Chasing Sustainable Development: A Network Approach to Rank Countries in the Agenda 2030

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Abstract

In 2015, the United Nations established the Agenda 2030 for sustainable development, addressing the major challenges the world faces and introducing the 17 Sustainable Development Goals (SDGs). How are countries performing in their challenge toward sustainable development? We address this question by treating countries and Goals as a bipartite complex network. While network science has been used to unveil the interconnections among the Goals, it has been poorly exploited to rank countries for their achievements. In this work, we show that the network representation of the countries-SDGs relations as a bipartite system allows one to recover aggregated scores of countries' capacity to cope with SDGs as the solutions of a network's centrality exercise, where more central countries are showing best performances in pursuing the SDGs. While the Goals are all equally important by definition, interesting differences self-emerge when non-standard centrality metrics, borrowed from economic complexity, are adopted. Innovation and Climate Action stand as contrasting Goals to be accomplished, with countries facing the well-known trade-offs between economic and environmental issues even in addressing the Agenda. In conclusion, the complexity of countries' paths toward sustainable development cannot be fully understood by resorting to a single, multipurpose, ranking indicator, while multi-variable analyses shed new light on the present and future of sustainable development.

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Key Points:

- A network representation of countries and SDGs fosters a complex-system approach to the Agenda 2030.
- Aggregated scores of countries' status in SDGs can be obtained as centrality metrics of this network.
- A data-based ranking self-emerges for countries' efficiency in pursuing SDGs.

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Abstract
In 2015, the United Nations established the Agenda 2030 for sustainable development, addressing the major challenges the world faces and introducing the 17 Sustainable Development Goals (SDGs). How are countries performing in their challenge toward sustainable development? We address this question by treating countries and Goals as a bipartite complex network. While network science has been used to unveil the interconnections among the Goals, it has been poorly exploited to rank countries for their achievements. In this work, we show that the network representation of the countries-SDGs relations as a bipartite system allows one to recover aggregated scores of countries' capacity to cope with SDGs as the solutions of a network's centrality exercise, where more central countries are showing best performances in pursuing the SDGs. While the Goals are all equally important by definition, interesting differences self-emerge when non-standard centrality metrics, borrowed from economic complexity, are adopted. Innovation and Climate Action stand as contrasting Goals to be accomplished, with countries facing the well-known trade-offs between economic and environmental issues even in addressing the Agenda. In conclusion, the complexity of countries' paths toward sustainable development cannot be fully understood by resorting to a single, multipurpose, ranking indicator, while multi-variable analyses shed new light on the present and future of sustainable development.

Plain Language Summary

In 2015, 193 countries, under the aegis of the United Nations, agreed in establishing the Agenda 2030 for sustainable development and defined the 17 Sustainable Development Goals to promote a more equal, just and sustainable future. In order to address change-making actions, monitoring countries' status in the achievement of the Goals is indispensable. We provide novel, data-based strategies to rank countries for their capacity to address the challenges posed by sustainable development. We promote the use of multi-indicator analyses to disentangle the inherent complexity in countries' paths toward sustainable development, also identifying countries acting as role models.

1 Introduction

Universality, integration and inclusion: these are the principles and cornerstones upon which the United Nations (UN) have constructed, in 2015, the Agenda 2030 for sustainable development (UN General Assembly, 2015; Abud et al., 2017). The Agenda, ratified by 193 countries, addresses through sustainable development the major challenges the world faces, such as environmental problems, climate change, economic growth, water, food and financial security, poverty and inequalities (Griggs et al., 2013; Deaton, 2013; UN General Assembly, 2019, 2020b); these also recently exacerbated by the Sars-CoV-2 pandemic (UN General Assembly, 2020a; Barbier & Burgess, 2020). The world is not new to the request of 'a global agenda for change'. Back in 1987, the report "Our Common Future" already introduced the key idea of a common action plan to address economic growth in equilibrium with the people and environment, thus preserving our world to meet human needs for today's and future generations (Brundtland et al., 1987). The beginning of the XXI century marked a shift in the way countries started being actively engaged in the implementation of sustainable development, with the establishment of the Agenda 2015, allowing the joint forces of UN and governments to achieve significant milestones in poverty and inequalities reduction, as well as in improved water access (Way, 2015; Servaes, 2017). In light of these achievements, and also of the limitations and gaps of such experience, the Agenda 2030 inherits and enlarges the views and objectives of the Agenda 2015 (Servaes, 2017). In practical terms, today's Agenda addresses a more equal, just and sustainable future by introducing the 17 Sustainable Development Goals - SDGs (UN General Assembly, 2015). The 17 Goals are constructed upon 5 pillars: people, prosperity, planet, peace and justice, and partnership; and connections and spillover effects among the Goals are unavoidably present (UN General Assembly, 2020c; Griggs et al., 2017; Pradhan et al., 2017; Nerini et al., 2019; Nilsson et al., 2018; van Soest et al., 2019; Sachs et al., 2019; Guerrero & Castañeda Ramos, 2020; Requejo-Castro et al., 2020; Tremblay et al., 2020). In line with the Charter of the United Nations, the Sustainable Development Goals have no pyramidal structure and there is no Goal prioritized with respect to the others, thus advocating for equal efforts in the designing of proper policies to meet these goals (Art. 40 of the Agenda) (UN General Assembly, 2015). In fact, each Goal targets the implementation of policies, totalling 169 targets across the 17 Goals (Guerrero & Castañeda Ramos, 2020). Targets also mark the need for data and measurements of the status of countries with respect to the achievement of the Goals. Countries ratifying the Agenda are encouraged to pursue sustainable development by defining national strategies with a global vision of their actions (UN General Assembly, 2015; Abud et al., 2017), thus contributing to the common action plan necessary to foster change (UN General Assembly, 2015; Brown, 2003; Capra & Luisi, 2014; Sachs et al., 2019) and embracing the cornerstones of the Agenda.

Since 2015, 5 years have already passed and countries are only left with 10 years to meet all the targets within the Agenda. To monitor the progresses of countries is a necessary step (Allen et al., 2018), a required one to define responsibilities and identify possible structural limitations and difficulties toward sustainability (Biggeri et al., 2019; Jacob, 2017; Schmidt-Traub et al., 2017). In fact, the Agenda is not a legal condition, and governments maintain the sovereignty in choosing what is the most appropriate strategy to be placed in the field (UN General Assembly, 2015). Moreover, countries exhibit remarkable heterogeneity in the challenges they have to face, an issue which is crucial in global sustainable development (UN General Assembly, 2015, 2020a). Finally, the interconnections among SDGs and their targets, also define trade-offs and synergies within different sectors of development (Griggs et al., 2017), which are enhanced by the strategies each country implements (Le Blanc, 2015; The Economist, 2015). These factors unavoidably create different responses at the country level (Biggeri et al., 2019; Sachs et al., 2020; UN General Assembly, 2019, 2020b).

It is clear then that the ensemble of countries and Goals within the Agenda 2030 is a complex system of its own (Gentili, 2021) (i.e., characterized by non-trivial and non-random interactions among many entities (Ladyman et al., 2013)), which requires proper mathematical approaches to be analyzed. Indeed, the presence of interconnections among the Goals and, no less, of synergies and trade-offs among development sectors, can be unveiled thanks to the use of complex network theory (see, e.g., Le Blanc (2015) and Guerrero and Castañeda Ramos (2020)). At the same time, within the development topic, the strategy of indexing is often used to rank countries for their performances, thus making the creation of aggregated scores necessary (Cooley & Snyder, 2015) (notable examples are the Human Development Index (Anand & Sen, 1994) and the Multidimensional Poverty Index (Alkire et al., 2011)), and the Agenda 2030 makes no exception. To create aggregated scores of performances entails mathematically valuing the contribution of each Goal to the overall countries' output, according to which compute a final score. In the construction of aggregated indices, many options can be pursued to weight these contributions (Nardo et al., 2005; European Commission JRC and OECD, 2008; Booysen, 2002). A possible strategy would be to mathematically implement the egalitarian principle of the Agenda (i.e., all Goals must be of equal importance), thus entailing assigning the same weights of SDGs (see, e.g., the SDG Index by Sachs et al. (2020); (Schmidt-Traub et al., 2017; Lafortune et al., 2018)); nevertheless, other suitable strategies may exist (see, e.g., the Integrated Sustainable Development Index by Biggeri et al. (2019)).

So far, the complex network analysis of the SDGs system and the creation of aggregated scores have been treated in parallel, without relevant overlaps. Instead, we argue that the combination of data and network science may help in disentangling the dynamics of development and in defining data-driven weights for the creation of more refined and comprehensive aggregated scores. In fact, due to the heterogeneity of countries and the challenges they face, it is expected that some SDGs are reached first by some countries with respect to others, a fact that calls for metrics in which these dynamics are taken into account and unveiled by the analysis of the data. In this work, we propose to tackle the definition of rankings of countries by promoting the use of the hidden bipartite network structure of the system defined by countries and Goals performances to highlight and disentangle the intrinsic complexity of this system. The network representation of the countries' performances in SDGs allows one to use the centrality metrics tools to obtain aggregated scores of sustainable development, hence introducing bottom-up and data-driven weights of the Goals. More importantly, our analysis allows one to take a data-driven picture of the possible current strategies of policy implementation in countries and disclose crucial features of countries' efficiency in sustainable development.

2 Results and Discussion

2.1 Unveiling the Hidden Network of Countries and Goals

As established by the United Nations (UN General Assembly, 2020c), progresses in the Sustainable Development Goals (and so, targets) are estimated using a set of indicators providing quantitative information about countries performances; each indicator measures the attainment of certain targets across the 17 SDGs. Let I_{cgk} be the k-th value of the indicator I within Goal g recorded in country c. For the sake of comparison across indicators and Goals, most applications consider the I_{cgk} values to be normalized according to least and optimal indicator values, resulting in a percentage of achievement of the indicator ranging from 0 to 100 (Lafortune et al., 2018; Cho et al., 2016; Biggeri et al., 2019) (see Section 4.1). Moreover, per each country c, one single value of achievement P in each Goal g is obtained as the average of the recorded and available values of the indicator I_{cgk} within the Goal. Namely,

$$P_{cg} = \frac{1}{N_{cg}} \sum_{k=1}^{N_{cg}} I_{cgk}, \tag{1}$$

where N_{cg} is the number of indicators in Goal g for country c (see Section 4.1). An aggregated score S_c of the countries' status can be generally defined as a weighted sum of Goal-specific performances

$$S_c \propto \sum_{g} P_{cg} \cdot w_g, \tag{2}$$

where w_g are the Goal-specific weights and the proportionality symbol considers the presence of any possible scaling factor.

Within this framework, our aim is to cast the computation of aggregated scores of SDGs for countries through the use of network science, so to unveil and exploit the complex structure of the Agenda. Let us consider the values P_{cg} as the starting point for our reasoning. We consider these values to be structured as a matrix $\mathbf{P}$ with C rows, i.e., the number of countries in the analysis, and 17 columns, as many as the Goals. Seen through network science lenses, the matrix $\mathbf{P}$ reveals the presence of a bipartite system in which countries and Goals are connected via recorded performances. In network theory, the matrix $\mathbf{P}$ describing these links is denominated as incidence matrix (Newman, 2010). We consider the network structure of countries and Goals emerging from the data taken from the latest SDG Index and Dashboard, referring to year 2020 (Sachs et al., 2020) (see Section 4.1), as exemplified in Figure 1. The data-set constitutes of 115 indicators across the Goals, 30 of which are specifically defined for the members of the Organization for Economic Co-operation and Development (OECD). The Dashboard only includes countries covering at least 85% of the indicators, totalling 166 out of 193 UN countries.

The bipartite network representation offers the chance to borrow mathematical tools of network's centrality to define the importance of the nodes in the system and rank them accordingly (Newman, 2010). Bipartite networks are characterized by the existence of two different sets of nodes, as in this case countries and Goals, and one centrality score can be computed for each set. The simplest measure of centrality, the nodes' degree k, assumes the importance of the node to be described by the number and strength of its connections (Shaw, 1954). This provides the value $k_c = \sum_{g=1}^{17} P_{cg}$ for countries (Shaw, 1954), thus implicitly setting $w_g = 1$ for all 17 Goals in the computation of the score S_c in Eq (2). Notice that, in this countries-SDGs network, the link P_{cg} between the nodes describes the existence of a connection between a country and a Goal but also the magnitude of this connection, represented by the recorded performance of the country in that SDG (as plot in Figure 1). Therefore, according to the degree, k_c, countries having an higher percentage of achievement across SDGs have better chances of being central – and so they are higher in ranking position –, no matter the Goal. This rationale reflects the egalitarian principle of the Agenda, for which all SDGs have equal importance in being achieved (UN General Assembly, 2015). We recall that, in light of this principle, the SDG Index by Sachs et al. (2020) is defined as (Lafortune et al., 2018)

$$SDG\ Index = \frac{1}{17} \sum_{g=1}^{17} P_{cg},$$

one recognizes that the SDG Index corresponds to the degree centrality of countries ($k_c = \sum_g P_{cg}$) scaled by a factor 17.

The degree only measures the local information of nodes' connections and so it does not depict the global structure of the network (for further details see, e.g., Bonacich (1987); Benzi and Klymko (2015)). Therefore, although in line with the principle of equal importance of SDGs, to rank countries with equal Goal weights entails not accounting for

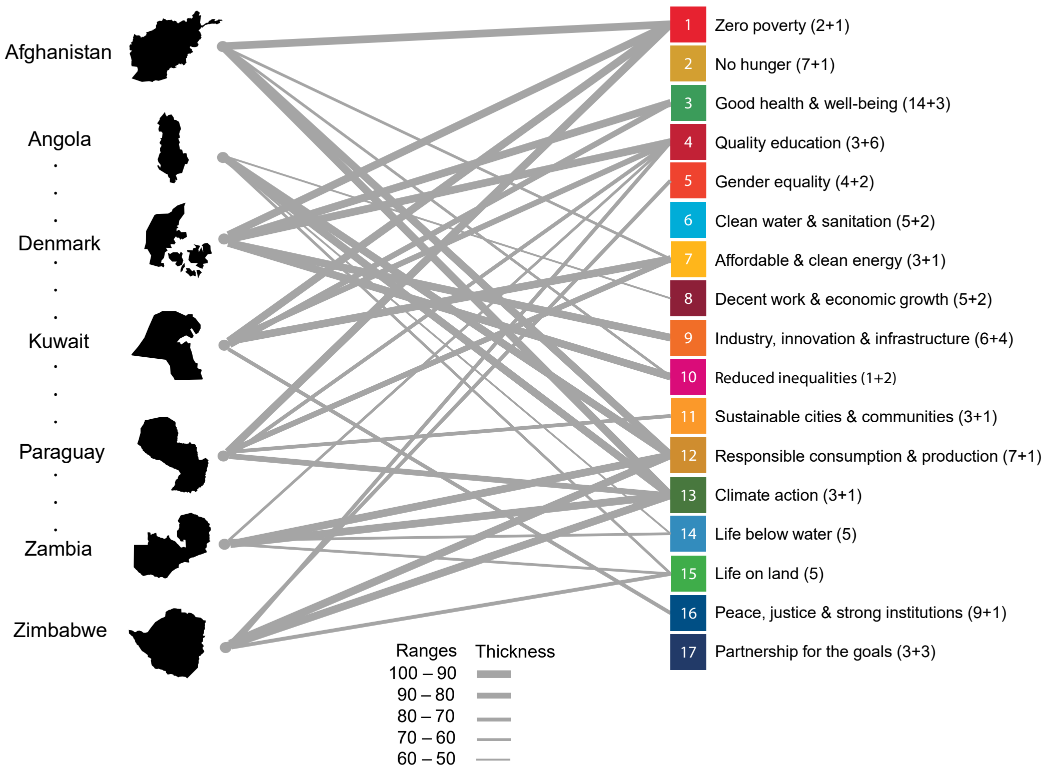

Figure 1. The bipartite network of countries and Goals. Qualitative representation of the bipartite network constituted by countries and Goals. On the left, we list seven of the countries that can be found by browsing the 2020 Dashboard, as sorted in alphabetical order (Sachs et al., 2020) (the first and last two countries and the ones found at first, second and third quarter of the list). On the right, the 17 SDGs are reported. Brackets specify the total number of indicators in each Goal as the sum of the number of globally defined and the OECD specific indicators according to the 2020 Dashboard (Sachs et al., 2020). For each country, we plot its largest five performance values P_{cg}. The links have been classed in ranges of 10% of performances, and the thickness of the links is determined accordingly: therefore, the thicker the links, the better the performances of the country within the Goals.

the complex behavior in sustainable development we aforementioned. Such behavior can be highlighted introducing network-comprehensive measures of centrality. Thanks to their global outlook on the network, these kind of metrics explore different dimensions of the SDG topic (and consequently, countries' status) and allows one to naturally define bottom-up weighting approaches.

The need for global centrality measures arises when considering the heterogeneity of countries' performances across the Goals, as we address in Figure 2. The figure plots countries' performances as defined by the 2020 SDG Index and Dashboard (Sachs et al., 2020) (see Section 4.1). In Figure 2, countries are ordered according to their ranking position as defined by their degree (or, equivalently, the SDG index). These countries' performances (which from hereon we define as 'spectra') are relative ones, as they are obtained by subtracting the average performance of the countries, $k_c/17$ (i.e., their SDG Index), from the Goal-specific performance, P_{cg}. This allows one to compare relative Goal performances of all countries according to their efforts in sustainable development, thus identifying areas where countries are investing more/less efforts and disclosing differences in their strategies. At glance, the heterogeneity of the spectra stands out. Countries exhibit very contrasting behaviours among them and across the Goals, witnessing the fact that the world is not moving as a unique ensemble toward the achievement of sustainable development. As mentioned, this is possibly due to the heterogeneity of countries contexts and challenges, as well as the differences in national strategies that possibly enhance such heterogeneity across SDGs. To group countries according to their degree can help understanding these differences. Figure 2 shows the existence of two limit behaviors of the 28 top and the 28 bottom performing countries according to the SDG Index (or degree), i.e., of classes 1 and 6, whose spectra are almost completely out of phase. These dynamics are more evident within Goals of environmental performances and exploitation, from Goal 12 to 15. As the spectra clearly show, the first 28 best countries in degree (class 1 in light blue) are poorly engaging toward the achievement of SDG 12 and 13. In particular, Norway is the relative worst performers in Climate Action, a Goal in which the country performs almost −60% with respect to its SDG Index. Instead, there are many low-degree countries (class 6 in violet) whose climate actions are highly valued, as the Central African Republic (CAF), in which this relative performance value is 60% more of the SDG score of the country. Even if less accentuated, the spectra of top and bottom degree countries are also out of phase in SDG 17, the one invoking partnership, in which countries nearer to fulfil most of the Agenda are actually the worst relative performers (e.g., Latvia – LVA). Other examples of this out of phase behavior of the countries in class 1 and 6 figure in correspondence of Goals 1, 2, 7 and 14 (Zero Poverty, Zero Hunger, Clean Energy and Life Below Water, respectively). Drops of performances occur for top-degree countries in Goals 2 and 14, while for bottom-degree countries in Goals 1 and 7. For example, Singapore attainment of SDG 14 is −60% with respect to its average performance in sustainable development. Yemen stands as an exception of such pattern since, in Goal 1, this country performs 40% better than its average value.

The spectra depict the complexity of the global variety of approaches toward sustainable development, in which the specificity of countries' characteristics has its role in determining the attainment of the Goals. Therefore, we argue that analyses designed to consider and embed this complexity can shed new light about the state of the art in sustainable development. The introduction of network theory is a first step toward this direction and allows us to define novel aggregated scores based on data-driven definition of the weights w_g in Eq (2).

2.2 A Data-Driven Weighting of Countries

A first revision of the degree centrality in bipartite networks consists in weighting the connection of the node proportionally to the centrality value of the node at the other edge. Therefore, countries connected to more central SDGs obtain a higher scoring value, and *vice versa*. According to this rationale, to define the aggregated score S_c in Eq (2) entails setting $w_g = v_g$, where v_g is the centrality value for Goal g and thus solving the

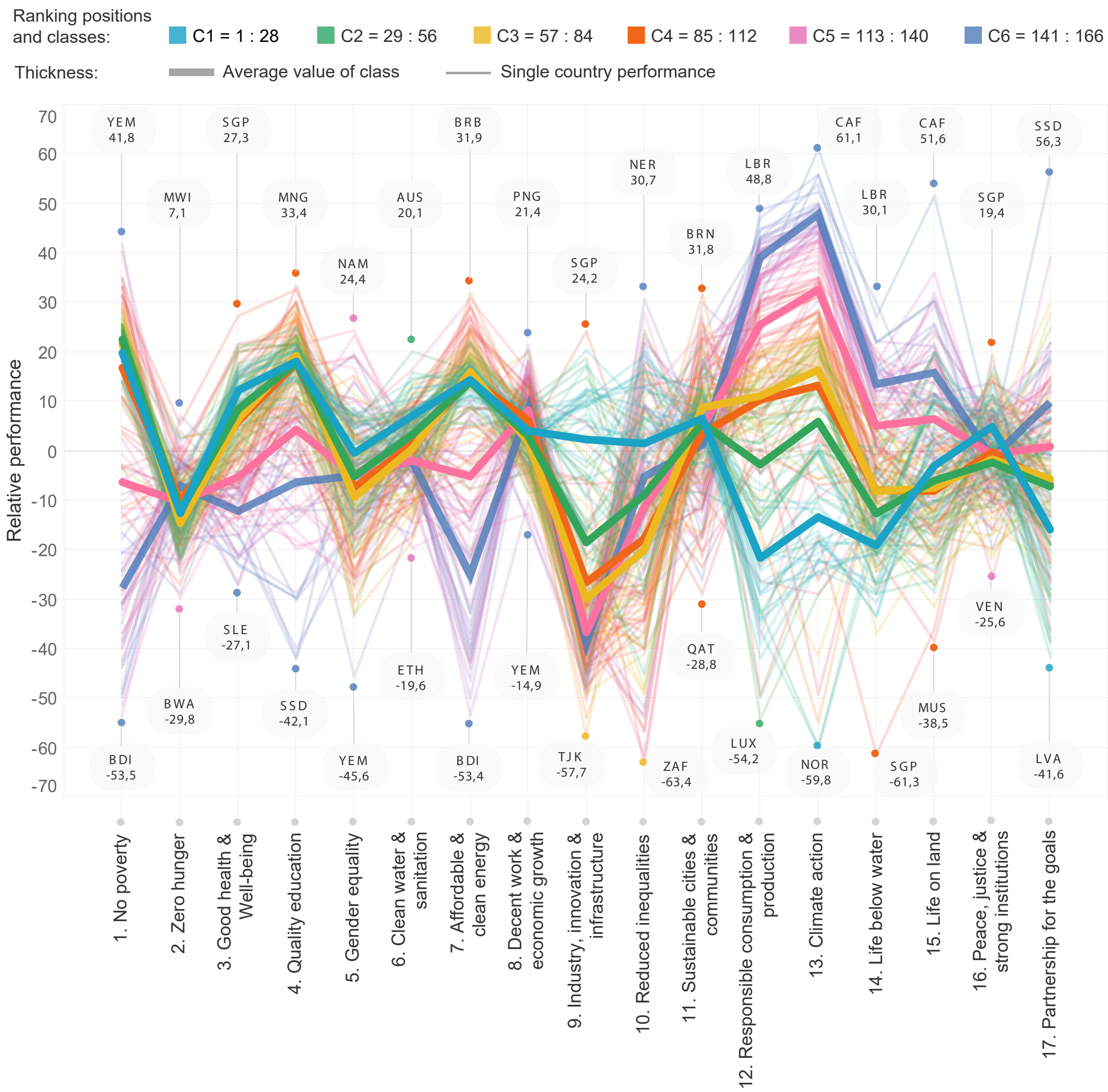

Figure 2. The spectra of countries' relative performances, obtained as $P_{cg} - (k_c/17)$. Countries are first ranked and then clustered according to their average performance (i.e., the SDG index or, equivalently, their degree). Based on the ranking positions, we define six classes of performance: light blue (countries in positions $1-28$), green ($29-56$), yellow ($57-84$), magenta ($85-112$), pink ($113-140$) and violet ($141-166$). The classes' average spectra of relative performances are shown in thicker lines. Top and bottom relative performers in each Goal are pointed out, and their performance value is color-coded as their corresponding class.

system of coupled equations

$$\begin{cases} S_c \propto \sum_g P_{cg} v_g, \\ v_g \propto \sum_c P_{cg} S_c. \end{cases} \quad (3)$$

Mathematically, the solution of this system is obtained by computing the so-called 'singular vectors' of the matrix **P** which determine the eigen-centrality vectors for countries and Goals, respectively (Everett & Borgatti, 2013) (see Section 4.2). While the degree is a local measure of centrality, the eigenvector is a global one, as it considers for the computation of the scores all possible links and strengths in the network (Newman, 2010; Bonacich, 1987; Benzi & Klymko, 2015). However, as we show in Figure S1, the eigenvector centrality brings no further information in terms of rankings than the one by the degree centrality (99.9% in both Pearson's and Spearman's correlation measures, see Figure S1). This lack of added value is due to the intrinsic correlation that the degree and eigenvector centrality show when the spectral gap – i.e., the delta between the first and second largest singular value of the incidence matrix (see Section 4.2) – is large (Benzi & Klymko, 2014). For this particular bipartite network, the second largest singular value is roughly one fourth of the principal singular value, implying high correlation between the degree and eigenvector centrality (Benzi et al., 2013) (see Section 4.2). Therefore, in the countries-SDGs network, the use of non-uniform weights as in Eq (3) is almost ineffective in changing the point of view about the state of sustainable development, and other rationale about countries inter-plays with Goals must be introduced to remove the degree-bias that characterizes the eigenvector centrality (Benzi et al., 2013).

The use of the centrality metrics defined within the field of Economic Complexity (EC) (Hidalgo & Hausmann, 2009; Tacchella et al., 2012; Sciarra et al., 2020) can help in the characterization of more complex inter-plays between countries and Goals. Based on the data regarding the export baskets of countries, EC aims at determining the stage of innovation and competition countries find theirselves at (Hidalgo & Hausmann, 2009). EC methods update the simplest proxy of innovation, i.e., the degree of countries in the bipartite system of trade, blamed for not considering the sophistication of the traded products (Sciarra et al., 2020). In fact, the idea upon which EC theory is constructed is that, in a looping system, if a product is only exported by few countries, this item is more knowledge-intensive than other items exported by many other countries. (In EC, the word 'knowledge' intends knowledge of production, resources, human and capital investments, eventually (Hausmann et al., 2007).) This determines higher EC scores of more knowledge-intensive goods. Therefore, products' EC score proxy the sophistication of products. The presence of knowledge-intensive items in the export baskets reflects the potential of countries in driving innovation. (Hidalgo & Hausmann, 2009; Tacchella et al., 2012; Sciarra et al., 2020). Clearly, weights are self-emerging from the methodology and its grounding rationale.

In a similar manner, we can adapt the EC theory and methods to the network of countries and SDGs, therefore introducing new reasoning about how countries act in sustainable development. In tailoring the EC framework to the SDGs one, we assume that, if within a Goal only few countries record near to optimal performance values, this Goal is more knowledge-intensive than the others, thus resulting in a higher EC score. Countries recording such optimal performances are those ones in more favorable conditions to attain the Goals. In fact, in here, we translate 'knowledge' into policy and intervention designs and implementations; awareness and preparedness to face the challenges, all well known factors for affecting countries performances in sustainable development (Volkery et al., 2006; Griggs et al., 2013; Kroll, 2015; Lopez-Calva et al., 2017; Sachs et al., 2020; Guerrero & Castañeda Ramos, 2020). Notice that, while the conceptual scheme of combining capabilities for driving innovation (human and capital resources, investments, policies (Sciarra et al., 2020)), which is typical of the economic complexity, is reasonably suitable for the productive system, it is not in the field of sustainable development. As we discussed, this latter area is mainly characterized by countries' historical phases and challenges, followed by the ensemble of decisions, planning, strategies and willingness that nations experience along their path toward sustainable development (Garmer, 2017; Sachs et al., 2020; Ashford, 2000).

To the best of our knowledge, Cho et al. (2016) is the only existing example in literature proposing to adapt EC methodologies and centrality metrics to score countries performances within the Agenda 2030. However, our work differs from that one in both data and methodology. In fact, our analysis extends at the world level and it is not limited to the Asian regions (see Section 4.1). Moreover, while Cho et al. (2016) used the *Method of Reflection* from Hidalgo and Hausmann (2009), in this work we use the *GENeralized Economic comPlexitY* framework, said GENEPY, which has been shown to reconcile the contrasting methodologies on economic complexity and also a reliable method for processing non-binary incidence matrices as the one of the countries-SDGs bipartite system (Sciarra et al., 2020). For the sake of clarity, in the following, the adaptation of the GENEPY framework to the context of the Agenda 2030 is defined as SDGs-GENEPY.

The SDGs-GENEPY rationale defines two related centrality properties, S_c for countries and Y_g for SDGs, defined through the following system

$$\begin{aligned} S_c &\propto \frac{1}{k_c} \sum_g P_{cg} \frac{Y_g}{k'_g}, \\ Y_g &\propto \frac{1}{k'_g} \sum_c P_{cg} \frac{S_c}{k_c} \end{aligned} \tag{4}$$

in which $k_c = \sum_g P_{cg}$ is the degree of the countries, therefore the sum of all Goals' performances (i.e., the value of the aggregated score supposing $w_g = 1$ for all SDGs). The term $k'_g = \sum_c P_{cg}/k_c$, that we define as 'adjusted Goal's degree', is the degree of Goal g accounting for the relative performances of countries within it (relative performances of countries can either be computed as the subtraction of the average performances, as in Figure 2, or using the ratio P_{cg}/k_c, and the same results hold, see Figure S2). Therefore, to evaluate the aggregated score of countries' status S_c according to the SDGs-GENEPY entails assuming $w_g = Y_g/k'_g$ in Eq (2). Notice that, similarly to the eigenvector centrality, the metrics provided by the SDGs-GENEPY framework are also global ones since they account for the overall structure of the network (Sciarra et al., 2020) (see Section 4.3). Nevertheless, although the mathematical structure of Eq (4) is formally an eigenvector one (see Section 4.3), the resulting S_c centrality metrics is no longer degree-dominated due to the division of the S_c values by the degree k_c.

A resume of the different weighting strategies for the Sustainable Development Goals that we adopted in this work is given in Table 1.

Table 1. Weighting approaches through different centrality metrics. In the formulas: S_c is the aggregate score for country c, generally defined according to Eq (2); P_{cg} is the value of countries' performances in Goal g; w_g is the weighting value defined in Eq (2); v_g is the centrality score for SDGs according to the eigenvector centrality; Y_g is the centrality score for SDGs according to the SDGs-GENEPY framework, Eq (4), and $k'_g = \sum_c P_{cg}/k_c$ is the adjusted Goals' degree (see Sections 2.2 and 4.3).

Centrality measure	**Aggregate score**	**Weighting value**
Degree	$S_c = \sum_g P_{cg}$	$w_g = 1$
Eigenvector	$S_c \propto \sum_g P_{cg} v_g$	$w_g = v_g$
SDGs-GENEPY	$S_c \propto \sum_g P_{cg} Y_g / k'_g$	$w_g = Y_g / k'_g$

2.3 A Picture of Global Responses in Sustainable Development

The application of the economic complexity theory to the bipartite network of countries and SDGs provides useful insights about how countries are currently responding to the call for actions toward a more equitable, just and sustainable future. We exemplify these results through the application of the SDGs-GENEPY framework on the data from the 2020 Dashboard by Sachs *et al.* (Sachs et al., 2020) (see Section 4.1). Let us start from the results obtained from the computation of the SDGs-GENEPY values for Goals, and, consequently, of the weights Y_p/k'_g. In Figure 3, the weighting values Y_p/k'_g are shown. The top-weighted Goal is SDG 9 pertaining with Innovation, followed by Zero Hunger and Reduced Inequalities, SDG 2 and 10, respectively. Climate Action (SDG 13)

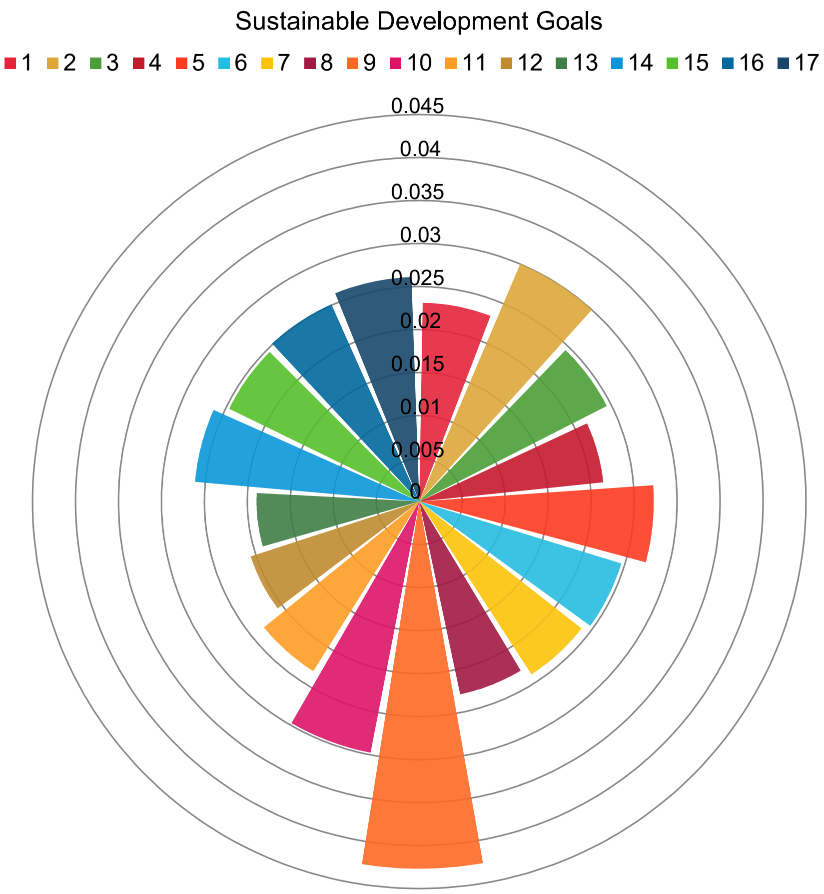

Figure 3. The SDGs-GENEPY weights of the Sustainable Development Goals. The radial bar chart plots the SDGs-GENEPY weights Y_g/k'_g for all Goals (see Section 2.2, Eqs (4), and Section 4.3).

is the least weighted, preceded by SDGs 12 and 4, pertaining with sustainable consumption and education, respectively. The wide differences among the weights demonstrate that the SDGs-GENEPY framework is able to capture the contrasting performances among top and bottom ranked countries, shown in Fig 2. In fact, this weighting of Goals reflects the poor performances by (generally) high performing countries in some SDGs (e.g., Norway in SDG 9, as will be further detailed). Moreover, these results provide a further evidence that the SDGs are not equally integrated in national strategies all around the world. As a consequence, the SDGs-GENEPY weighting values of less prioritized Goals is lower than that of more prioritized ones.

Such a weighting approach determines the ranking of countries according to SDGs-GENEPY score, which differs from the one by the degree centrality. In Figure 4 we map countries' rankings according to the SDGs-GENEPY index and the degree value (panels (a) and (b), respectively); panel (c) resumes the differences between the two by scattering the ranking values, with countries color-coded according to Regions, as defined in the 2020 Dashboard (Sachs et al., 2020) (see Section 4.1). As the Figure shows, although the two rankings are mostly aligned (Pearson's correlation coefficient 0.81), significant differences arise. As most remarkable examples, we cite here Singapore (SGP), which jumps from the lower half of the chart to the top of it, moving from position 93 in degree to position 4 in the SDGs-GENEPY S_c, and South Africa (ZAF), moves from 110 in degree to 49 in the SDGs-GENEPY score. Instead, Chile (CHL) moves from the 28-th position in degree, to the 51-th in the SDGs-GENEPY score and Cuba (CUB), which downgrades from the 56-th position in degree to the 126-th in SDGs-GENEPY S_c.

To explain the reasons behind these variations, we refer to Norway as a relevant example: Norway is among the top absolute performers within SDG 9 (having largest weighting value Y_g/k'_g), together with South Korea and Singapore. Most countries perform poorly within this Goal – only 50% of the value is above the 40% of Goal achievement, as also represented in Figure 2. As a consequence, the SDGs-GENEPY framework

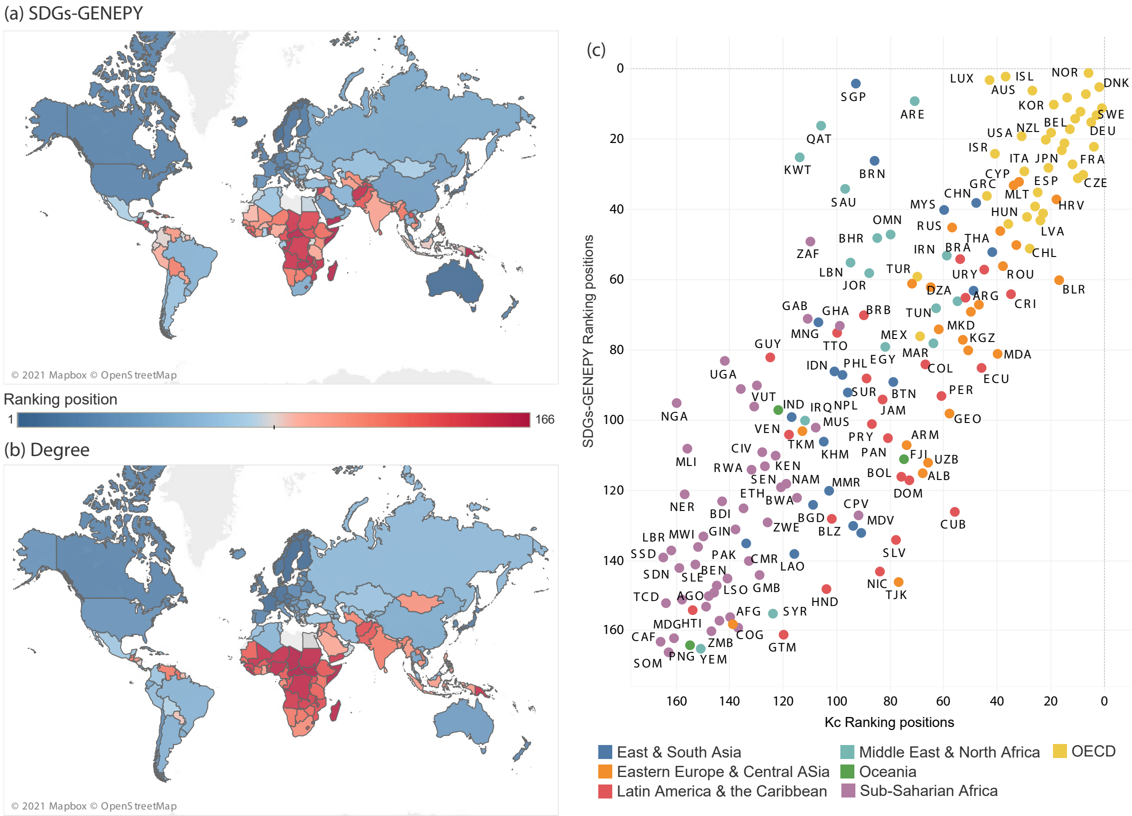

Figure 4. Countries rankings according to the degree and SDGs-GENEPY values. In panel (a), countries are colored according to the ranking position computed by the SDGs-GENEPY score. In panel (b) shows the ranking position computed by the degree or, equivalently, the SDG Index (Sachs et al., 2020). In both maps, ranking position is defined according to descending score (1 = best performer, 166 = worst performer). In panel (c) we scatter the values of the two rankings: on the x-axis is the degree ranking, on the y-axis, the SDGs-GENEPY one. Countries are color-coded according to their Region as specified in the legend, in accordance with the region division in the 2020 Dashboard (Sachs et al., 2020). Countries lying along the diagonal share the same ranking position both in SDGs-GENEPY and SDG Index.

assigns a higher weight to countries which are better performers in this Goal. Also, Norway figures as the best absolute performer in Goal 10, and reaches good performances in Goal 2, thus explaining the upgrading of the North-European country from the sixth to the first position in the SDGs-GENEPY S_c ranking. Another relevant example is represented by the case of Singapore, a nation that due to its outstanding performances in more knowledge-intensive SDGs, has reached the third position in SDGs-GENEPY. In contrast, Norway and Singapore are among the worst relative performers in SDGs 13 and 12, respectively (see Figure 2), but their low performances in these SDGs are comparatively less relevant within the SDGs-GENEPY framework, due to the lower weight values assigned to these two Goals.

Therefore, the SDGs-GENEPY approach we propose has two main advantages. Firstly, the weights $w_g = Y_g/k'_g$ are self-emerging from the data, and they account for the relative performances of countries as measured by term k'_g. Secondly, the division of the SDGs-GENEPY S_c values for k_c removes the undesired degree-biased, which is known to affect eigenvector-based centrality measures (Benzi et al., 2013), thus providing useful insights about the countries' status in sustainable development. These characteristics of the SDGs-GENEPY framework can be interpreted in light of further considerations about the Agenda 2030. Countries whose relative performance value P_{cg}/k_c in Goal g is greater than that in other SDGs, give a higher contribution to the term k'_g. Its inverse $1/k'_g$ possibly diagnoses structural limitations in achieving the Goal: higher values of $1/k'_g$ are obtained for those Goals in which only few countries have positive relative performances. Therefore, we can assume that heavier (in sense of weights) Goals are also those ones that some countries favor with national strategies, to the detriment of other Goals. This is witnessed by the fact of having found Climate Action and Innovation as, respectively, the lowest and greatest weighted Goals, whose $w_g = Y_g/k'_g$ values are mainly determined by the relative performances of higher-income and outperforming countries, such as Norway (see Figure 2).

3 Conclusions

The problem of defining aggregated scores in sustainable development is a recurrent one, which needs to be addressed to track the path toward the achievement of the Goals within the Agenda 2030. Many strategies can be pursued for their computation (see, e.g., Sachs et al. (2020); Biggeri et al. (2019)); nevertheless, the complexity of the Agenda 2030 should not be neglected when defining aggregated scores. In light of this complexity, in this work we have introduced a novel perspective on sustainable development in which we addressed, within a network science framework, the need for ranking countries for their status with respect to the Agenda. In particular, we show that the countries-SDGs system can be structured as a bipartite network and that, by using the centrality tools, different weighting approaches naturally emerge for the computation of aggregated scores to rank countries.

Thanks to this network representation of the system, we show that the SDG Index identified by Sachs *et al.* (Sachs et al., 2020) – which, in line with the Agenda's principles, considers equal weights for all Goals – corresponds to measure the degree of countries. In network science, the degree centrality measures the local behavior of the node and it does not account for the complex interconnections of the system (Benzi & Klymko, 2015). A first step toward the use of global metrics to account for the structure of the network is the use of the eigenvector centrality. However, we have demonstrated that in the countries-SDGs system, the degree and eigenvector centrality substantially carry the same information. Besides the formal reasoning about the spectral gap, the strong correlation between the two centrality metrics is due to the fact that countries' performances in SDGs are mutually correlated (see Figure S3). This fact highlights that countries set in similar development conditions (*sensu*, Baldwin et al. (2019)) tend to emulate each other performances (Reinert, 2009) and explains why, when ranked for their degree, nearby ranking-positioned countries show similar behavioral patterns (see Fig. 2 and Figure S3). Nevertheless, heterogeneity of countries' performances beyond their average value (or equivalently, the degree) is clear from Fig. 2. This suggests the need for more subtle metrics able to unravel the complexity of the system, a need we address through the GENeralized Economic complexity framework (SDGs-GENEPY) (Sciarra et al., 2020).

For the creation of an aggregate score, the SDGs-GENEPY framework considers the relative performances of countries within each Goals, from which the weighting values are defined. Within this framework, the Goals' weights highlight how countries differently value the Goals and their corresponding sectors of sustainable development. The fact of having found the maximum and minimum weights in correspondence of Goal 9 and 13, Innovation and Climate Action, respectively, once again puts under the spotlight the trade-offs between economic and environmental issues (Beg et al., 2002), especially in more advanced realities in sustainable development. In fact, this weighting hierarchy is determined by best performers in the SDGs' arena (such as Norway and Singapore) and testifies the intrinsic compromise among political willingness, opportunities and capacities to move toward sustainable development (Garmer, 2017; Sachs et al., 2020; Ashford, 2000). This compromise stands against the fact that these same countries are considered to be in more favorable conditions to fulfill the Agenda, resulting in higher 'knowledge' (i.e., policy and intervention designs and implementations; awareness and preparedness to face the challenges (Volkery et al., 2006; Griggs et al., 2013; Kroll, 2015; Lopez-Calva et al., 2017; Sachs et al., 2020; Guerrero & Castañeda Ramos, 2020)).

Due to its capability to bring out the complex linkages within the SDGs-countries system, we can interpret the SDGs-GENEPY ranking of countries as a picture of shared responsibilities, where emerges the possibility for nations to act like role-models and promote the achievement of global sustainable development. In light of the emulation phenomena among countries (Reinert, 2009), we argue that to identify role-model countries is rather relevant and in can pave the way to a new strategy for boosting sustainable development in the next decade. In particular, our ranking can be used as an '*ex post*' and complementary tool to the Rapid Integrated Assessment – RIA – analysis (Abud et al.,

2017) which the United Nations conduct to monitor the willingness of countries in integrating the Goals within their national strategies. In this sense, our analysis would effectively provide insights about the implementation of such plans, also providing a tool for comparing the efforts across countries.

In conclusion, although we have shown the potential of the SDGs-GENEPY approach in changing the perspective, we argue that such complex system as the one defined within the Agenda 2030 should not be shrunk to a single ranking indicator. To fully understand countries' path toward sustainable development, we promote the use of multiple and parallel mathematical analyses, as, e.g., compute both the degree and SDGs-GENEPY ranking. In fact, we argue that a bird's-eye view of the compared rankings from different indicators provides useful information to address efforts for meeting the 2030 deadline.

4 Data and Methods

4.1 Data

Notwithstanding the call for efforts toward the standardization in the data collection by all National Statistical Systems, NSSs, launched by the Cape Town Global Action Plan in 2017 (StatCom, 2017), the data accessible at the UN Statistics Division (available at `https://unstats.un.org/sdgs/indicators/database/`) clearly show that work is still needed to have a comprehensive, homogeneous, and extensive database covering all countries and years under the Agenda 2030 and beyond. For this reason, the input data we are using are taken from the 2020 SDG Index and Dashboard (Sachs et al., 2020), which represent a commendable step forward in data collection, homogenization and assessment of countries progresses in sustainable development. The aim of the Dashboard is to provide yearly rankings of UN countries based on an aggregated score of all Goals' performances. The score is intended to be readable as a percentage of achievement of all the Goals, ranging from 0 to 100; therefore, countries close to 100 are approaching the complete fulfilling of the Agenda's Goals according to the indicators used to compute the score (Lafortune et al., 2018). The score is constructed upon a number of indicators providing quantitative information about countries performances. All listed indicators are normalized according to an optimum and a minimum value of indicator performance to ensure comparability and aggregation of measurements (we refer the reader to (Lafortune et al., 2018; Sachs et al., 2020) for further details). Listed indicators are updated every year, accounting for advances in monitoring and research. In order to provide statistical-sound results, we only refer to 2020 data, thus not inferring any possible missing data back in other years' Dashboards. The 2020 Dashboard includes 166 out of 193 UN countries. The data-set constitutes of 115 indicators across the Goals, 30 of which are specifically defined for the members of the Organization for Economic Co-operation and Development (OECD). This entails that, with respect to the same Goal g, the term N_{cg} (from which, in Eq (1), the value of performance P_{cg} is obtained) differs between OECD and other countries. The Dashboard also introduces Regional scores, assigning countries to 7 different Regions around the world, namely: Sub-Saharan Africa, Middle East and North Africa – MENA –, East and South Asia, Eastern Europe and Central Asia, Latin America and the Caribbean – LAC –, Oceania and OECD group, which we use to color-code countries in Figure 4. In line with the methodology exemplified with the SDG Index, we replaces countries' missing data with the Regional score in that same Goal (Lafortune et al., 2018).

4.2 Eigenvector Centrality

Let u_c be the eigencentrality of country c and v_g the eigencentrality of Goal g. By definition, the eigencentrality value for country c is its degree weighted by the centrality of all Goals, and *vice-versa* (Newman, 2010). In this work, the centrality score for countries u_c coincides with the computation of S_c when setting $w_g = v_g$ in Eq. (2). The computation of the eigenvectors of a matrix requires the matrix to be squared. Incidence matrices of bipartite networks, such as the matrix $\mathbf{P}$ in this work, are rectangular, instead. In order to compute the eigenvector centrality of countries and Goals, the matrices $\mathbf{A} = \mathbf{PP}'$ and $\mathbf{B} = \mathbf{P}'\mathbf{P}$ are introduced, where $\mathbf{P}'$ is the transpose matrix of the matrix $\mathbf{P}$ (Everett & Borgatti, 2013; Golub & Van Loan, 2012). The system in Eqs 3 can hence be solved in closed form as

$$\sigma_1^2 \mathbf{u_1} = \mathbf{A}\mathbf{u_1},$$
$$\sigma_1^2 \mathbf{v_1} = \mathbf{B}\mathbf{v_1}, \qquad (5)$$

in which the term σ_1 is the largest singular value of the matrix $\mathbf{P}$ (Golub & Van Loan, 2012), or, equivalently, the square root of the largest eigenvalue λ_1 of the matrices $\mathbf{A}$ and $\mathbf{B}$. The vector $\mathbf{u_c}$ and $\mathbf{v_g}$ are the singular vectors of the matrix $\mathbf{P}$ associated to σ_1 or, equivalently, the eigenvectors of $\mathbf{A}$ and $\mathbf{B}$ associated to the largest eigenvalue λ_1 (Everett & Borgatti, 2013; Golub & Van Loan, 2012). Notice that, due to the mutual relationship between eigen- and singular values, the spectral gap can be equivalently measured between the two largest eigenvalues of the matrices $\mathbf{A}$ and $\mathbf{B}$ or between the singular values of the matrix $\mathbf{P}$.

4.3 The SDGs-GENEPY Framework

The SDGs-GENeralized Economic comPlexitY scoring and weighting approach is set in a linear algebra framework. The SDGs-GENEPY framework aims at defining two properties X_c for countries and Y_g for SDGs, that can account for the EC rationale and so embed the interplay between countries and Goals. In this rationale, SDGs in which most countries have poor performances around the world are less knowledge-intensive than others. Countries recording optimal performances in those Goals with poor global attainment are those ones with a higher change-making power, but also more responsible for a prioritization of certain Goals. This can be mathematically obtained by defining the system of equations in Eqs (4). Similarly to the eigenvector centrality, a closed solution for this system is provided by solving the coupled singular vectors $\mathbf{X}$ and $\mathbf{Y}$ associated to the largest singular value σ_1 of the matrix $\mathbf{W}$ defined as

$$W_{cg} = \frac{P_{cg}}{k_c k'_g}.$$

The matrix $\mathbf{W}$ helps in defining the EC rationale and in providing a symmetric representation of the bipartite system for which the $\mathbf{X}$ and $\mathbf{Y}$ are determined. In fact, the vector $\mathbf{X}$ for countries is the eigenvector of the largest eigenvalue of the matrix $\mathbf{N}$ defined as

$$N_{cc^*} = \mathbf{W}\mathbf{W}' = \sum_g \frac{P_{cg}P_{c^*g}}{k_c k_{c^*} (k'_g)^2}; \tag{6}$$

the vector $\mathbf{Y}$ for SDGs is the eigenvector of the largest eigenvalue of the matrix $\mathbf{G}$ defined as

$$Z_{gg^*} = \mathbf{W}'\mathbf{W} = \sum_c \frac{P_{cg}M_{cg^*}}{k_c^2 k'_g k'_{g^*}}. \tag{7}$$

In this work, the centrality score for countries X_c coincides with the computation of SDGs-GENEPY S_c values, when setting $w_g = Y_g/k'_g$ in Eq. (2).

For further details, we refer the readers to Sciarra et al. (2020) for a complete description of the algebra beyond the framework. However, some comments are due to the readers to completely follow along the reasoning behind this work. Thanks to the differences in the input bipartite system, to adapt the GENEPY framework to the Agenda 2030 (i.e., SDGs-GENEPY we introduced in this work) provides a simpler mathematical rationale than the one presented in the original work for trade. Building upon the export data, the GENEPY index in Sciarra et al. (2020) is a multidimensional centrality score for economic complexity in which two eigenvectors of the matrix $\mathbf{N}$ for countries are combined in quadratic form (or $\mathbf{G}$ for products, which in this work has its counterpart in $\mathbf{Z}$ for SDGs). Without any loss of information, in this work we limit our analysis to the first eigenvectors of the matrices $\mathbf{N}$ and $\mathbf{Z}$, for countries and Goals, respectively. In fact, the eigenvectors associated to smaller eigenvalues bring no relevant added information and their quadratic terms in the formulation of the SDGs-GENEPY score can be neglected (see Figure S4). Moreover, the diagonal values of the matrices $\mathbf{N}$ and

Z are left as computed in accordance with Eq (6) and Eq (7), respectively (differently from the export case, the diagonal values do not bias the results, see Figure S5). Finally, with respect to the trade case, a further difference consists in the fact that the incidence matrix of the bipartite network of countries and SDGs defines non-binary, so weighted, connections among the nodes.

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Author contributions statement C.S. conceived the study; prepared the data and conducted the analysis. C.S., G.C., L.R. and F.L. analysed the data and results. C.S. produced the figures and wrote the manuscript. C.S., G.C., L.R. and F.L. edited the manuscript. All authors reviewed the manuscript.

Data availability Data on the Sustainable Development Goals' indicators supporting the findings of this study are taken from the 2020 SDG Index and Dashboard by Sachs et al. (2020) and freely available at [`https://www.sdgindex.org/`].

Code availability The code for the computation of the GENEPY framework is publicly and freely available at [`https://zenodo.org/record/3876721`].

Additional information Supplementary Information accompanies this paper.

The authors declare no competing interests.

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