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The influence of bottlenecks on innovation systems performance: Put the slowest climber first

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ABSTRACT

This paper contributes to the literature with a methodology that helps identify the functions that constrain the overall performance of an innovation system, hence providing clear guidelines to policymakers on the direction of their interventions. This methodology relies on the notion of penalty for bottleneck, which is defined as the weakest link or the binding constraint that holds back system performance. These penalty bottlenecks are applied to all the indicators that characterize innovation systems, and consider its input-output mix when assessing their performance through a Productivity Innovation Index. The data provided by the 2021 edition of the European Innovation Scoreboard are used to illustrate the utility of the method introduced in the paper.

We first identify the input and output bottlenecks for every country. Second, we report the productivity loss due to the existence of these bottlenecks. Third, we evidence the responsiveness of the Productivity Innovation Index to bottleneck alleviation, from three different perspectives: (i) application of a 10 % alleviation to the input bottleneck; (ii) application of a 10 % alleviation to the output bottleneck; and (iii) application of a 5 % alleviation to both the input and output bottlenecks, respectively.

1. Introduction

How to measure innovation at the territorial level is one of the most challenging endeavors in the field of innovation policy, due to the absence of a commonly accepted theory on how to characterize innovation systems aimed at informing innovation policy (Grupp and Schubert, 2010). To address this challenge, a plethora of composite indices have been developed, among which the index of the Massachusetts Innovation Economy, the Bloomberg Innovation Index, the Global Innovation Index, and the Summary Innovation Index of the European Innovation Scoreboard can be mentioned. These performance evaluation practices are all based on the use of a composite (i.e., synthetic) index that provides a ranking of the territories under study.

However, due to the methodology underlying the construction of these synthetic indices, they are driven by a 'more-the-better' rationale, which assumes that the larger the value of the individual indicators feeding the synthetic index, the larger the value of the latter, and hence, the better the performance of the territory under study (Zabala-Iturriagagoitia et al., 2007; Barbero et al., 2021). This 'the-more-the-better' logic concurs with the so-called linear model of innovation (Edquist, 2014), which due to its simplicity, still dominates innovation policy. According to this dominant (albeit flawed) logic, to improve the performance of an innovation system it would just be necessary to increase investments into Research and Development (R&D), as the rest of the necessary activities to bring innovations to the society and the market would 'naturally' spillover from these R&D activities.

Composite and synthetic indices are becoming increasingly relevant, not as instruments to accurately measure innovation, but rather to annually provide rankings of territories according to their performance. These rankings have strong policy implications since many political decisions are made on the conclusions drawn from them (Kozłowski, 2015; Edquist et al., 2018). However, according to several authors, their contribution to the practice of innovation policy is limited (Arundel, 2007; Mairesse and Mohnen, 2009; Schibany and Streicher, 2008).

Hence, a research gap exists as regards the need to develop methodologies that provide sound scientific evidence leading to better resource reallocation decisions and to more effective and efficient innovation policies beyond the narrow 'the-more-the-better' logic (Paruolo et al., 2013). To provide an answer to this research gap we contribute to the literature on the evaluation of innovation systems' performance by proposing a methodology that helps identify the bottlenecks that constrain the overall performance of innovation systems. With it, we aim to provide clear guidelines to policymakers on the direction of their interventions (Mazzucato, 2018).

Our contribution departs from Acs et al. (2014) who identify the *bottlenecks* that constrain the performance of a system. Their methodology is based on the theory of the weakest link (Harrison and Hirshleifer, 1989) and the theory of constraints (Tol and Yohe, 2007). These theories state that the performance of any dynamic system is characterized by interdependencies and feedback loops, as is the case of innovation systems, and that its overall performance depends on elements that may hold back the system's performance (Acs et al., 2014, p. 482). According to these theories, any system could only improve as long as its weakest links (i.e., the bottlenecks that constrain the whole system) are strengthened. Hence, Acs et al. (2014) apply a penalty bottleneck to those factors that restrain the performance of the system. However, to assess this systemic performance, they rely on an index (i.e., the Global Entrepreneurship and Development Index) which is built through the arithmetic average of multiple indicators, and hence, still follows the linear logic of 'the-more-the-better'.

To break with this dominant linear logic, we adopt a productivity approach, following the underlying conceptual framework connecting innovation inputs and outputs suggested by Edquist et al. (2018). We thus extend the notion of bottleneck to the input and output functions of innovation systems. We contend that both the excessive use of innovation inputs and the underproduction of innovation outputs are detrimental to the overall performance of any system. This implies that output bottlenecks will be represented by those indicators having the lowest values, signaling deficits in production levels in that dimension. In the case of input indicators what will be instead penalized is to have the largest values, which signals an excessive consumption of certain resources. This productivity approach is applied to the data provided by the 2021 edition – last available year – of the European Innovation Scoreboard (EIS) (European Union, 2021), which includes statistical information for all 27 European Union countries plus the United Kingdom.

As Acs et al. (2014) discuss, when assessing the performance of a system, it is not only important to consider the scale of each constituent, but rather which are the results that the whole system can achieve given the relative scale of all constituents or subsystems. They illustrate this need for balance through a metaphor that we also deem useful here (p. 488). To bake a cake several ingredients are needed in certain proportions. If we only have one ingredient (e.g., eggs), we may get an omelet, but never a cake. Similarly, if we have all the required ingredients to bake a cake, but the amount we have for one of them (e.g., flour) is limited, the amount to be used in all the other ingredients should also be reconsidered, reducing them in the proportion set by the ingredient that sets the constrain. In this approach, from a productivity perspective, the different elements that are required for a system to perform (i.e., the ingredients) interact in rather fixed proportions, implying that the degree of substitutability among them is limited and, therefore, the excessive use of some input factors in relation to other required inputs, or the underproduction of some outputs compared to other outputs, hamper the performance of the system. An innovation system may perform excellently in some of its input or output subsystems (e.g., knowledge development), but if this 'strength' is not complemented with a similar capacity in other subsystems (e.g., absorptive capacity), the performance of the system cannot be assumed to be balanced and comprehensive, just as it is impossible to bake a cake with lots of water but no eggs.

Additionally, if the performance of a system is understood under the simplistic logic of 'the-more-the-better', the complementary functions corresponding to input usage and output production will be missing, because the efficient use of the available resources should not prescribe their increase at all costs. This may not only end in decreasing returns to innovation investments (an issue already studied and confirmed by Barbero et al., 2021), but may also fall into the trap of having a fragile and unbalanced system (Parsons, 2006) if either the inputs to the system or its outputs are not proportional. As a result, it seems reasonable to consider that the performance of a system should be assessed depending on the balance among the input functions characterizing it, and their ability to be transformed into concrete, multidimensional, and equilibrated results (i.e., adopting a productivity standpoint that evaluates output production in terms of input consumption). With the novel methodology introduced here we can identify the bottlenecks and their impact on the productivity of an innovation system, as well as assess the effect that their alleviation may bring to its overall innovation performance.

The remaining of the manuscript is structured as follows. Section 2 reviews the literature on innovation systems, justifying the research gap addressed in the paper and evidencing its theoretical and managerial relevance. Section 3 presents the bottleneck methodology developed by Acs et al. (2014) in the context of national entrepreneurial systems, and which we adapt and extend here for benchmarking innovation systems from a productivity lens. It also describes the data used in the empirical part of the research. Section 4 presents the results of our study. First, it identifies the systemic bottlenecks for every country. Second, it reports the productivity loss due to the existence of bottlenecks, calculated through penalized (constrained) productivity innovation indices. Third, it evidences the responsiveness of the productivity innovation index to bottleneck alleviation, from three different perspectives: (i) when a 10 % alleviation is applied to the input bottleneck; (ii) when a 10 % alleviation is applied to the output bottleneck; and (iii) when a 5 % alleviation is applied both to the input and output bottlenecks, respectively. Finally, Section 5 concludes the study, by providing a theoretical discussion of its contribution to the literature and to the practice of innovation policymaking.

2. Innovation systems, saturated systems?

Innovation is one of the main engines of economic growth and social welfare. The literature has for long discussed the importance of policy decisions in shaping innovation systems (Nelson and Romer, 1996; Barbosa and Faria, 2011). Innovation systems are resource allocation systems the purpose of which is to create the conditions for the emergence, generation, diffusion and uptake of innovations (Barbero et al., 2021), and which are influenced by country-specific institutional settings and regulated by country-specific policies (Taylor, 2016).

Policy is not a matter of putting all resources into one basket, but rather having a holistic understanding of the different domains to be targeted by the intervention (Kapsali, 2011; Borrás and Edquist, 2019). The role of the public sector cannot be exclusively reduced to allocating more and more resources to support innovation. First, because public expenditure is financially constrained. And second, because as in any system with limited resources, policymakers face trade-offs in resource allocation decisions. As a result, increasing the funding dedicated to a particular subsystem (e.g., public procurement) implies reducing that additional funding from another part of the system (e.g., higher education).

Despite the above caveats, the policy field in general, and the measurement of innovation in particular, are governed by a 'the-more-the-better' logic (Zabala-Iturriagagoitia et al., 2007; Edquist et al., 2018; Barbero et al., 2021). Under this paradigm, increasing investments in the innovation system should lead to a better systemic performance, regardless the areas in which these investments are made. This 'the-more-the-better' logic is supportive of the idea of a linear model of

innovation (Rodríguez-Pose and Crescenzi, 2008). In spite of the mounting evidence that has proven the linear model of innovation to be biased, it still plays a dominant position in policy circles (see one of the critics by Edquist, 2014). Indeed, one of the implications of the supremacy of the linear model is that most countries deploy similar policy interventions, irrespective of their innovation performance and the challenges these may face (Izsak et al., 2015; Cunningham and Link, 2016).

A clear example of the dominance of the linear model of innovation, the existence of a 'the-more-the-better' logic, and the risk and ineffectiveness of these two rationales is the Lisbon strategy (European Parliament, 2000), which defined that 3 % of GDP should be spent on R&D across the European Union by 2010. Since these results were not achieved, the same target was again defined, but for 2020. As argued above, policy needs, above all, to provide directionality to the system (Mazzucato, 2018). However, to provide directionality, it is first necessary to identify the direction the system should take and, contemporarily, determine the policy areas to be addressed, the amount of policy support required by each of them, and the degree of substitutability or complementarity among them.

Edquist et al. (2018) and Barbero et al. (2021) question composite indicators like the Summary Innovation Index (SII). On the one hand, Edquist et al. (2018) identify, based on innovation systems' thinking, the input and output components based on the functions characterizing the system. Following the deliberation made by Edquist et al. (2018), the performance of an innovation system is thus defined as its efficiency (or productivity). On the other hand, Barbero et al. (2021) argue that the SII index proposed by the EIS can be interpreted as a measure of the size or scale of the innovation system, but not of its performance. As the authors discuss, this is due to the fact that if any of the indicators included in the SII of a particular country increase from one year to another (e.g., business R&D) while all the others remain constant, the SII of that country would also automatically increase. However, this by no means would imply that the country would show a better performance; on the contrary, it would show a lower performance, as one of the indicators increases, but the system is not able to capitalize on that increase in investment, by producing better results. In both cases, they conclude that traditional 'the-more-the-better' indices fail to capture how efficiently innovations systems perform when allocating scarce resources.

The idea of approaching innovation systems' performance from an efficiency perspective has already been discussed in the literature. Carayannis et al. (2016, p. 65-67) present the applications done to date using Data Envelopment Analysis (DEA). These include studies in which efficiency is approached in a single stage (Zabala-Iturriagagoitia et al., 2007; Cherchye et al., 2008; Nasierowski and Arcelus, 2012; Edquist et al., 2018), studies in which efficiency is estimated either in two or more stages (Chen and Guan, 2010; Guan and Chen, 2012), in the form of a network DEA (Carayannis et al., 2015; Kou et al., 2016), and in dynamic contexts (Aparicio et al., 2020; Barbero et al., 2021; Zabala-Iturriagagoitia et al., 2021). However, the previous studies have not managed to elucidate which are the dimensions that penalize the performance of the whole innovation system, which justifies the novel approach followed in this paper. Formally, DEA yields an efficiency score measuring the relative productivity of a country's innovation system compared to those of other countries. Countries with the highest productivity values are assigned a normalized efficiency score of one, while the scores of inefficient countries indicate how far these systems are from their best-performing benchmarks (e.g., a value of 0.5 indicates that the country is half as productive as those exhibiting the best performance). The methodology proposed in this study also relies on a productivity definition of performance but does not resort to DEA methods as it develops the bottleneck approach proposed by Acs et al. (2014).

Corrente et al. (2021) also criticize composite indices as the SII because they lack a proper scheme for weighting the indicators incorporated in the analysis according to their relative importance. These authors highlight the importance of classifying indicators according to a hierarchical structure that assigns weights, considering the preferences of decision-makers (i.e., triple helix agents corresponding to university, industry and government). They perform a survey among individuals belonging to these groups and determine a range of rank acceptability indices for different indicators. Finally, using EIS data from 2016, they provide a ranking of EU countries on each criterion for all three agents, this ranking differing substantially from the standard SII.

In this study, we develop a new methodology that complements studies like those above by focusing on the existence of functional systemic bottlenecks in innovation systems, both on the input and output sides. This approach is based on the literature developing a functional approach to the systems' logic, which aims at explaining how systems actually work and how policies need to target all the activities and functions being undertaken in them (Edquist, 2011; Kashani and Roshani, 2019; Rakas and Hain, 2019). Such a functional approach is regarded as a "a useful analytical supplement… as it provides a 'process' focus [as compared] to the traditional 'structural' focus of systems of innovation studies" (Mahroum and Al-Saleh, 2013, p. 322).

Galli and Teubal (1997) were the frontrunners in this stream and, in their early contribution, distinguished between hard and soft functions (see Table 1). Liu and White (2001) then argued that all innovation systems should accomplish five functions: research, implementation, end-use, linkage, and education. Edquist (2005, 2011) introduced a list of ten activities, representing those factors that influence, support, hinder, ease and promote the development of innovation processes. Hekkert et al. (2007) introduced a novelty to the previous approaches, by adopting a technological perspective, rather than a territorial one, leading to the following set of functions: (i) entrepreneurial activities; (ii) knowledge development; (iii) knowledge diffusion through networks; (iv) guidance of the search; (v) market formation; (vi) resources mobilization; and (vii) creation of legitimacy/counteract resistance to change. Bergek et al. (2008) also adopted a technological systems approach, suggesting very similar functions to those already identified by Hekkert et al. (2007). In turn, Mahroum and Al-Saleh (2013) consider that an innovation system can be represented by five value-creation functions: creating, accessing, anchoring, diffusing, and exploiting. Finally, the approach followed by the EIS could also be included here. According to it, the functioning of an innovation system would be represented by the combination of twelve functions, ranging from the development of attractive research systems to employment and sales impacts (see Table 1).

Despite the multiple functional understandings provided by the extant literature, a commonality to the previous contributions is that they tend to assume "full substitutability between system components, [so that] a loss in one component can be fully compensated by a corresponding increase in another system component" (Acs et al., 2014, p. 483). This understanding, however, supports the dominant 'the-more-the-better logic' discussed above, without questioning the existence of "possible bottleneck factors that hold back system performance" (Ibid, p. 477).

The notion of the bottleneck of a system was introduced by Acs et al. (2014) in the context of entrepreneurship. According to these authors, the performance of any dynamic system critically hinges upon the element that has the worst value. Consequently, the performance of the system as a whole, rather than depending on the overall (average) strengths of the system, should be evaluated in terms of its weakest dimensions. As a corollary, any system is subject to potential improvements, conditioned to the fact that its weakest links are reinforced. From this perspective, the configurations that would render the most stable

Table 1

A functional approach to the analysis of innovation systems.

Galli and Teubal (1997)	Liu and White (2001)	Edquist (2005, 2011)	Hekkert et al. (2007)	Bergek et al. (2008)	Mahroum and Al-Saleh (2013)	EIS (2021)
Hard: R&D activities (public)	Research (basic, development, engineering)	Provision of R&D	Entrepreneurial activities	Knowledge development and diffusion	Creating knowledge	Human resources
Hard: the supply of scientific and technical services to third parties (business sector and public administration)	Implementation (manufacturing)	Competence building	Knowledge development	Influence on the direction of search	Accessing knowledge	Attractive research systems
Soft: diffusion of information, knowledge, and technology	End-use (customers of the product or process output)	Formation of new product markets	Knowledge diffusion through networks	Entrepreneurial experimentation	Anchoring knowledge	Digitalization
Soft: policy making	Linkage (bringing together complementary knowledge)	Articulation of quality requirements	Guidance of the search	Market formation	Diffusing knowledge	Finance and support
Soft: design and implementation of institutions concerning patents, laws, standards, etc.	Education	Creating and changing organizations	Market formation	Legitimation	Exploiting knowledge	Firm investments
Soft: diffusion of scientific culture		Networking through markets and other mechanisms	Resources mobilization	Resource mobilization		Use of information technologies
Soft: professional coordination		Creating and changing institutions	Creation of legitimacy/ counteract resistance to change	Development of positive externalities		Linkages
		Incubation activities				Innovators
		Financing of innovation processes				Intellectual assets
		Provision of consultancy services				Employment impacts
						Sales impacts
						Environmental sustainability

Source: own elaboration.

and effective results would be those in which the different functions are in certain proportionate levels (i.e., a balanced system). This novel perspective challenges 'the-more-the-better' logics, as it helps to identify those areas that have the potential for large marginal improvements (i. e., where bottlenecks exist) and those that are already 'saturated', since a marginal improvement in the latter would produce no additional gains in the overall systemic performance (Barbero et al., 2021). In addition, it also helps to understand innovation policy as a 'moving target' (Zabala-Iturriagagoitia et al., 2021), facilitating the constant 'diagnose' of innovation systems to identify which policies may lead to higher returns at each moment in time.

In this regard, besides the already mentioned theories of the weakest link and constraints, the assumption that equity within the innovation system is a desirable goal is also rooted in economic theory. The standard assumptions resulting in well-behaved transformation functions yield convex isoquants in the input space and concave isoquants in the output space. This implies decreasing marginal rates of substitution among inputs and increasing marginal rates of transformation among outputs, thereby penalizing extreme or unbalanced mixes. Hence, a more balanced use of inputs and production of outputs will lead to increased productivity levels by avoiding the use of resources to such levels that their marginal productivities are limited due to the scarcity of other resources. This does not rule out that innovation systems may benefit from specializing in some input or output dimension in relative terms (i.e., assigning different weights to the indicators when aggregating them), but the underlying rationale favoring balanced proportions in the use of inputs and the production of outputs remains.

3. Methodology

To assess the extent to which the previous functions are being undertaken and the results achieved through them, these need to be fed by data. In this paper, we use the 2021 edition of the EIS, which provides a series of 32 indicators that aim at evaluating the performance of innovation systems.[1] These indicators offer a concrete basis to consider the functions that define alternative characterizations of innovation systems like those reported in Table 1. The EIS groups the 32 indicators in 12 distinct functions ('dimensions' using its terminology). These functions, ranging from 'Human resources' to 'Environmental sustainability', can be categorized as input or output pillars of innovation systems, as we justify in what follows. Subsequently, considering the input or output nature of the functions, a Productivity Innovation Index (PII) measuring the performance of innovation systems is calculated. The bottom-up structure of the PII is shown in Table 2.[2]

Edquist et al. (2018) discuss at length the conceptual meaning of innovation performance through a PII, defined as the ratio of aggregate innovation output to aggregate innovation input. They provide a

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Table 2

Description of the EIS indicators entering the Productivity Innovation Index.

	Pillar	Functions	Indicators: Input (I) and Output (O)
Productivity Innovation Index (PII)	Input	Human resources	1.1.1 New doctorate graduates (I)
			1.1.2 Population aged 25–34 with tertiary education (I)
			1.1.3 Lifelong learning (I)
		Attractive research systems	1.2.1 International scientific co-publications (I)
			1.2.2 Top-10 % most cited publications (I)
			1.2.3 Foreign doctorate students (I)
		Digitalization	1.3.1 Broadband penetration (I)
			1.3.2 Individuals who have above basic overall digital skills (I)
		Finance and support	2.1.1 R&D expenditure in the public sector (I)
			2.1.2 Venture capital expenditures (I)
			2.1.3 Direct government funding and government tax support for business R&D (I)
		Firm investments	2.2.1 R&D expenditure in the business sector (I)
			2.2.2 Non-R&D innovation expenditures (I)
			2.2.3 Innovation expenditures per person employed (I)
		Use of information technologies	2.3.1 Enterprises providing training to develop or upgrade ICT skills of their personnel (I)
			2.3.2 Employed ICT specialists (I)
			3.2.1 Innovative SMEs collaborating with others (I)
		Linkages	3.2.2 Public-private co-publications (I)
			3.2.3 Job-to-job mobility of Human Resources in Science & Technology (I)
	Output	Innovators	3.1.1 SMEs with product innovations (O)
			3.1.2 SMEs with business process innovations (O)
		Intellectual assets	3.3.1 PCT patent applications (O)
			3.3.2 Trademark applications (O)
			3.3.3 Design applications (O)
		Employment impacts	4.1.1 Employment in knowledge-intensive activities (O)
			4.1.2 Employment in innovative enterprises (O)
		Sales impacts	4.2.1 Medium and high-tech product exports (O)
			4.2.2 Knowledge-intensive services exports (O)
			4.2.3 Sales of new-to-market and new-to-enterprise innovations (O)
		Environmental sustainability	4.3.1 Resource productivity (O)
			4.3.2 Air emissions in fine particulates (PM2.5) in Industry (O)
			4.3.3 Development of environment-related technologies (O)

Source: own elaboration based on European Union (2021).

rationale for the classification of the EIS indicators as inputs or outputs — grouped as pillars and denoted respectively by (I) and (O) in Table 2. The classification criterion is the following (Ibid, p.199):

- "Innovation inputs: variables referring to the resources (human, material and financial; private as well as governmental) used not only to create innovations but also to bring them to the market.
- Innovation outputs: variables referring to new products and processes, new designs and community trademarks, as well as marketing and organizational innovations, which are connected to the market, and which can either be new to the world, the industry and/or to the firm".

While Edquist et al. (2018) consider a baseline model consisting of a subset of inputs and outputs, we enhance their analysis by including all available EIS indicators, which allows us to capture other factors contributing to innovation (e.g., inputs such as population with tertiary education, or new doctorate graduates), and additional variables measuring the impact of innovation on the economy as a whole (e.g., outputs such as employment in knowledge-intensive activities, or medium and high-tech product exports). With it, we aim to avoid the potential selection bias and allow for the comparability of our results with those of the SII index and the ranking of countries it provides.

As already argued, we depart from the underlying idea developed by Acs et al. (2014), and extend it methodologically to measure productivity in the context of innovation systems. The main contribution of their methodology lies in the introduction of a penalty for bottleneck (see Tarabusi and Palazzi, 2004). They define a bottleneck "as the weakest link or the binding constraint" in the system, being this "represented by the lowest value within a given set of normalized index components" (Acs et al., 2014, p. 483). Accordingly, if a bottleneck is alleviated, the function and pillar it belongs to, and ultimately the entire index would show a significant improvement. Acs et al. (2014) consider all indicators as outputs when calculating the "Global Entrepreneurship and Development Index" (GEDI), defined through their arithmetic mean.[3] We extend their notion of bottleneck to the output and input components of innovation systems. From an output perspective, the weakest link corresponds to the output with the lowest value, which is holding back the production of innovation from a productivity perspective (i.e., by reducing the numerator of the PII). From the input perspective, the weakest link corresponds to the input with the highest value, signaling an excessive consumption of resources from a productivity perspective (i.e., by increasing the denominator of the PII).

The value of the PII is calculated by dividing the arithmetic average of the output indicators by the arithmetic mean of the input indicators. It has therefore to be noted that the paper does not estimate the PII based on efficiency methodologies such as DEA (as already done in the literature – see Section 2) but rather introduces a new methodology that allows capturing the bottlenecks that constrain the overall PII, either from the input or output sides. These averages can be directly calculated from the individual indicators, or by calculating the average of the indicators at the function levels as an intermediate step. These provide aggregate values of the different output and input functions, which can be compared across countries, as we illustrate in the results section (see

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[3] The functional form of the GEDI mirrors that of the SII of the EIS, by calculating the arithmetic mean of all indicators, without differentiating between their input or output function. The way the indicators are penalized due to the existence of bottlenecks (i.e., considering their gap with the indicator with the lowest value) implies that they are treated as outputs under the 'more-the-better' logic of the linear model of innovation (e.g., ruling out decreasing returns to scale, as evidenced by Barbero et al., 2021). In these approaches, ignoring that some indicators are inputs mischaracterizes the innovation system and its performance, since increasing them is seen as a positive outcome per se, disregarding their effect on the indicators classified as outputs.

Section 4). Our analysis evidences how the existence of country-specific input and output bottlenecks hampers the performance of the innovation system by holding back potential productivity gains. We do so by comparing the values of the PIIs constrained by the bottlenecks with those that would be observed when these constrains are alleviated, resulting in increased productivity, in three different scenarios: (i) application of a 10 % alleviation to the input bottleneck; (ii) application of a 10 % alleviation to the output bottleneck; and (iii) application of a 5 % alleviation to both the input and output bottlenecks, respectively (see Table 5). With these three bottleneck alleviation strategies we aim to evidence how the performance of innovation systems (i.e., measured through the PII) increases when these bottlenecks are addressed by specific policies.

The EIS adjusts the values of the ι_{ij}^t, $j = 1, …, 32$, indicators observed in country i and time t using the max-min normalization, implying that the normalized values belong to the range $\iota_{ij}^t \in [0, \ 1]$. To rightly characterize the productivity of innovation systems in terms of the resources used by the system (I) and the production achieved (O), we adapt our notation to the classification presented in Table 2, which identifies the input and output subsets of the ι_{li}^t indicators. We denote innovation output indicators of country i in period t by $y_i^t = (y_{i1}^t, …, y_{im}^t, ….. y_{iM}^t) \in \mathbb{R}_+^M$, while the innovation outputs indicators are represented by the vector $x_i^t = (x_{i1}^t, …, x_{in}^t, ….. x_{iN}^t) \in \mathbb{R}_+^N$ – the dimensions being $M = 13$ and $N = 19$. Then, following Edquist et al. (2018), we adopt the PII_i^t, calculated as the ratio of aggregate output Y_i^t to aggregate input X_i^t, using the arithmetic average as aggregating function; i.e.,[4]

$$PII_i^t = \frac{Y_i^t}{X_i^t} = \frac{\sum_{m=1}^M \mu_m y_{im}^t}{\sum_{n=1}^N \nu_n x_{in}^t}, \quad \mu_m = 1 \Big/ M, \quad \nu_n = 1 \Big/ N, \quad i = 1, …, I. \quad (1)$$

Following the methodology outlined by Acs et al. (2014), the PII for all countries is calculated according to the following algorithm, which consists of 4 steps[5]:

1. **Harmonization of the output and input pillars: Equalizing the pillar averages**. The different averages of the normalized values of the indicators across countries belonging to either the output or input dimensions, y_{im}^t and x_{in}^t, imply that reaching the same indicator values across countries may require different efforts and resources. For example, higher average values for some outputs, e.g., 'Innovators' (indicators 3.1.1 or 3.1.2 in Table 2), may be harder to

achieve if compared to other outputs with lower average value – e.g., 'Intellectual assets' (indicators 3.3.1, 3.3.2 or 3.3.3). This is relevant in the evaluation of the effects of alleviating bottlenecks, since the proposed quantitative change (improvement) in the values of the weakest output or input indicators is the same for all indicators and countries. To place all indicators on equal footing, and following Acs et al. (2014), we calculate the average of each output and input indicator:

$$\bar{y}_m^t = \sum_{i=1}^I y_{im}^t \Big/ I, \quad \text{for } m = 1, …, \ M, \quad \bar{x}_n^t = \sum_{i=1}^I x_{in}^t \Big/ I, \quad \text{for } n = 1, …, \ N. \quad (2)$$

and, subsequently, transform (rescale) the value of the indicators in such way that the average of all M outputs indicators across countries are equalized among themselves, and equivalently for the N input indicators—see also Szerb et al. (2013, p. 42). That is, the reference means are calculated as $\bar{y}^t = \sum_{m=1}^M \bar{y}_m^t / M$ for the output indicators and $\bar{x}^t = \sum_{n=1}^N \bar{x}_m^t / N$ for the input indicators. To achieve this result the following exponential function is applied to the indicators—keeping the potential values in the [0,1] range:

$$\tilde{y}_{im}^t = (y_{im}^t)^{k_m}, \quad m = 1, …, \ M, \quad \tilde{x}_{in}^t = (x_{in}^t)^{k_n}, \quad n = 1, …, \ N, \quad (3)$$

where k_m and k_n represent the "strength of adjustment" for each m output and n input, respectively. These authors determine that the k-th moments of y_m^t and x_n^t are exactly the needed averages: $\bar{y}^t$ and $\bar{x}^t$. Therefore, it is possible to determine the k-th values by finding the roots of the following set of equations:

$$\left(\sum_{i=1}^I (y_{ir}^t)^{k_r} \Big/ I \right) - \ \bar{y}^t = \sum_{i=1}^I (y_{ir}^t)^{k_r} - I \ \bar{y}^t = \ 0,$$
$$\left(\sum_{i=1}^I (x_{ir}^t)^{k_r} \Big/ I \right) - \bar{x}^t = \sum_{i=1}^I (x_{ir}^t)^{k_r} - I \ \bar{x}^t = \ 0, \quad (4)$$

where the last equalities mirror Eq. (5) in Acs et al. (2014, p.486). Since these functions are decreasing and convex, they can be solved by the Newton-Raphson method. After recovering the output and input k values, these are substituted in Eq. (3) to calculate the transformed values $\tilde{y}_{im}^t$ and $\tilde{x}_{in}^t$.[6]

2. **Penalization due to output deficits and input excesses:** After these transformations, the Penalty for Bottleneck (PFB) methodology is used to create the indicator-adjusted PFB values. Following Acs et al. (2014) the penalty function for output indicators is defined as:

$$\widehat{\tilde{y}}_{im}^t = min(\tilde{y}_{im}^t) + \left(1 - e^{-\left(\tilde{y}_{im}^t - min(\tilde{y}_{im}^t) \right)} \right), \quad i = 1, …, I, \quad m = 1, …, M, \quad (5)$$

where $\widehat{\tilde{y}}_{im}^t$ is the modified, post-penalty value of output indicator m in country i, that is $\tilde{y}_{im}^t$, which is in itself the transformed value—according to Eq. (3)—of the normalized indicator m in country i, and $min(\tilde{y}_{im}^t)$ is the lowest value of all m output indicators in country i. Based on Eq. (5), any output indicator greater than the minimum value is penalized by the existence of the bottleneck (deficit of production in that output dimension), i.e., $\widehat{\tilde{y}}_{im}^t < \tilde{y}_{im}^t$, and the greater the disparity the greater the

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[4] It would be possible to assign different weights to the input and output indicators using alternative aggregating functions. Edquist et al. (2018) rely on linear programming techniques such as DEA that search for the most favorable weights (μ_m^t, ν_n^t) that result in the maximum feasible productivity level of (x_i^t, y_i^t) relative to that of the remaining innovation systems. Corrente et al. (2021) rely on a multiple-criteria decision-making approach being the conjunction of three methodologies, namely, the multiple-criteria hierarchy process, the Choquet integral and the stochastic multicriteria acceptability analysis (MCHP-Ch-SMAA). These could be useful to incorporate the preferences of a panel of experts, which could be composed of individuals from the university (academics), industry (managers) and government (officials).

[5] Acs et al. (2014) include two previous steps dealing with the treatment of outliers (capping) and the normalization of the variables, so their values range from 0 to 1 (normalization). These two steps are unnecessary for us since the EIS follows a thorough statistical process ensuring the reliability of published country data and, as aforementioned, normalizes the values using the max-min approach. Billaut et al. (2010, p. 251) discuss relevant methodological issues related to the aggregation of normalized indicators. In particular, the normalization approach proposed by Acs et al. (2014) may be prone to several methodological flaws when performing intertemporal comparisons using data from different years (in case the maximum and minimum values used for normalization are updated).

[6] As remarked by Acs et al. (2014, p. 486) the strength (and direction) of the output adjustment parameter k_m is the following: $k_m < 1$ if $\bar{y}_m^t < \tilde{y}_m^t = \bar{y}^t$; $k_m = 1$ if $\bar{y}_m^t = \tilde{y}_m^t = \bar{y}^t$; $k_m > 1$ if $\bar{y}_m^t > \tilde{y}_m^t = \bar{y}^t$ - and equivalently for the k_n input adjustment factors.

penalization.[7]

The Penalty for Bottleneck (PFB) for the inputs follows equal rationale, but since the bottleneck is associated to the largest input value, the modified, post-penalty values of the remaining inputs are increased. Hence, the inverse function of (5) is considered:

$$\widehat{\widehat{x}}_{in}^{t} = max\left(\widetilde{x}_{in}^{t}\right) - \left(1 - e^{-\left(max\left(\widetilde{x}_{in}^{t}\right) - \widetilde{x}_{in}^{t}\right)}\right), \quad i = 1, ..., I, \quad m = 1, ..., N. \quad (6)$$

Now, any input indicator smaller than the maximum value is penalized by the existence of the bottleneck (excessive resource consumption in that input dimension), i.e. $\widehat{\widehat{x}}_{in}^{t} > \widetilde{x}_{in}^{t}$, and, once again, the greater the disparity the greater the penalization.[8]

As discussed by Acs et al. (2014, p. 484), thanks to the penalizing method, "improving the score of the weakest index component will have a greater effect on the index than will the act of improving the score of stronger index components". This reasoning is equally valid regardless the output or input dimensions, when extended to our context evaluating innovation performance through the PII.

3. **Aggregation of the output and input pillars:** As shown in Table 2, the EIS is structured into 12 functions, out of which 5 are categorized as outputs and 7 as inputs. The aggregate output and input values for any country are calculated as the arithmetic average of the PFB-adjusted indicators by output and input functions, which is equivalent to the arithmetic average of the individual indicators, i.e.,

$$Outputs: \quad \widehat{\widehat{Y}}_{i}^{t} = \sum_{m=1} \widehat{\widehat{y}}_{im}^{t} \bigg/ M, \quad i = 1, ..., I, \quad (7)$$

$$Inputs: \quad \widehat{\widehat{X}}_{i}^{t} = \sum_{n=1}^{N} \widehat{\widehat{x}}_{in}^{t} \bigg/ N, \quad i = 1, ..., I. \quad (8)$$

where $\widehat{\widehat{Y}}_{i}^{t}$ is the aggregate composite of the modified, post-penalty values of the $m = 1, ..., 13$ output indicators $\widehat{\widehat{y}}_{im}^{t}$. Likewise, $\widehat{\widehat{X}}_{i}^{t}$ is the aggregate composite of the modified, post-penalty values of the $n = 1, ..., 19$ input indicators $\widehat{\widehat{x}}_{in}^{t}$.

4. **Calculation of the Productivity Innovation Index:** Mirroring Eq. (1) the PII is calculated as the ratio of the penalized output aggregate to the penalized input aggregate, i.e., once they have been adjusted for the PFB. From this perspective, the productivity of the innovation systems is determined through the following PII[9]:

$$\widehat{\widehat{PII}}_{i}^{t} = \frac{\widehat{\widehat{Y}}_{i}^{t}}{\widehat{\widehat{X}}_{i}^{t}} = \frac{\sum_{m=1} \widehat{\widehat{y}}_{im}^{t} \bigg/ M}{\sum_{n=1}^{N} \widehat{\widehat{x}}_{in}^{t} \bigg/ N}, \quad i = 1, ..., I. \quad (9)$$

It is easy to prove that the penalized $\widehat{\widehat{PII}}_{i}^{t}$ cannot be greater than the unpenalized PII_{i}^{t} defined in Eq. (1), i.e., $\widehat{\widehat{PII}}_{i}^{t} \leq PII_{i}^{t}$—since $\widehat{\widehat{Y}}_{i}^{t} \leq Y_{i}^{t}$ and $\widehat{\widehat{X}}_{i}^{t} \geq X_{i}^{t}$. Consequently, we can calculate the percentage productivity loss due to the constraints imposed on the system by the output and input bottlenecks:

$$Loss\ PII_{i}^{t} = \left(\frac{\widehat{\widehat{PII}}_{i}^{t}}{PII_{i}^{t}} - 1\right) \times 100, \quad i = 1, ..., I. \quad (10)$$

This methodology represents a response to the request made by Paruolo et al. (2013) as to the need to develop statical methodologies that model the relationship between a particular variable and the composite index characterizing the performance of a particular decision-making unit.

4. Results

This section is structured into three parts. First, we identify the input and output bottlenecks that constrain the performance of all the innovation systems considered in the paper. Second, we report the productivity loss due to the existence of these bottlenecks. Third, we evidence the responsiveness of the PII to bottleneck alleviation, from three different perspectives: (i) application of a 10 % alleviation to the input bottleneck; (ii) application of a 10 % alleviation to the output bottleneck; and (iii) application of a 5 % alleviation to both the input and output bottlenecks, respectively.

4.1. Systemic input and output bottlenecks

This section reports the extent to which the PII would represent cases of innovation systems with an unbalanced structure due to the existence of bottlenecks that hamper the overall productivity of the system. The PFB introduced by Tarabusi and Palazzi (2004) helps identify the weakest function of an innovation system, thereby providing a direct insight to policymakers, "because this is where policy effort should produce the greatest system-level improvement" (Acs et al., 2014, p. 487). These conclusions are thus fundamental to feed policy, as they provide direct directionality to policymakers. Table 3 highlights the input and output bottlenecks by country.[10]

Our results indicate that the main input bottlenecks constraining innovation productivity in Europe are 2.1.3. Direct government funding and government tax support for business R&D (observed in 6 countries), 1.3.1. Broadband penetration (5 countries), 2.1.2. Venture capital expenditures (4 countries), 2.2.2. Non-R&D innovation expenditures (4 countries), 2.2.3. Innovation expenditures per person employed (4 countries), and 3.2.1. Innovative SMEs collaborating with others (4 countries). In turn, the main output bottlenecks correspond to 3.1.2. SMEs with business process innovations (6 countries), 4.2.2. Knowledge-intensive services exports (6 countries), 4.2.3. Sales of new-to-market and new-to-enterprise innovations (3 countries), 4.3.2. Air emissions in fine particulates in industry (3 countries), and 4.3.3. Development of environment-related technologies (3 countries).

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[7] As Acs et al. (2014, p. 484) argue, "the largest potential difference between two index values is 1 (i.e. since all indicators are normalized between 0 and 1), when a particular country exhibits the highest value for one index component (across all countries) and the lowest value for another index component, again across all countries. In this case, the maximum penalty is 0.37. It also means that the best indicator performance just compensates for the bad performance of the worst indicator by only 63 %".

[8] Again, if a country presents the highest and lowest values across the input dimension, i.e., 1 and 0, the maximum penalty for the null input is 0.37, increasing its value by this magnitude, i.e., it can only compensate for the worst input indicator by 63 %.

[9] It is possible to express Eq. (9) in terms of the original output and input values by calculating the set of weights that would yield this result. Specifically, let us define the output and input weights as $\widehat{\widehat{\mu}}_{im} = \left(\widehat{\widehat{y}}_{im}^{t} / y_{im}^{t}\right) / M, \quad m = 1, ..., M, \quad i = 1, ..., I$ and $\widehat{\widehat{\nu}}_{in} = \left(\widehat{\widehat{x}}_{in}^{t} / x_{in}^{t}\right) / N, \quad n = 1, ..., N, \quad i = 1, ..., I$, respectively. Then, $\widehat{\widehat{PII}}_{i}^{t} = \frac{\sum_{m=1}^{M} \widehat{\widehat{\mu}}_{im} y_{im}^{t}}{\sum_{n=1}^{N} \widehat{\widehat{\nu}}_{in} x_{in}^{t}}, \quad i = 1, ..., I$. Consequently, applying the penalty for bottlenecks approach is equivalent to calculate expression (1) with a set of input and output penalizing weights consistent with this methodology. These calculations are available from the authors upon request.

[10] Please note that the numbers included in Table 3 are those representing each individual indicator, as shown in Table 2.

Table 3
Systemic input and output bottlenecks by country - indicators with the lowest value (output) and highest value (inputs).

Country	Input bottlenecks					Output bottlenecks	
Belgium	2.2.3					4.3.3	
Bulgaria	2.2.2					3.1.2	
Czech Republic	2.2.2					3.3.1	
Denmark	1.3.1	2.1.1				4.2.3	
Germany	2.2.3					3.3.2	
Estonia	3.2.1					4.3.2	
Ireland	2.2.3					4.3.3	
Greece	3.2.1					4.2.1	
Spain	1.3.1					3.1.1	
France	2.1.3					3.3.2	
Croatia	2.2.2					4.2.2	
Italy	2.1.3					4.2.2	
Cyprus	1.1.2	2.1.2	3.2.1			4.3.3	
Latvia	1.1.2					4.3.2	
Lithuania	1.1.2					4.2.2	
Luxembourg	1.2.3	2.1.2				4.2.3	
Hungary	2.1.3					3.1.2	
Malta	2.3.1					4.2.2	
the Netherlands	1.2.2					4.2.3	
Austria	2.2.1					4.2.2	
Poland	2.1.3					3.1.2	
Portugal	1.3.1					4.3.2	
Romania	1.3.1					3.1.2	4.1.2
Slovenia	2.1.3					4.2.2	
Slovakia	2.2.2					3.1.2	
Finland	1.1.3	2.1.2	2.3.1	2.3.2	3.2.1	4.3.1	
Sweden	1.1.3	1.3.1	2.2.1	2.2.3	2.3.2	4.3.1	
United Kingdom	1.1.1	2.1.2	2.1.3			3.1.2	

Source: own elaboration.

4.2. Productivity loss due to the systemic bottlenecks

We report in Table 4 the values of the productivity losses observed in all countries due to the existence of the previous bottlenecks. This productivity loss is calculated through the comparison between the penalized (constrained) $\widehat{\widehat{PII}}$ and the corresponding PII without applying the PFB, see Eq. (10).

It is worth observing how the $\widehat{\widehat{PII}}$ of all European countries is significantly affected by the existence of the bottlenecks. As a matter of fact, the productivity loss ranges between −11.43 % in the case of the Netherlands and −43.29 % in Cyprus. This evidences how the input and output bottlenecks have a direct impact on the performance of innovation systems. The three countries which suffer the biggest productivity losses due to these bottlenecks are Cyprus (−43.29 %), Romania (−38.87 %) and Hungary (−38.87 %). On the other side, the Netherlands (−11.43 %), Belgium (−12.46 %) and the Czech Republic (−13.29 %) would be the countries whose innovation systems are less harmed by productivity losses. Our results highlight how the official rankings provided by the EIS cannot be effective for defining long-term innovation policies, as they do not capture which are the factors that constrain innovation systems' performance. The existence of bottlenecks holds back innovation systems' productivity, and hence, in the absence of PFBs, the conclusions that may be drawn from the analysis of the productivity of innovation systems would be biased, as it would be 'inflated' as compared to the real productivity once the effect of these bottlenecks are taken into consideration, as shown in Table 4.

In terms of the ranking, Bulgaria leads the countries with the highest levels of productivity in both scenarios (i.e., unpenalized and penalized). In turn, Portugal and the United Kingdom would be the countries with the lowest PIIs. A set of countries keep the same relative position in the ranking derived from the PII without and with the penalty (i.e., Bulgaria, Luxembourg, Poland). Other set of countries do substantially change their relative positions when the rankings derived from the unpenalized and penalized PIIs are compared. For example, Cyprus, Lithuania and

Hungary improve their relative positions when the rankings of the unpenalized and penalized PII are compared. On the contrary, the Netherlands, Belgium, Finland and Sweden worsen their relative positions when the unpenalized PII is compared with the penalized PII. However, in spite of these exceptions, most countries keep their relative positions stable in both rankings. We thus contend that focusing only on the information provided by the ranking may lead to wrongly conclude that the (input and output) bottlenecks associated to innovation systems do not alter their relative performance. However, as Table 4 shows, the information provided by the PII is irrefutable as to the economic impact of bottlenecks on the performance of innovation systems. Hence, in line with Grupp and Mogee (2004), Paruolo et al. (2013), or Schibany and Streicher (2008) among others, we contend that instead of emphasizing the positions that certain territorial units occupy in rankings (as done by most innovation scoreboards and indices), more attention should be devoted to the information contained in the synthetic indices that lead to such rankings, as only these will provide concrete guidelines for the intervention of policymakers.

In Fig. 1 we benchmark the performance of four countries (Denmark, United Kingdom, Portugal and Bulgaria) comparing the values of each of the functions identified by the EIS (see Table 2). This comparison is done in two scenarios: a) when the functions are not penalized using the PFB method (see black line); b) when the functions are subject to the PFB but not to the bottleneck alleviation (see dashed line). The rationale for the selection of these four countries is twofold. On the one hand, each of these countries belongs to one of the four categories introduced by Barbero et al. (2021), so they can be considered as representative of a larger subsample of countries with similar structural settings.[11] Accordingly, Denmark acts as the representative of the countries with High innovation inputs and High innovation performance (HIHP), the United Kingdom is the representative of the countries with High innovation inputs and Low innovation performance (HILP), Portugal characterizes the countries with Low innovation inputs and High innovation performance (LIHP), and Bulgaria would denote the countries with Low innovation inputs and Low innovation performance (LILP). On the other hand, these are the four countries that show the largest productivity gains in any of the three strategies for bottleneck alleviation depicted in Table 5 (see Section 4.3.).

Due to methodology presented in Section 3, and which determines the strength of the PFB to the identified input and output bottlenecks, the values of the input functions increase in all cases from the unpenalized context provided by the EIS data to the penalized context, while the output functions decrease in all cases from the reality delineated by the EIS to the penalized context. As Fig. 1 shows, the value of the PFB is different in each case, as it depends on the number of bottlenecks and the scale of the penalty (see Tables 3 and 4 above).

4.3. Responsiveness of the PII to bottleneck alleviation

Table 5 shows the responsiveness of the PII to bottleneck alleviation for all the 28 countries considered in the paper. The different bottleneck alleviation strategies used in this section aim at illustrating how the reallocation of resources (inputs) and production (outputs) helps to

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[11] Barbero et al. (2021) study the existence of decreasing returns to scale in innovation activities and propose a classification of countries' performance in terms of innovation performance and inputs' scale (size) in the following categories (Ibid., p. 11): (i) High innovation inputs and high innovation performance (HIHP) - France, Netherlands, Denmark, Germany, Austria; (ii) High innovation inputs and low innovation performance (HILP) - Sweden, Finland, Switzerland, Estonia, Belgium, Iceland, Czech Republic, Ireland, United Kingdom, Norway, Slovenia; (iii) Low innovation inputs and high innovation performance (LIHP) - Portugal, Luxembourg, Spain, Cyprus, Slovakia, Italy, Malta, Greece; and (iv) Low innovation inputs and low innovation performance (LILP) - Lithuania, Poland, Croatia, Hungary, Bulgaria, Romania, Latvia.

Table 4
Productivity Innovation Index without and with penalty for bottleneck.

| Country	Averaged inputs Unpenalized	Averaged outputs Unpenalized	PII Unpenalized	Average inputs Penalized	Average outputs Penalized	$\widehat{PII}$ penalized	% change
Belgium	0.695	0.635	0.913	0.747	0.597	0.799	−12.46 %
Bulgaria	0.157	0.320	2.036	0.179	0.261	1.461	−28.24 %
Czech Republic	0.413	0.489	1.182	0.452	0.463	1.025	−13.29 %
Denmark	0.730	0.642	0.879	0.779	0.455	0.584	−33.55 %
Germany	0.578	0.754	1.304	0.672	0.716	1.066	−18.24 %
Estonia	0.606	0.598	0.987	0.691	0.442	0.639	−35.22 %
Ireland	0.604	0.545	0.902	0.670	0.468	0.698	−22.60 %
Greece	0.337	0.514	1.528	0.417	0.404	0.968	−36.60 %
Spain	0.493	0.399	0.809	0.585	0.336	0.574	−29.10 %
France	0.576	0.542	0.942	0.669	0.502	0.751	−20.25 %
Croatia	0.332	0.385	1.160	0.385	0.322	0.836	−27.94 %
Italy	0.410	0.641	1.562	0.503	0.602	1.198	−23.29 %
Cyprus	0.495	0.511	1.031	0.633	0.370	0.585	−43.29 %
Latvia	0.254	0.266	1.047	0.290	0.226	0.777	−25.74 %
Lithuania	0.437	0.435	0.997	0.557	0.349	0.627	−37.13 %
Luxembourg	0.653	0.621	0.952	0.725	0.544	0.751	−21.10 %
Hungary	0.359	0.356	0.993	0.481	0.292	0.607	−38.87 %
Malta	0.393	0.607	1.544	0.448	0.518	1.156	−25.12 %
the Netherlands	0.682	0.599	0.877	0.720	0.559	0.777	−11.43 %
Austria	0.593	0.665	1.123	0.658	0.616	0.937	−16.54 %
Poland	0.315	0.288	0.914	0.351	0.240	0.683	−25.24 %
Portugal	0.491	0.350	0.713	0.612	0.288	0.471	−33.86 %
Romania	0.127	0.204	1.603	0.176	0.172	0.980	−38.87 %
Slovenia	0.449	0.487	1.085	0.498	0.449	0.901	−16.94 %
Slovakia	0.292	0.393	1.345	0.338	0.321	0.949	−29.42 %
Finland	0.768	0.620	0.808	0.809	0.536	0.663	−17.92 %
Sweden	0.769	0.683	0.888	0.808	0.619	0.766	−13.76 %
United Kingdom	0.731	0.505	0.691	0.778	0.389	0.500	−27.70 %

Source: own elaboration.

increase the performance of innovation systems, offering a specific directionality to innovation policies for each country. Table 5 is structured into 4 blocks, each showing:

(1) the baseline model. It shows the differences between the PII before and after the application of the PFB.[12]

(2) the effect of alleviating only the input bottleneck by 10 %. This strategy reassigns 10 % (0.1 in absolute value) of the input with the maximum value to the input with the minimum value.

(3) the effect of alleviating only the output bottleneck by 10 %. This strategy increases the output with the minimum value with 10 % (0.1 in absolute value) by reallocating 10 % (0.1 in absolute value) of the output with the highest value.

(4) the effect of alleviating both the input and output bottlenecks by 5 % each. This strategy reassigns 5 % (0.05 in absolute value) of the input with the highest value to that with the lowest value, and 5 % (0.05 in absolute value) of the output with the highest value to that with the lowest value.

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[12] Please note how the baseline model is exactly the same as that reported in Table 4, but without repeating the information for the inputs and the outputs.
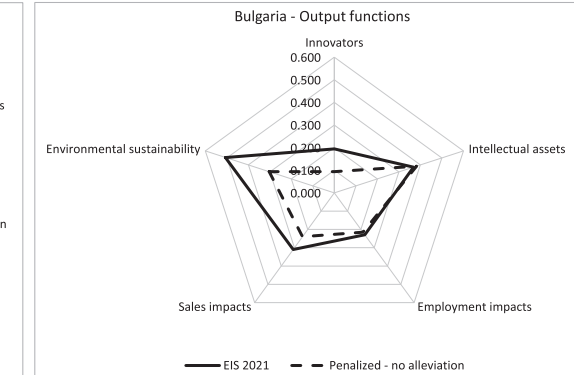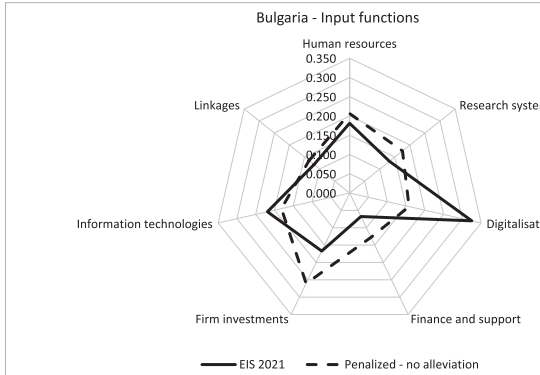
a.- Denmark
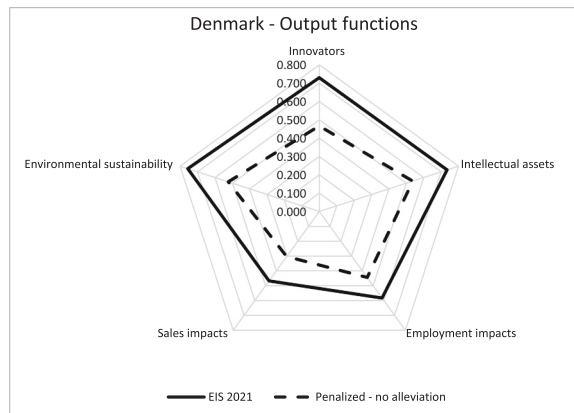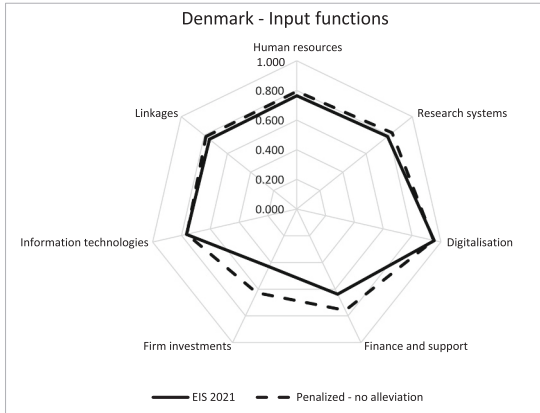
b.- United Kingdom
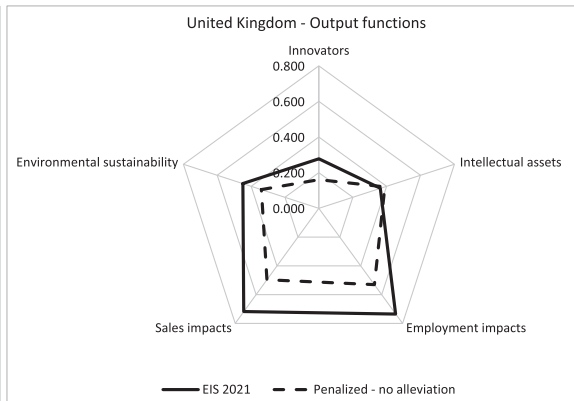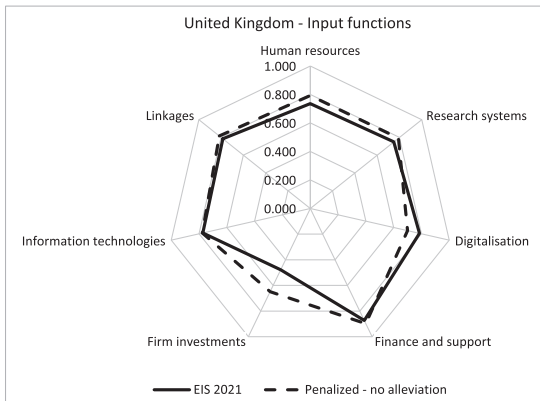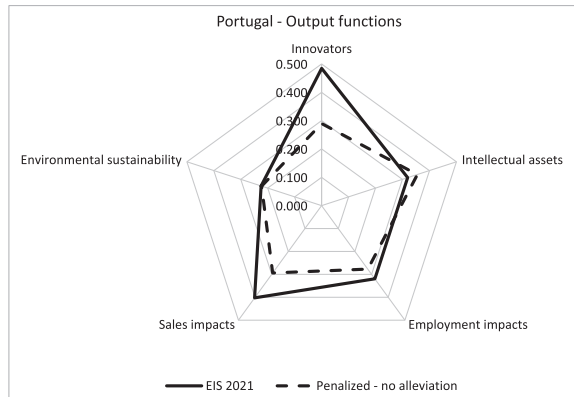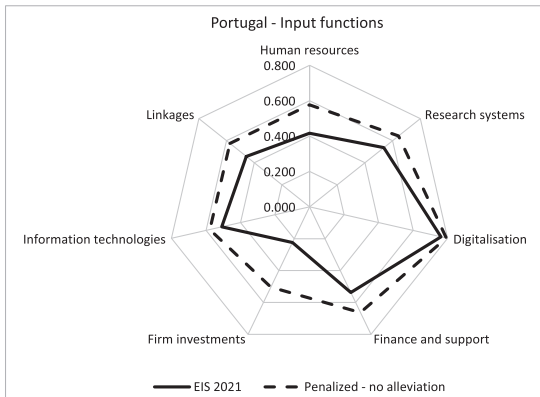

c.- Bulgaria

d.- Portugal

Fig. 1. Differences in the input and output functions of innovation systems: penalized and non-penalized values.
Source: own elaboration.

In each block we provide the values of the inputs and the outputs after the application of the corresponding penalty and alleviation, the values of the resulting PII, and the % change between the penalized $\widehat{\widehat{PII}}$ according to the respective bottleneck alleviation strategy and the $\widehat{\widehat{PII}}$ with the penalty in the baseline model. We also highlight in bold the strategy that would help to maximize the improvement in the PII in each country, namely: an input-oriented strategy by which the input bottleneck should be alleviated, an output-oriented strategy by which the output bottleneck should be alleviated, or a mixed strategy by which both the input and output bottlenecks should be alleviated in the same proportion.

Alleviating the input bottlenecks would bring on average an improvement of productivity of 3.75 % to European countries. In turn, alleviating the output bottlenecks would increase the PII by 5.31 %. Finally, considering both input and output bottlenecks produces the largest returns in terms of productivity gains, as it leads, on average to an increase of 5.66 % in the PII.

However, the strategy of contemporaneously alleviating the input and output bottlenecks is not the most effective strategy in all countries. As Table 5 shows, some countries achieve their largest improvements in the PII when an input strategy is achieved. This is the case of Germany, Spain, Italy and Slovakia, for whom alleviating the inputs is the most sensible strategy to follow in the short term, as it would lead their innovation systems to increase their productivity by 4.27 %, 5.91 %, 7.01 % and 7.44 %, respectively. For another set of countries, adopting a strategy of alleviating the outputs would produce the largest increase in terms of productivity. This is the case of Denmark (10.42 %), Estonia (8.18 %), Ireland (6.10 %), Croatia (8.45 %), Latvia (9.36 %), Lithuania (9.25 %), Luxembourg (4.96 %), the Netherlands (1.11 %), Austria (3.67 %), Portugal (9.72 %), Finland (6.08 %), Sweden (4.59 %) and the United Kingdom (9.78 %). Finally, countries like Belgium (3.35 %), Bulgaria (9.97 %), Czech Republic (2.19 %), Greece (8.57 %), France (4.45 %), Cyprus (5.34 %), Hungary (9.61 %), Malta (6.28 %), Poland (5.50 %), Romania (7.63 %) and Slovenia (5.22 %) would need to adopt both an input and output alleviation strategy to achieve the largest improvements in terms of productivity.

In Fig. 2 we evidence the differences of the four countries considered in Section 4.2. (i.e., Denmark, United Kingdom, Portugal and Bulgaria) in terms of their bottleneck alleviation strategy, to graphically illustrate why an input, output, or a mixed strategy is the most effective one to adopt in the short term. Fig. 2 depicts, for each of these four countries, the input and output combinations that would emerge from each of the three bottleneck alleviation strategies discussed above, and compare them with the input and output combinations that emerge from the context in which the penalty is applied to the PII, but without any bottleneck.[13] As it can be observed, the circle (application of the PFB but without any alleviation) represents in all cases the lowest productivity of all alternatives, i.e., the line with the lowest slope.[14] The line highlighted in bold in each case (i.e. the line with the largest slope) is the one that determines the bottleneck alleviation strategy that provides the largest productivity gains to each country.

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[13] Due to space constrains, and because of the large number of tables and figures that would be needed to report the results for all European countries when these are subject to the three different bottleneck alleviation strategies, these are not included in the paper, but are available upon request.

[14] Please note that given the definition of productivity, understood as a ratio of the aggregate innovation output to aggregate innovation input, the PII can be graphically estimated as the slope of the lines from the origin to each of the vertices of the symbols representing the input-output combination of each bottleneck alleviation strategy.

5. Conclusions and discussion

This paper contributes to the literature with a methodology that allows identifying and measuring the impact of bottlenecks on innovation systems. In line with Freeman and Soete (2009) our purpose with this research is to continue devoting attention to the development of composite (innovation) indicators, keeping an open and critical mind with the aim of improving their reliability, and in particular, their potential to feed (innovation) policy (Proksch et al., 2017).

The application of the methodology followed in this study, originally developed by Acs et al. (2014), and which we have further developed here, helps to accomplish one of the main goals of the European Innovation Scoreboard, namely, to assist policymakers "by permitting a comparison of the relative success or failure of the innovation system, or through the identification of specific aspects of the innovation system which perform well or poorly" (Arundel and Hollanders, 2008, p. 30). As Mahroum and Al-Saleh (2013, p. 321) discuss, "innovation policy necessitates the development of measurement tools that assist governments in both developing, and evaluating the effectiveness of, policy interventions".

Our results evidence that all countries in Europe can improve their innovation performance by alleviating those (input and output) bottlenecks that constrain the performance of their respective systems. This a novel contribution to the literature, since, as argued above, the penalty for bottleneck approach has never been applied to the context of innovation systems before. The methodology also brings new value-added to policymakers, as it identifies the bottlenecks that constrain innovation performance, and hence, those areas that would require policy intervention.

The main goal of the methodology is to identify existing input and output bottlenecks that handicap the performance of the system as a whole, thereby providing directionality to policymakers (i.e., the failures that should be targeted primarily by innovation policy). In addition, the logic of the method introduced in the paper goes against 'the-more-the-better' logics by relying on the notion of productivity to evaluate the performance of innovation systems. By differentiating between inputs and outputs, aiming at increasing the resources to the system may not be desirable per se, since we should consider how inputs are transformed into outputs, while not taking for granted that returns to investments always exist. Accordingly, the overall performance of a system would be directly dependent on the performance of the weakest link, but not on that of the remaining functions, as they would be saturated (i.e., no matter how much these saturated parts of the system are improved, the system will still be held back by its weakest function). Moreover, our simulations (i.e., applying several bottleneck alleviation strategies) reallocate resources devoted to produce outputs that are saturated by exhibiting the highest values, to other outputs whose production is the lowest, constituting a bottleneck of the system. Equivalently, saturated inputs, which would represent those that are used in excess, are reallocated to other input functions whose quantities are the lowest in relative terms and which lead to higher marginal productivities.

The main limitation of the method lies in that it is not able to discriminate the pertinence (or not) of the indicators for measuring innovation in every country. The assumptions behind the composite indices being used at present are that all the indicators that are considered in the EIS are somehow relevant for the overall innovation performance of all European countries, and that each indicator enters the index with the same weight for all territories, and hence, the relative relevance of each indicator is equal across all territories. However, it might also be the case that, intendedly, a country decides not to invest any resources into a specific policy, or decides to specialize into the production of a specific type of innovation. In these cases, missing or a shortage of funding/outputs would be interpreted as a bottleneck for the system, while this might be just a response to a rational political decision. We therefore believe that a potential avenue for further research might be the use of 'supervised' models that define ex-ante the weight

Table 5
Responsiveness of the PII to bottleneck alleviation.

Country	Baseline		Input alleviation - reassigns inputs from Maximum to Minimum by 10 %				Output alleviation - reassigns outputs from Maximum to Minimum by 10 %				Mixed alleviation - reassigns inputs and outputs by 5 %			
	PII unpenalized	PII penalized - no alleviation	Inputs alleviated	Outputs penalized	PII alleviated	% change	Inputs penalized	Outputs alleviated	PII alleviated	% change	Inputs alleviated	Outputs alleviated	PII alleviated	% change
	(1)	(2)	(3)	(4)	(5)	(6) = ((5)/(2))-1)*100	(7)	(8)	(9)	(10) = ((9)/(2))-1)*100	(11)	(12)	(13)	(14) = ((13)/(2))-1)*100
Belgium	0.91	0.80	0.73	0.60	0.81	1.77 %	0.75	0.61	0.81	1.91 %	**0.74**	**0.61**	**0.83**	**3.35 %**
Bulgaria	2.04	1.46	0.17	0.26	1.54	5.34 %	0.18	0.28	1.55	6.06 %	**0.17**	**0.27**	**1.61**	**9.97 %**
Czech Republic	1.18	1.03	0.45	0.46	1.04	1.11 %	0.45	0.47	1.04	1.54 %	**0.45**	**0.47**	**1.05**	**2.19 %**
Denmark	0.88	0.58	0.77	0.45	0.59	1.65 %	**0.78**	**0.50**	**0.65**	**10.42 %**	0.77	0.48	0.62	6.27 %
Germany	1.30	1.07	**0.64**	**0.72**	**1.11**	**4.27 %**	0.67	0.72	1.07	0.73 %	0.65	0.72	1.10	3.20 %
Estonia	0.99	0.64	0.68	0.44	0.65	2.05 %	**0.69**	**0.48**	**0.69**	**8.18 %**	0.68	0.46	0.68	6.77 %
Ireland	0.90	0.70	0.66	0.47	0.70	0.93 %	**0.67**	**0.50**	**0.74**	**6.10 %**	0.67	0.48	0.73	4.03 %
Greece	1.53	0.97	0.39	0.40	1.03	6.73 %	0.42	0.44	1.05	8.32 %	**0.40**	**0.42**	**1.05**	**8.57 %**
Spain	0.81	0.57	**0.55**	**0.34**	**0.61**	**5.91 %**	0.59	0.34	0.58	1.64 %	0.57	0.34	0.60	4.31 %
France	0.94	0.75	0.65	0.50	0.77	2.20 %	0.67	0.52	0.78	4.34 %	**0.66**	**0.51**	**0.78**	**4.45 %**
Croatia	1.16	0.84	0.36	0.32	0.89	6.82 %	**0.38**	**0.35**	**0.91**	**8.45 %**	0.37	0.34	0.91	8.28 %
Italy	1.56	1.20	**0.47**	**0.60**	**1.28**	**7.01 %**	0.50	0.61	1.21	0.67 %	0.49	0.60	1.25	4.05 %
Cyprus	1.03	0.58	0.62	0.37	0.60	2.42 %	0.63	0.39	0.61	4.67 %	**0.63**	**0.39**	**0.62**	**5.34 %**
Latvia	1.05	0.78	0.27	0.23	0.83	6.29 %	**0.29**	**0.25**	**0.85**	**9.36 %**	0.28	0.24	0.85	9.30 %
Lithuania	1.00	0.63	0.53	0.35	0.66	5.97 %	**0.56**	**0.38**	**0.68**	**9.25 %**	0.54	0.37	0.68	8.63 %
Luxembourg	0.95	0.75	0.71	0.54	0.76	1.67 %	**0.73**	**0.57**	**0.79**	**4.96 %**	0.72	0.56	0.78	3.80 %
Hungary	0.99	0.61	0.44	0.29	0.66	8.91 %	0.48	0.31	0.64	6.24 %	**0.46**	**0.31**	**0.67**	**9.61 %**
Malta	1.54	1.16	0.43	0.52	1.20	4.14 %	0.45	0.55	1.23	6.26 %	**0.44**	**0.53**	**1.23**	**6.28 %**
the Netherlands	0.88	0.78	0.72	0.56	0.78	0.37 %	**0.72**	**0.57**	**0.79**	**1.11 %**	0.72	0.56	0.79	1.08 %
Austria	1.12	0.94	0.65	0.62	0.95	0.98 %	**0.66**	**0.64**	**0.97**	**3.67 %**	0.65	0.63	0.96	2.92 %
Poland	0.91	0.68	0.34	0.24	0.70	2.72 %	0.35	0.25	0.71	3.54 %	**0.34**	**0.25**	**0.72**	**5.50 %**
Portugal	0.71	0.47	0.57	0.29	0.50	6.70 %	**0.61**	**0.32**	**0.52**	**9.72 %**	0.59	0.30	0.51	8.78 %
Romania	1.60	0.98	0.17	0.17	1.04	5.78 %	0.18	0.18	1.01	3.04 %	**0.17**	**0.18**	**1.05**	**7.63 %**
Slovenia	1.08	0.90	0.48	0.45	0.93	3.18 %	0.50	0.47	0.94	4.70 %	**0.49**	**0.46**	**0.95**	**5.22 %**
Slovakia	1.35	0.95	**0.31**	**0.32**	**1.02**	**7.44 %**	0.34	0.33	0.98	3.26 %	0.32	0.33	1.01	6.68 %
Finland	0.81	0.66	0.80	0.54	0.67	0.75 %	**0.81**	**0.57**	**0.70**	**6.08 %**	0.81	0.55	0.69	3.61 %
Sweden	0.89	0.77	0.80	0.62	0.77	0.76 %	**0.81**	**0.65**	**0.80**	**4.59 %**	0.80	0.63	0.79	2.86 %
United Kingdom	0.69	0.50	0.77	0.39	0.51	1.23 %	**0.78**	**0.43**	**0.55**	**9.78 %**	0.77	0.41	0.53	5.77 %

Source: own elaboration.

a.- Denmark

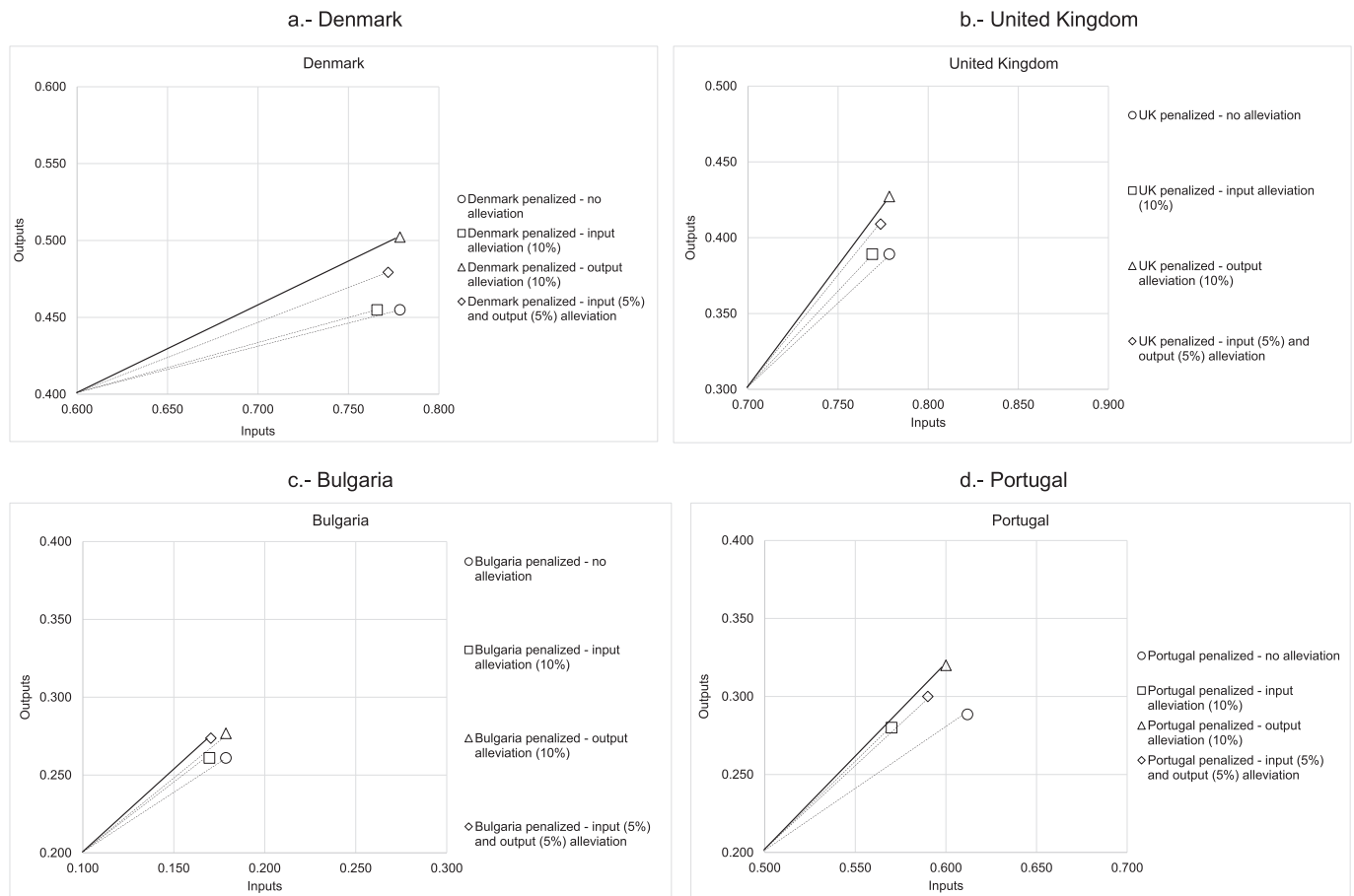## b.- United Kingdom

c.- Bulgaria

d.- Portugal

Fig. 2. Differences in bottleneck alleviation strategy.
Source: own elaboration.

restrictions that would represent a balanced system in each country. Considering the involvement of experts and societal actors in attributing relative weights to the indicators being used in the performance evaluation (Corrente et al., 2021) may reduce the range of solutions being searched by the mathematical models, what may lead to more representative and reliable results. That way, the possible minimum values that may respond to a policy decision could be detected and the bottlenecks would not be applied to them. Another possible means to identify which the right quantities in each component of the system might be, would be the use of methods such as the one developed in this study but from a dynamic perspective, as suggested by Zabala-Iturriagagoitia et al. (2021).

Potts (2009), among others, argues that the goal of efficiency "crowds out" the goal of innovation (p. 36) and that accordingly, the pursuit of efficiency is inconsistent with the goal of effective innovation. This paper contributes to clarifying this scientific debate, by evidencing that the performance of innovation systems is to a great extent determined by the weakest link in the system, which acts as a bottleneck, reducing the potential performance of the system as a whole, which in the paper we asses through the productivity innovation index. Our research shows how targeting those bottlenecks would directly lead to a reconfiguration of the functions of an innovation system and to productivity gains resulting from more efficient and effective systemic performance.

We agree with Potts (2009) in that the effectiveness of new (innovation) policies cannot be known a priori. However, our study shows how it is possible to simulate the gains that the innovation system would have in its overall performance if an intervention were produced on the alleviation of its main bottleneck(s), either on the input side, on the

output side, or alleviating both inputs and outputs. The three simulations we consider in the study (10 % alleviation to input bottlenecks, 10 % alleviation to output bottlenecks, and 5 % alleviation both to input and output bottlenecks) could thus be interpreted as an experimental policy intervention. This experimentation does not entail any costs, as it helps to identify the potential behavior of an innovation system, as compared to that actually observed, if the intervention targets specific bottlenecks. As our results have evidenced, the most effective strategy to improve the system's productivity is context dependent. Some countries improve their productivity when inputs are alleviated, others when the outputs are alleviated and others when a combination of outputs and inputs is used. Hence, the new methodology we introduce in the paper helps to understand innovation policy as a 'moving target', facilitating the constant 'diagnose' of innovation systems to identify which policies may lead to higher returns at each moment in time.

These simulations can thus be used to identify the right quantities to be devoted to each of the constituents and functions of an innovation system, and to provide guidance to policymakers at the aggregate level (e.g., to European Union officials). However, in this case it would be necessary to simulate a coordinated action across countries, where each nation addresses its own bottlenecks. This coordinated action would change the innovation performance of all countries simultaneously, which results in a new global scenario where all countries see their relative positions improved in absolute terms, but whose ranking may be better or worse. This is a matter of further research. At the individual level, it does not seem very realistic that a country defines a particular policy vis a vis all the other countries, without considering the existence of strategic behavior, prompting third countries to take further action (e. g., as with fiscal policy, environmental policy, and so on). Innovation

policy is contemporary to all countries, and hence, if a country defines a policy to minimize the effects of a bottleneck (i.e., failure), it seems reasonable to assume all the other countries would do the same. Hence, country rankings and bottlenecks need to be constantly monitored, depending on this dynamic policymaking.

Declaration of competing interest

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial or non-financial interest in the subject matter or materials discussed in this manuscript.

The authors also confirm that this manuscript has not been published elsewhere and is not under consideration by another journal. On behalf of all authors, the corresponding author states that there is no conflict of interest. All authors have also approved the manuscript and agree with its submission to TFSC.

Data availability

The data are publicly available

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