	11.966***	12.003***
0.05	0	0	0	0	0	0	0	0
0.07	−0.210***	−0.203***	−10.551***	−10.550***	36.564***	36.602***	36.564***	36.602***
0.1	−0.465***	−0.465***	28.683***	28.687***	54.709***	54.747***	54.709***	54.747***
Inverse Herfindahl index (levels)								
	$invHH_u^{R,S}$	$invHH_p^{R,S}$	$invHH_u^{R,NS}$	$invHH_p^{R,NS}$	$invHH_u^{T,S}$	$invHH_p^{T,S}$	$invHH_u^{T,NS}$	$invHH_p^{T,NS}$
0.01	15.774***	15.559***	1.196***	1.202	1.001	1.001	1.001	1.001

Table 6 (continued)

g^{ex}	Market I $M_u^{R,S}$	Market II $M_p^{R,S}$	Market III $M_u^{R,NS}$	Market IV $M_p^{R,NS}$	Market V $M_u^{T,S}$	Market VI $M_p^{T,S}$	Market VII $M_u^{T,NS}$	Market VIII $M_p^{T,NS}$
0.03	14.928***	14.962***	1.135***	1.125***	1.001	1.000	1.001	1.000
0.05	17.769	17.640	1.277	1.264	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 (difference from baseline)				Quality (difference from baseline)			
	Utilitarian research A_u^R	Pure research A_p^R	Utilitarian teaching A_u^T	Pure teaching A_p^T	Solutions-oriented utilitarian $\bar{a}_u^S$	Non-solutions-oriented utilitarian $\bar{a}_u^{NS}$	Solutions-oriented pure $\bar{a}_p^S$	Non-solutions-oriented pure $\bar{a}_p^{NS}$
0.01	0.558***	0.640***	33.277***	33.335***	0.795***	0.685***	0.784***	0.675***
0.03	0.289***	0.287***	6.142***	6.092***	0.420***	0.315***	0.427***	0.315***
0.05	0	0	0	0	0	0	0	0

Table 6 (continued)

g^{ex}	Market I $M_u^{R,S}$	Market II $M_p^{R,S}$	Market III $M_u^{R,NS}$	Market IV $M_p^{R,NS}$	Market V $M_u^{T,S}$	Market VI $M_p^{T,S}$	Market VII $M_u^{T,NS}$	Market VIII $M_p^{T,NS}$
0.07	−0.232***	−0.232***	12.534***	12.675***	−0.183***	−0.307***	−0.182***	−0.304***
0.1	−0.520***	−0.521***	16.213***	17.427***	−0.487***	−0.603***	−0.478***	−0.607***

The table displays the log-difference between the experiment and the baseline scenario for key variables of interest across 50 Monte Carlo runs. Therefore, the average baseline values are set as equal to 0. The exception is represented by the Inverse Herfindahl index, whose representations in *levels* conveys greater information than in *differences*. We removed a hundred of periods to wash the warm-up simulation phase away. We recall the content of Table 1: Market I (solutions-oriented utilitarian research); Market II (solutions-oriented pure research); Market III (non-solutions-oriented utilitarian research); Market IV (non-solutions-oriented pure research); Market V (solutions-oriented utilitarian teaching); Market VI (solutions-oriented pure teaching); Market VII (non-solutions-oriented utilitarian teaching); Market VIII (non-solutions-oriented pure teaching). Variables are defined as follows. *Production*, when referring to research Markets, is the aggregation across universities of the research outputs in Eq. (2); conversely, it is the aggregation of teaching outputs computed in Eq. (17) when dealing with teaching Markets. *Employment* is the aggregation of employment levels across universities as described in Sect. S1.2 of the online Supplementary Material. The *Inverse Herfindahl index* is the inverse of the weighted-average market share of each Market (with market shares as weights) and determines the number of universities with production levels significantly larger than zero, thus ranging from one (monopoly) to N, i.e., the total number of universities. Research *Productivity* is the weighted-average of Eq. (5) across universities (weights are market shares); likewise, teaching productivity is the weighted-average of Eq. (10). Productivity measures do not change across Markets but with respect to the type of knowledge produced ($j = u, p$). Research *Quality* is the weighted average of Eq. (4) across universities (weights are market shares). Research quality does not change by Market but only by type of knowledge produced ($j = u, p$) and between solution-oriented v. non-solution oriented ($v = S, NS$) research. See Sect. 3.1 for further information on productivity and quality dynamics. Baseline values are for $g^{ex} = 0.05$: please refer to Table 10 for baseline log averages

Statistical significance from the benchmark values is computed with a t-test: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

Table 7 Experiments on the growth rate of teaching demand

g^T	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
	$M_u^{R,S}$	$M_p^{R,S}$	$M_u^{R,NS}$	$M_p^{R,NS}$	$M_u^{T,S}$	$M_p^{T,S}$	$M_u^{T,NS}$	$M_p^{T,NS}$
Production (difference from baseline)								
	R_u^S	R_p^S	R_u^{NS}	R_p^{NS}	T_u^S	T_p^S	T_u^{NS}	T_p^{NS}
0.01	0	0	0	0	0	0	0	0
0.03	0.001	0.002	−0.793***	−0.786***	25.228***	25.230***	25.228***	25.230***
0.05	0.003	0.003	−1.426***	−1.438***	26.436***	26.425***	26.436***	26.425***
0.07	0.002	0.002	−1.461***	−1.464***	26.496***	26.494***	26.496***	26.494***
0.1	0.002	0.002	−1.611***	−1.621***	26.471***	26.462***	26.471***	26.462***
Employment (difference from baseline)								
	$L_u^{R,S}$	$L_p^{R,S}$	$L_u^{R,NS}$	$L_p^{R,NS}$	$L_u^{T,S}$	$L_p^{T,S}$	$L_u^{T,NS}$	$T_p^{T,NS}$
0.01	0	0	0	0	0	0	0	0
0.03	−0.014***	−0.016***	−0.810***	−0.810***	17.804***	17.871***	17.804***	17.871***
0.05	−0.017***	−0.013***	−1.472***	−1.476***	24.444***	24.482***	24.444***	24.482***
0.07	−0.011***	−0.019***	−1.504***	−1.506***	24.473***	24.511***	24.473***	24.511***
0.1	−0.020***	−0.015***	−1.663***	−1.664***	24.311***	24.349***	24.311***	24.349***
Inverse Herfindahl index (levels)								
	$invHH_u^{R,S}$	$invHH_p^{R,S}$	$invHH_u^{R,NS}$	$invHH_p^{R,NS}$	$invHH_u^{T,S}$	$invHH_p^{T,S}$	$invHH_u^{T,NS}$	$invHH_p^{T,NS}$
0.01	17.769	17.640	1.277	1.264	1.001	1.001	1.001	1.001

Table 7 (continued)

g^T	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
	$M_u^{R,S}$	$M_p^{R,S}$	$M_u^{R,NS}$	$M_p^{R,NS}$	$M_u^{T,S}$	$M_p^{T,S}$	$M_u^{T,NS}$	$M_p^{T,NS}$
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 (difference from baseline)				Quality (difference from baseline)			
	Utilitarian research	Pure research	Utilitarian teaching	Pure teaching	Solutions-oriented utilitarian	Non-solutions-oriented utilitarian	Solutions-oriented pure	Non-solutions-oriented pure
	A_u^R	A_p^R	A_u^T	A_p^T	$\bar{a}_u^S$	$\bar{a}_u^{NS}$	$\bar{a}_p^S$	$\bar{a}_p^{NS}$
0.01	0	0	0	0	0	0	0	0
0.03	0.017***	0.018***	7.214***	7.146***	0.021***	0.015***	0.019***	0.022***
0.05	0.010***	0.008***	7.243***	7.218***	0.000	0.024***	0.020***	0.018***

Table 7 (continued)

g^T	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
	$M_u^{R,S}$	$M_p^{R,S}$	$M_u^{R,NS}$	$M_p^{R,NS}$	$M_u^{T,S}$	$M_p^{T,S}$	$M_u^{T,NS}$	$M_p^{T,NS}$
0.07	0.007***	0.007***	7.686***	8.142***	−0.003***	0.029***	0.014***	0.025***
0.1	0.011***	0.010***	10.153***	9.556***	−0.003***	0.034***	0.027***	0.025***

The table displays the log-difference between the experiment and the baseline scenario for key variables of interest across 50 Monte Carlo runs. Therefore, the average baseline values are set as equal to 0. The exception is represented by the Inverse Herfindahl index, whose representations in *levels* conveys greater information than in *differences*. We removed a hundred of periods to wash the warm-up simulation phase away. We recall the content of Table 1: Market I (solutions-oriented utilitarian research); Market II (solutions-oriented pure research); Market III (non-solutions-oriented utilitarian research); Market IV (non-solutions-oriented pure research); Market V (solutions-oriented utilitarian teaching); Market VI (solutions-oriented pure teaching); Market VII (non-solutions-oriented utilitarian teaching); Market VIII (non-solutions-oriented pure teaching). Variables are defined as follows. *Production*, when referring to research Markets, is the aggregation across universities of the research outputs in Eq. (2); conversely, it is the aggregation of teaching outputs computed in Eq. (17) when dealing with teaching Markets. *Employment* is the aggregation of employment levels across universities as described in Sect. S1.2 of the online Supplementary Material. The *Inverse Herfindahl index* is the inverse of the weighted-average market share of each Market (with market shares as weights) and determines the number of universities with production levels significantly larger than zero, thus ranging from one (monopoly) to N, i.e., the total number of universities. Research *Productivity* is the weighted-average of Eq. (5) across universities (weights are market shares); likewise, teaching productivity is the weighted-average of Eq. (10). Productivity measures do not change across Markets but with respect to the type of knowledge produced ($j = u, p$). Research *Quality* is the weighted average of Eq. (4) across universities (weights are market shares). Research quality does not change by Market but only by type of knowledge produced ($j = u, p$) and between solution-oriented v. non-solution oriented ($v = S, NS$) research. See Sect. 3.1 for further information on productivity and quality dynamics. Baseline values are for $g^T = 0.01$: please refer to Tab. 10 for baseline log averages. Statistical significance from the benchmark values is computed with a t-test: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

the pursuit of solutions-oriented research with aggregate improvements in production and employment growth. Nonetheless, some universities start accumulating absolute technological advantages that contribute to reducing the competitive pressure in all the corresponding markets. Increased concentration is associated with lower research quality and slower productivity growth. 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.[11] Such negative outcomes are yet not present in teaching markets. The increase in productivity growth via learning-by-doing helps top institutions to keep on the pace set by aggregate demand such that they could afford higher employment growth.

Interesting becomes the distribution of universities. 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 privilege mission-oriented activities.

To conclude these Sections, we remind that a stylised fact of several university systems is the persistence in research and teaching performance of old, diversified universities together with the emergence of new specialised actors. Then, the analysis of a sequential entry of universities seems an interesting and realistic exercise to perform. In the online Supplementary Material we extend the baseline setting with an entry-exit mechanism. Introducing entry dynamics reveals that higher turnover and the presence of innovative entrants are associated, within the model, with stronger aggregate performance indicators. These effects are more pronounced when entrants display higher innovative capabilities, which intensify competitive pressure and expand the common knowledge base. Gathered these results, we draw implications for policy and discuss the opened avenues for future research in the last Section.

7 Conclusions

The role of the university in society, its evolution across time and institutional contexts, and its interaction with other socio-economic actors have long been central concerns in economic analysis (Cowan et al. 2010). In this paper, we approached this broad debate by conceptualising the university as an evolutionary organisation whose trajectories emerge from the interplay between internal learning mechanisms and the institutional environment in which it operates. Our objective was not to evaluate specific policy interventions, but to investigate whether scientific and pedagogical trajectories can be understood as endogenous outcomes of micro-dynamics shaped by funding rules and demand structures.

To address this question, we developed an ABM that explicitly embeds complementarities and trade-offs between research and teaching under alternative public funding configurations. Several general insights emerge from the analysis.

First, policies aimed at maximising performance in a specific domain do not necessarily require maximising funds targeted at that domain. Because research and teaching

[11] This reinforces the earlier finding that diversity of contributors is structurally linked to the cumulative properties of the knowledge base.

Table 8 Experiments on the growth rate of solutions-oriented research demand

g^R	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
	$M_u^{R,S}$	$M_p^{R,S}$	$M_u^{R,NS}$	$M_p^{R,NS}$	$M_u^{T,S}$	$M_p^{T,S}$	$M_u^{T,NS}$	$M_p^{T,NS}$
Production (difference from baseline)								
	R_u^S	R_p^S	R_u^{NS}	R_p^{NS}	T_u^S	T_p^S	T_u^{NS}	T_p^{NS}
0.01	0	0	0	0	0	0	0	0
0.03	22.363***	22.358***	−4.679***	−3.288***	26.059***	26.061***	26.059***	26.061***
0.05	22.138***	22.132***	−31.267***	−31.261***	25.297***	24.582***	25.297***	24.582***
0.07	22.197***	22.171***	−32.306***	−32.280***	24.601***	25.807***	24.601***	25.807***
0.1	22.680***	22.691***	−32.680***	−32.745***	26.289***	25.156***	26.289***	25.156***
Employment (difference from baseline)								
	$L_u^{R,S}$	$L_p^{R,S}$	$L_u^{R,NS}$	$L_p^{R,NS}$	$L_u^{T,S}$	$L_p^{T,S}$	$L_u^{T,NS}$	$T_p^{T,NS}$
0.01	0	0	0	0	0	0	0	0
0.03	22.402***	22.360***	−4.700***	−3.293***	24.279***	24.317***	24.279***	24.317***
0.05	22.343***	22.346***	−30.604***	−30.604***	23.420***	23.459***	23.420***	23.459***
0.07	22.449***	22.452***	−31.582***	−31.582***	23.383***	23.423***	23.383***	23.423***
0.1	22.905***	22.900***	−32.083***	−32.083***	23.875***	23.913***	23.875***	23.913***
Inverse Herfindahl index (levels)								
	$invHH_u^{R,S}$	$invHH_p^{R,S}$	$invHH_u^{R,NS}$	$invHH_p^{R,NS}$	$invHH_u^{T,S}$	$invHH_p^{T,S}$	$invHH_u^{T,NS}$	$invHH_p^{T,NS}$
0	16.290***	16.684***	1.234	1.181**	99.908***	99.908 ***	99.908***	99.908***

Table 8 (continued)

g^R	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
	$M_u^{R,S}$	$M_p^{R,S}$	$M_u^{R,NS}$	$M_p^{R,NS}$	$M_u^{T,S}$	$M_p^{T,S}$	$M_u^{T,NS}$	$M_p^{T,NS}$
0.1	15.839***	15.940***	1.308	1.303	1.005***	1.005***	1.005***	1.005***
0.3	17.805	17.756	1.319	1.275	1.001	1.001	1.001	1.001
0.5	17.640	17.508	1.154***	1.240	1.000	1.000	1.000	1.000
0.8	17.313	17.588	1.228***	1.177**	1.000	1.000	1.000	1.000
	Productivity (difference from baseline)				Quality (difference from baseline)			
	Utilitarian research	Pure research	Utilitarian teaching	Pure teaching	Solutions-oriented utilitarian	Non-solutions-oriented utilitarian	Solutions-oriented pure	Non-solutions-oriented pure
	A_u^R	A_p^R	A_u^T	A_p^T	$\bar{a}_u^S$	$\bar{a}_u^{NS}$	$\bar{a}_p^S$	$\bar{a}_p^{NS}$
0.01	0	0	0	0	0	0	0	0
0.03	−0.013***	0.003	105.458***	125.331***	0.020***	−0.017***	0.006**	−0.030***
0.05	−0.696***	−0.603***	18.645***	226.825***	−0.141***	−8.688***	−0.216***	−0.296***

Table 8 (continued)

g^R	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
	$M_u^{R,S}$	$M_p^{R,S}$	$M_u^{R,NS}$	$M_p^{R,NS}$	$M_u^{T,S}$	$M_p^{T,S}$	$M_u^{T,NS}$	$M_p^{T,NS}$
0.07	−0.759***	−0.602***	279.940***	229.044***	−0.261***	−0.334***	−0.124***	−0.189***
0.1	−0.522***	−0.602***	15.056***	280.077***	−0.073***	−0.145***	−0.170***	−0.250***

The table displays the log-difference between the experiment and the baseline scenario for key variables of interest across 50 Monte Carlo runs. Therefore, the average baseline values are set as equal to 0. The exception is represented by the Inverse Herfindahl index, whose representations in *levels* conveys greater information than in *differences*. We removed a hundred of periods to wash the warm-up simulation phase away. We recall the content of Table 1: Market I (solutions-oriented utilitarian research); Market II (solutions-oriented pure research); Market III (non-solutions-oriented utilitarian research); Market IV (non-solutions-oriented pure research); Market V (solutions-oriented utilitarian teaching); Market VI (solutions-oriented pure teaching); Market VII (non-solutions-oriented utilitarian teaching); Market VIII (non-solutions-oriented pure teaching). Variables are defined as follows. *Production*, when referring to research Markets, is the aggregation across universities of the research outputs in Eq. (2); conversely, it is the aggregation of teaching outputs computed in Eq. (17) when dealing with teaching Markets. *Employment* is the aggregation of employment levels across universities as described in Sect. S1.2 of the online Supplementary Material. The *Inverse Herfindahl index* is the inverse of the weighted-average market share of each Market (with market shares as weights) and determines the number of universities with production levels significantly larger than zero, thus ranging from one (monopoly) to N, i.e., the total number of universities. Research *Productivity* is the weighted-average of Eq. (5) across universities (weights are market shares); likewise, teaching productivity is the weighted-average of Eq. (10). Productivity measures do not change across Markets but with respect to the type of knowledge produced ($j = u, p$). Research *Quality* is the weighted average of Eq. (4) across universities (weights are market shares). Research quality does not change by Market but only by type of knowledge produced ($j = u, p$) and between solution-oriented v. non-solution oriented ($v = S, NS$) research. See Sect. 3.1 for further information on productivity and quality dynamics. Baseline values are for $g^R = 0.01$: please refer to Table 10 for baseline log averages.

Statistical significance from the benchmark values is computed with a t-test: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

are technologically and organisationally interdependent, extreme specialisation may undermine the very performance it intends to enhance. Across a wide range of simulations, more balanced allocations, reminiscent of Humboldtian complementarities, tend to sustain stronger and more stable system-level outcomes.

Second, funding regimes that reduce competitive pressure in research markets and concentrate resources on a narrow subset of institutions may weaken aggregate research quality. As the number of active contributors shrinks, the common knowledge base becomes thinner, limiting absorptive learning and the probability of further discoveries. Concentration thus affects not only distributional patterns but also the dynamic properties of the knowledge system.

Third, generalised increases in funding do not automatically translate into higher long-run performance when allocation mechanisms reinforce incumbency advantages. Without mechanisms that preserve diversity and entry, additional resources may coexist with stronger concentration and weaker cumulative learning dynamics.

Fourth, the interaction between uniform wage dynamics and heterogeneous productivity growth generates a Baumol-disease mechanism within the academic system. Institutions experiencing below-average productivity growth face rising labour costs that are only partially offset by internal improvements, thereby reinforcing divergence across universities.

These findings are consistent with interpretations of scientific leadership that emphasise complementarities between research and teaching (Dosi et al. 2006; Mowery and Sampat 2004). While Humboldt-like configurations originated in Europe, certain institutional environments have proven more capable of sustaining organisational arrangements that preserve such complementarities (Borsato and Llerena 2025, 2026; Rodríguez-Navarro and Narin 2018). Rather than endorsing any particular national model, our results suggest that institutional systems able to maintain competition, diversity, and cross-activity complementarities exhibit greater structural resilience.

The analysis is necessarily stylised and therefore subject to limitations. The third mission is modelled as government demand for solutions-oriented knowledge, abstracting from the broader spectrum of contemporary university-industry-society interactions. Future research could extend the framework to incorporate private funding sources (Borsato and Llerena 2026; Gulbrandsen and Smeby 2005; Muscio et al. 2013), alternative governance structures for knowledge-transfer activities (Perkmann et al. 2013; Audretsch 2014), and the evolving civic engagement dimension of universities, including the role of social sciences and humanities (Dobson and Ferrari 2023; Goddard et al. 2016). Moreover, the present framework abstracts from individual scientist careers. Modelling scientists as mobile agents accumulating competencies across institutions (Borsato and Lorentz 2023; Almudi et al. 2012) would allow the joint evolution of organisational and individual trajectories to be analysed, potentially reshaping the interaction between funding rules and knowledge dynamics.

Finally, our allocation mechanism is reputation-based. Exploring alternative selection rules, e.g., mechanisms designed to sustain smaller institutions or foster entry, may alter the balance between concentration and diversity. Investigating these alternative institutional designs represents a promising avenue for further theoretical and empirical work.

Overall, the paper contributes to the understanding of universities as evolving organisations whose long-run trajectories depend not only on the quantity of resources available, but on the structural configuration of funding rules and the feedback mechanisms they generate. Institutional design shapes not merely resource allocation, but the evolutionary architecture of knowledge production.

Appendix A. Baseline Scenario: Further Details

See Tables 9 and 10, Figs. 3 and 4.

Table 9 Parameter list

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 10 Monte Carlo baseline: average levels for key statistics

Period	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
	$M_u^{R,S}$	$M_p^{R,S}$	$M_u^{R,NS}$	$M_p^{R,NS}$	$M_u^{T,S}$	$M_p^{T,S}$	$M_u^{T,NS}$	$M_p^{T,NS}$
Production								
t	R_u^S	R_p^S	R_u^{NS}	R_p^{NS}	T_u^S	T_p^S	T_u^{NS}	T_p^{NS}
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
100-2500	15.740	15.740	41.293	41.294	17.504	17.504	17.504	17.504
Employment								
t	$L_u^{R,S}$	$L_p^{R,S}$	$L_u^{R,NS}$	$L_p^{R,NS}$	$L_u^{T,S}$	$L_p^{T,S}$	$L_u^{T,NS}$	$T_p^{T,NS}$
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
100-2500	11.468	11.470	37.065	37.065	10.362	10.324	10.362	10.324

Table 10 (continued)

Period	Market I	Market II	Market III	Market IV	Market V	Market VI	Market VII	Market VIII
	$M_u^{R,S}$	$M_p^{R,S}$	$M_u^{R,NS}$	$M_p^{R,NS}$	$M_u^{T,S}$	$M_p^{T,S}$	$M_u^{T,NS}$	$M_p^{T,NS}$
	Productivity				Quality			
	Utilitarian research	Pure research	Utilitarian teaching	Pure teaching	Solutions-oriented utilitarian	Non-solutions-oriented utilitarian	Solutions-oriented pure	Non-solutions-oriented pure
t	A_u^R	A_p^R	A_u^T	A_p^T	$\bar{a}_u^S$	$\bar{a}_u^{NS}$	$\bar{a}_p^S$	$\bar{a}_p^{NS}$
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
100-2500	4.214	4.213	3.469	3.502	4.274	4.331	4.275	4.331

The table provides log-average statistics across 50 Monte Carlo runs for key variables of interest. We removed a hundred of periods to wash the warm-up simulation phase away, i.e., the first time window is $T = 400$. We recall the content of Tab. 1: Market I (solutions-oriented utilitarian research); Market II (solutions-oriented pure research); Market III (non-solutions-oriented utilitarian research); Market IV (non-solutions-soriented pure research); Market V (solutions-oriented utilitarian teaching); Market VI (solutions-oriented pure teaching); Market VII (non-solutions-oriented utilitarian teaching); Market VIII (non-solutions-oriented pure teaching). Variables are defined as follows. *Production*, when referring to research Markets, is the aggregation across universities of the research outputs in Eq. (2); conversely, it is the aggregation of teaching outputs computed in Eq. (17) when dealing with teaching Markets. *Employment* is the aggregation of employment levels across universities as described in Section S1.2 of the online Supplementary Material. Research *Productivity* is the weighted-average of Eq. (5) across universities (weights are market shares); likewise, teaching productivity is the weighted-average of Eq. (10). Productivity measures do not change across Markets but with respect to the type of knowledge produced ($j = u,\ p$). Research *Quality* is the weighted average of Eq. (4) across universities (weights are market shares). Research quality does not change by Market but only by type of knowledge produced ($j = u$, p) and between solution-oriented v. non-solution oriented ($v = S,\ NS$) research. See Sect. 3.1 for further information on productivity and quality dynamics

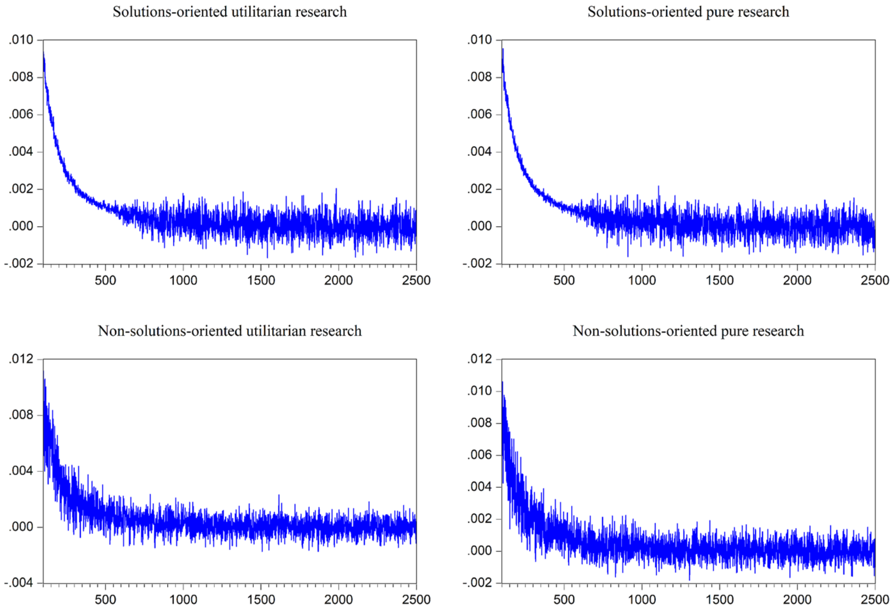

Fig. 3 Average quality growth from a representative MC simulation

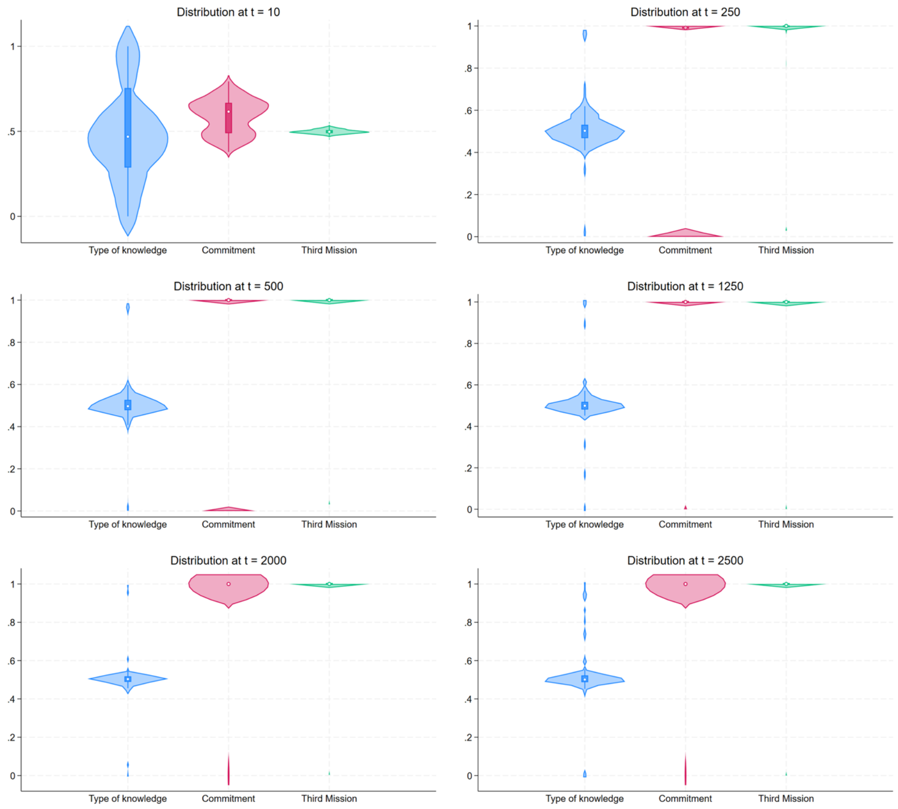

Fig. 4 The distribution of universities in the baseline scenario. Note: For selected time periods and parameter values, these violin plots represent the distribution of universities across type of knowledge being produced, commitment to teaching and research activities, and third mission. The type of knowledge measures the share of utilitarian knowledge produced in total research; the commitment refers to the share of labour time pursuing research *vis-a-vis* teaching; the third mission denotes the share of mission-oriented funds that a university obtains out of total funding. The white dot points to the median of the distribution, the straight line is about the interquartile range while the humps refer to the density of the distribution. Plots refer to a representative MC simulation

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

Declarations

Conflict of interest None.

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