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A network approach to rank countries chasing sustainable development

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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 complex bipartite 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 aggregate scores of countries' capacity to cope with SDGs as the solutions of a network's centrality exercise. 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.

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[1,2]. The Agenda, ratifi d 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[3–5]; these also recently exacerbated by the Sars-CoV-2 pandemic[6,7]. 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[8]. 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[9,10]. 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[10]. In practical terms, today's Agenda addresses a more equal, just, and sustainable future by introducing the 17 Sustainable Development Goals SDGs[1]. The 17 Goals are constructed upon five pillars: people, prosperity, planet, peace and justice, and partnership; and connections and spillover effects among the Goals are unavoidably present[11–20]. In line with the Charter of the United Nations, the Sustainable Development Goals have no pyramidal structure, and there is no Goal prioritised with respect to the others, thus advocating for equal efforts in the designing of appropriate policies to meet these goals (Art. 40 of the Agenda)[1]. In fact, each Goal targets the implementation of policies, totalling 169 targets across the 17 Goals[18]. 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[1,2], thus contributing to the common action plan necessary to foster change[1,17,21] and embracing the cornerstones of the Agenda. Nevertheless, the Agenda is not a legal condition, and governments maintain sovereignty in choosing the most appropriate strategy to be placed in the fi ld[1]. Moreover, on the one hand, countries exhibit remarkable heterogeneity in the challenges they have to face[1,6]; on the other hand, the interconnections among SDGs and their targets, also defi e trade-off and synergies within different sectors of development[12,22], which are enhanced by the strategies each country implements[23,24]. These factors unavoidably create different responses at the country level[4,5,25,26].

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It is clear then that the ensemble of countries and Goals within the Agenda 2030 is a complex system of its own[27] (i.e., characterised by non-trivial and non-random interactions among many entities[28]), which requires proper mathematical approaches to monitor the status of countries, and able to account for their heterogeneity and the interconnections across the Goals. Indeed, such interconnections among the Goals and, no less, the synergies and trade-offs among development sectors, can be unveiled thanks to the use of complex network theory (see, e.g., Le Blanc[23] and Guerrero et al.[18]). 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 aggregate scores necessary[29,30] (notable examples are the Human Development Index[31] and the Multidimensional Poverty Index[32]), and the Agenda 2030 makes no exception. To create aggregate scores of performances entails mathematically valuing each Goal's contribution to the overall countries' output, according to which compute a final score. In the construction of aggregate indices, many options can be pursued to weight these contributions[33,34]. 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.[26,35,36] and its applications at sub-national level[37]); nevertheless, other suitable strategies may exist (see, e.g., the Integrated Sustainable Development Index by Biggeri et al.[25]).

So far, the complex network analysis of the SDGs system and the creation of aggregate 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 defining data-driven weights to create more refined and comprehensive aggregate scores. In this work, we propose to tackle the defi ition of rankings of countries by promoting the use of the hidden bipartite network structure of the system defi ed by countries and Goals performances to highlight and unravel the intrinsic complexity of this system. Such representation of the Agenda 2030 allows one to use network methodologies to provide data-driven solutions to the problem of indexing of countries and weighting of the Goals.

Results

The complex network representation of countries and Sustainable Development Goals. As established by the United Nations[11], 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 normalised according to least and optimal indicator values, resulting in a percentage of achievement of the indicator ranging from 0 to 100[25,36,38] (see "Materials and methods" section). 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 "Materials and methods" section). An aggregate score S_c of the countries' status can be generally defined as a weighted sum of the 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 aggregate scores of SDGs for countries through the use of network science 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[39]. We consider the network structure of countries and Goals emerging from the data taken from the latest SDG Index and Dashboard, referring to the year 2020[26] (see "Materials and methods" section), as exemplified in Fig. 1.

The bipartite network representation offers the chance to borrow mathematical tools of network's centrality to defi e the importance of the nodes in the system and rank them accordingly[39]. Bipartite networks are characterised 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[39]. Th s provides the value $k_c = \sum_{g=1}^{17} P_{cg}$ for countries[39], thus implicitly setting $w_g = 1$ for all 17 Goals in the computation of the score S_c in Eq. (2). (A mirror metric is defined for the SDGs; namely, the quantity $k_g = \sum_c P_{cg}$ defi es the degree of a Goal g.) 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 Fig. 1). Therefore, according to the degree, k_c, countries with a higher percentage of achievement across SDGs have better chances of being central, so they are higher in ranking position, no matter the Goal. Th s rationale refl cts the egalitarian principle of the Agenda,

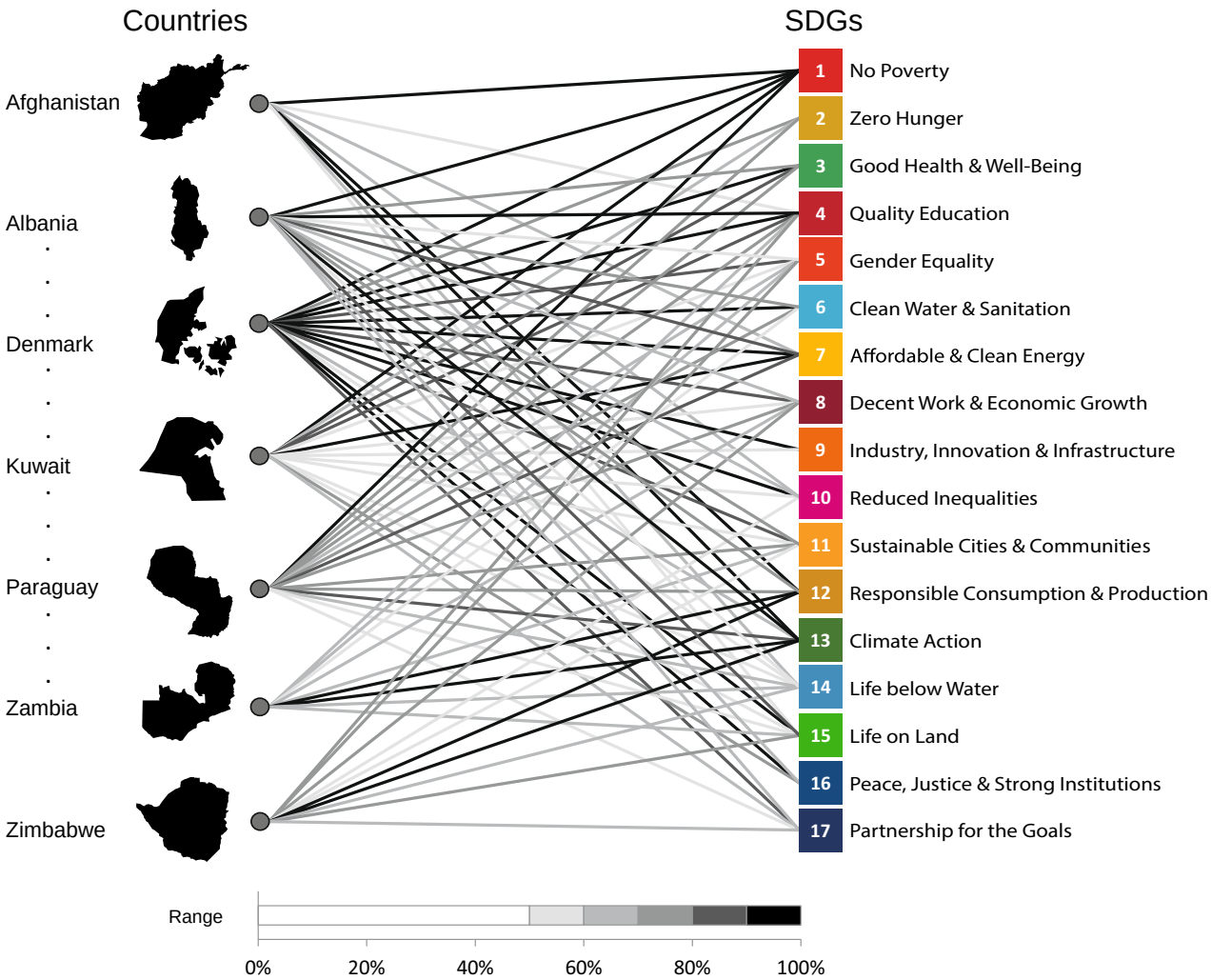

Figure 1. The bipartite network of countries and Goals. Qualitative representation of the bipartite network constituted by countries and Goals. On the left, e list seven of the countries that can be found by browsing the 2020 Dashboard, sorted in alphabetical order[26] (the fi st and last two countries and the ones found at fi st, second and third quarter of the list). On the right, the 17 SDGs are reported. For each country, we connect the SDGs via the performance values P_{cg} in each Goal, according to the 2020 Dashboard data[26]. The values P_{cg} are intended to be readable as a percentage of achievement of the Goals. We have classed these values in ranges of 10% of performances and colour-coded, in greyscale, accordingly: the darker the links, the better the performances of the country within the Goals. Countries' performances smaller than 50% have been left lank. The figu e has been generated using Matlab R2019b, [https://www.mathworks.com/products/matlab.html], and PowerPoint 2016.

for which all SDGs have equal importance in being achieved[1]. We recall that, in light of this principle, the SDG Index by Sachs et al.[26] is defined as[36]

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

and, one easily 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.,[40,41]). Therefore, although in line with the principle of the equal importance of SDGs, to rank countries with equal Goal weights entails not accounting for the complex interconnections in sustainable development we aforementioned.

The need for global centrality metrics to measure the complexity of the system clearly arises when considering the heterogeneity of countries' performances across the Goals, as we address in Fig. 2. The figu e plots countries' performances as defi ed by the 2020 SDG Index and Dashboard[26] (see "Materials and methods" section). In Fig. 2, countries are ordered according to their ranking position as defi ed by their degree (or, equivalently, the SDG Index). These countries' performances (which from hereon we defi e as 'spectra') are relative ones, as they