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Sustainable development goals research in higher education institutions: An interdisciplinarity assessment through an entropy-based indicator

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ABSTRACT

Since 2015, the United Nations has urged higher education institutions (HEIs) to adopt an interdisciplinary approach towards the Sustainable Development Goals (SDGs). In other words, universities are encouraged to transcend any single disciplinary perspective in exploring sustainable development issues. This study examines the importance of driving the scientific production of HEIs towards the SDGs as a concrete institutional contribution to sustainable development. While bibliometric tools for the SDGs are currently emerging, the existing models have not focused on interdisciplinarity or on their usefulness as decision-management tools to drive SDG-related research at a micro-scale (i.e. the institutional level). This study proposes a novel multi-step methodology. It develops an initial case study, which applies information system design theory (ISDT) to map and assess interdisciplinary research into each SDG at an Italian generalist university (University of Turin). Utilising a quantitative text analysis, we examined a database containing over 30,000 entries representing the university's SDG-related scientific production from 2015 to 2019. Subsequently, we conducted a social network analysis (SNA) of co-authorship to measure interdisciplinarity for each SDG. We defined interdisciplinarity as collaboration among researchers in diverse disciplines. We employed a modularity algorithm to select bottom-up clusters of researchers from diverse departments. Finally, we analysed the identified clusters to propose an Interdisciplinarity Sustainability Index (ISI) capable of identifying the most investigated and interdisciplinary SDGs. Ultimately, our results enable the quantification of interdisciplinary SDG research via the proposed methodology. The study helps to visualise inter-departmental collaborations and thus informs university managers' efforts to identify and coordinate compatible research groups to bridge inter-organisational boundaries.

1. Introduction

The UN's 17 Sustainable Development Goals (SDGs) included in the 2030 Agenda for sustainable development aim to guide countries towards a sustainable future and a more peaceful and inclusive society (Gupta & Vegelin, 2016; Lim, Jørgensen & Wyborn, 2018). Achieving these goals is only possible by reducing poverty, hunger, the gender gap and inequalities and increasing the sustainable management of resources and awareness about climate change (Reckien et al., 2017). The past five years have witnessed considerable progress towards achieving the SDGs. However, this progress remains uneven across countries and fields of application (i.e. climate change, improving health and living conditions, promoting quality education, etc.). These disparities underscore the need to involve all stakeholders in pursuing the respective objectives by 2030 (United Nations, 2020).

With their leading position in orienting education, research and societal outreach towards the sustainable development of people and societies, higher education institutions (HEIs) have been recognised worldwide as important stakeholders within the SDG framework (Klofsten, Fayolle, Guerrero & Mian, 2019; Leal Fihlo, Shiel, Paço & Mifsud, 2019). Importantly, the contributions of HEIs should not be gauged in terms of scientific production and the mere creation of knowledge. Rather, HEIs' contributions should be gauged in terms of their ability to address local grand challenges through collaboration, civic engagement and dissemination (Corazza & Saluto, 2021; Leal Filho et al., 2018; Findler et al., 2019; Waas, Verbruggen & Wright., 2010).

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For instance, The Times Higher Education (THE) impact ranking is an international bibliometric-based ranking, which evaluates HEIs based on SDG-related scientific production by considering the research productivity and the number of citations the scientific publications receive at the global level (Times Higher Education, 2021). Similarly, the QS World University Rankings evaluates, among other indicators, citations per faculty on a five-year basis (QS World University Rankings, 2022). Scholars believe that such assessments can promote HEI-based research related to the SDGs and even create positive competition among HEIs (Chankseliani & McCowan, 2021).

Sustainability scientists have recently demonstrated the SDGs' interdependence (Lucatello & Huber-Sannwald, 2020). Therefore, scholars have recognised interdisciplinarity as essential for SDG-related research (Castree et al., 2014; Nilsson et al., 2018; Keynejad, Yapa & Ganguli, 2021). This assertion is consistent with the recommendations of the seminar literature, which has highlighted the vital role of interdisciplinary research in solving the grand challenges of the 21st century (Gibbons, 1994; Castree et al., 2014; Nilsson et al., 2018; Popowitz & Dorgelo, 2018; Gilbertson, Craft & Potter, 2019). In recent decades, scholars have sought to illuminate the full potential of interdisciplinary research (Wagner, Roessner, Bobb & Klein, 2011; Leydesdorff & Rafols, 2011) by investigating both its psychological implications (Woiwode & Froese, 2020) and its assessment methodologies (Stirling, 2007). Unfortunately, the application of interfdisciplinary research in achieving the SDGs remains in its infancy. However, the academic community is making noticeable strides towards promoting the influential role of interdisciplinary research in achieving the SDGs (Brown, Werbeloff & Raven, 2019; Wohlgezogen, McCabe, Osegowitsch & Mol, 2020).

While the UN Statistical Commission has also supported regional and national data collection on the SDGs, no guidelines exist for data collection at the micro level, especially regarding single HEIs' contributions (Boeren, 2019). Thus, measuring HEIs' scientific production regarding the SDGs, especially when such efforts are interdisciplinary, remains a challenge and subject of debate (Zhou, Rudhumbu, Shumba & Olumide, 2020). From a business perspective, it is not yet clear how to convert useful bibliometric explorations into transformative managerial tools. Such tools are essential, however, to help decision-makers at an organisation level raise awareness and manage interdisciplinary collaborations towards sustainability (Griggs, Nilsson, Stevance & McCollum, 2017; Nilsson et al., 2018).

In addition to this research gap, this study addresses the need to support HEI decision-makers with various tools for the institutional mapping of SDG research contributions and for the evaluation of the interdisciplinarity of such contributions. Such tools must be adaptable and customisable to individual universities and their specific organisational features. To address this need, this study aims to design an information system (IS) artefact, following the principles of the information system design theory (ISDT), as defined by Gregor and Jones (2007), by answering the following research questions: 1) What are the main features an IS artefact should fulfil to measure the interdisciplinarity in scientific contributions related to SDGs within an HEI? and 2) How can such an IS artefact be designed to be robust to changes in indicators, fields/topics, cluster sizes or institutions analysed? The main rationale for adopting the ISDT principles as a theoretical framework emerges from the necessity to develop and design a replicable and scalable tool capable of being modified by future scholars without affecting its validity and the whole structure of the designed artefact. Thus, the main aim of this study is to present the fundamental components of an IS artefact required to assess interdisciplinarity in an HEI related to a specific topic, such as the SDGs.

This study presents a multi-step methodology and then applies it to the University of Turin in Italy as an initial case study. With clear reference to ISDT (Gregor & Jones, 2007), the study introduces an entropy-based indicator to assess each SDG's interdisciplinarity and identify the presence of the most active research groups within the HEI. Using an internal database for the entirety of scientific publications at the University of Turin from 2015 to 2019, we labelled each contribution according to a set of keywords for each SDG. We then sorted, ranked and scored them using a quantitative text analysis (QTA). We scored each publication based on whether a particular keyword appeared within its journal/conference title, contributions or abstract. Subsequently, we built a co-authorship network through a social network analysis (SNA). In this way, we sought to identify interdisciplinary collaborations by comparing the academic affiliations of authors (i.e. the department to which each author belongs) with a bottom-up classification realised using the modularity clustering algorithm (Blondel, Guillaume, Lambiotte & Lefebvre, 2008). Finally, we measured the interdisciplinarity level of each SDG by analysing the emerging bottom-up clusters through an entropy-based indicator.

The remainder of the paper is structured as follows. The first section offers a brief literature review related to the SDGs and interdisciplinarity in HEIs. This review focuses on the relationship between the SDGs, interdisciplinary research and its measurement. The Methods section describes the proposed multi-step methodology in detail. In the Results section, we apply the methodology to the case study and present the results, while in the Discussion section, we interpret the results based on ISDT. The Conclusion presents the final remarks and managerial implications.

2. Literature review

2.1. Sustainable development goals in HEIs

Currently, challenges related to sustainability are a matter of primary concern and importance for HEIs (Ruiz-Mallen & Heras, 2020; Ramisio et al., 2019; Leal Filho et al., 2018). HEIs are now working to address various sustainability-related challenges, which are linked to the institutions' tripartite mission of *conservation, research and education* (Etzkowitz & Webster, 1998). The interactions among *conservation, research and education* are conceptually and practically complex. However, these interactions become even more complex when the sustainability dimension is added. Since the late 1990 s, HEIs have been encouraged to pursue sustainability and integrate its principles into their mission (Leal Filho, 2010). However, these endeavours are challenging for HEIs and often leave them lagging behind industries and private companies (Lozano et al., 2013). Nevertheless, many HEIs have demonstrated their commitment towards the sustainable development agenda by signing declarations and charters (Lozano et al., 2013; Waas, Verbruggen & Wright, 2010). These include the Talloires Declaration in 1990 (Nejati, 2013) and the Principles for Responsible Management Education (PRME) in 2007 (UNGC, 2007). According to the United Nations Global Compact initiative, for instance, companies and institutions '*need integrative management tools that help embed environmental, social and governance concerns into their strategic thinking and daily operations*' to internalise sustainable development in the core business (Burghate, 2017). To this end, HEIs must support behavioural change among students, researchers and external stakeholders via various activities, such as business education, research and management development programmes (Findler et al., 2019; Leal Filho et al., 2018; Finnveden, Newman & Verhoef, 2019; Caeiro, Sandoval Hamón, Martins & Bayas Aldaz, 2020).

Following the earlier debate about sustainable development, the UN established the 17 SDGs, comprised of 169 targets, within the Agenda 2030. In doing so, the UN issued a special call for HEIs to actively promote and support the SDGs in education and research (Annan-Diab & Molinari, 2017; Utama et al., 2018). Thus, HEIs are expected to act as 'change agents' (Körfgen et al., 2018), advancing SDG ideals through problem-oriented research and consistent education programmes. Confirming Sterling's (1996) assertion at the beginning of the 'sustainability era', Wals (2014) suggests that universities might even view sustainability as an impetus for a more systemic transformation in their position towards society. Driving HEIs towards sustainable transformation remains difficult, however, because of barriers that are often organisational and related to each university's management and governance (see, for instance, the case of Lund University, discussed Lidgren, Rodhe & Huisingh (2006)).

The potential of SDGs to mobilise and maintain interests within an HEI requires the nexus of education, sustainable development and human development (Agbedahin, 2019). If the commitment of an HEI towards the SDGs is sincere and the organisation is transformed, local policymakers might improve their decision-making process regarding local sustainable development issues by relying on the university's highly skilled researchers and updated scientific knowledge to intervene locally (Miotto, Del-Castillo-Feito & Blanco-González, 2020; Moon, Mariadoss & Johnson, 2019; Plewa, Ho, Conduit & Karpen, 2016; Vilalta, Betts & Gómez, 2018). Moving out from campus, HEIs will thus become pivotal actors driving the sustainability transition (Körfgen et al., 2018; Tilbury, 2011).

Vaughter (2018) adds that when HEIs adopt a transformative organisational approach to sustainability, academia and civil society can provide factual support for the sustainability transition (Cotton et al., 2009; Krishnamurthy, 2020). Hence, scientific production should facilitate the creation of new knowledge. Local policymakers, in turn, can put this knowledge to use to tackle complex problems (Griggs, Nilsson, Stevance & McCollum, 2017). Nevertheless, guidance at the managerial level is limited regarding the impact of this transformational leadership on human resources working in HEIs (Singh, Del Giudice, Chierici & Graziano, 2020).

While SDGs in the last years have impacted HEIs' traditional curricula (Sánchez-Carracedo et al., 2019; Thomas, 2015), the research motivations and personal attitudes of scholars are a matter of individual interactions and are still under study. University managers can support and appropriately orient these interactions via policies and organisational techniques, such as research groups, research centres and dedicated budgets (Sonetti, Brown & Naboni, 2019; Sonetti, Barioglio & Campobenedetto, 2020). The ability to visualise and track the dynamics of internal research groups working for SDGs would provide university managers with an effective tool. Indeed, it would allow them to involve the best researchers with theoretical knowledge in the service of public policy—i.e. to promote impact or academic engagement (Ishizaka & Pereira, 2016). In addition, HEIs can encourage researchers to bridge and synthesise various perspectives and thereby develop a holistic and systemic approach for addressing sustainability challenges (Secundo, Ndou, Del Vecchio & De Pascale, 2020).

2.2. Interdisciplinarity for SDG-related research and the measurement challenge

Interdisciplinary research can promote the deep and multifaceted knowledge required to face the so-called grand challenges (Annan-Diab & Molinari, 2017; Eagan, Cook & Joeres, 2002; Zhou, Rudhumbu, Shumba & Olumide,2020; Zoller, 2015). To that end, the Talloires and Kyoto Declarations and the Copernicus Charter (DeFries et al., 2012; Waas, Verbruggen & Wright, 2010) have urged universities to transition towards interdisciplinary-oriented knowledge production (Clark & Wallace, 2015). Thus, the SDG agenda requires HEIs to overcome the '*silos-single-discipline*' paradigm, which typically results in fragmented fields of knowledge. A superior alternative, interdisciplinarity takes a multiple and holistic perspective towards sustainability issues. As Leal Filho et al. (2018, p. 134) argued, 'The multifaceted problems included in the SDGs and the individual targets necessitate interdisciplinary research and intersectoral collaboration to be achieved'.

Developing knowledge about how to effectively promote, design and deliver interdisciplinary research is fundamental to realise the SDG agenda. Brown, Deletic and Wong (2015) propose applying five principles to SDG research. These principles are as follows: forge a shared mission, develop T-shaped researchers, nurture constructive dialogue, give institutional support and bridge research, policy and practice. Establishing interdisciplinary academic departments is an increasingly common response to contemporary society's complex problems. Researchers are driven to collaborate and thereby discover new knowledge, understand the growing specialisation and complexity of science (Beaver, 2001) and develop a broader understanding of disciplines (Katz & Martin, 1997). Incentivising the institutionalisation of interdisciplinary research groups is among the support that HEIs must consider vital for enhancing SDG-related studies. These interdisciplinary groups have the potential to connect multiple sources of knowledge, which can serve institutions and societies (Nhamo & Mjimba, 2020). These diverse teams have exhibited the most significant potential in certain sectors, such as healthcare. This is because the valuable process of sharing diverse experiences, knowledge and backgrounds can reveal novel paths for experimentation and innovation (Secundo, Del Vecchio, Simeone & Schiuma, 2020). Meanwhile, knowledge translation, which is intended to make knowledge accessible to stakeholders in various contexts, is crucial for multidisciplinary teams (Cobianchi et al., 2020; Savory, 2006).

Because multidisciplinary teams have diverse backgrounds and skills, however, they require managerial and working practices that can foster the effective translation of knowledge (Cobianchi, et al., 2020). If these practices are lacking and the knowledge translation process does not work properly, some scientists might be uncomfortable with interdisciplinarity. Thus, some disciplines continue to encounter opposition to including interdisciplinarity as a valid criterion. When people or groups exhibit diversity, translation issues necessarily emerge, which, in turn, reduces work performance (Cobianchi, Del Mas & Angelos, 2021). Meanwhile, Summers, Childs and Corney (2005) argue that the excessive number of disciplines involved could represent another risk involved in interdisciplinarity. The higher the number of disciplines, the greater is the need for successful coordination. Other institutional barriers include the scarcity of funding for interdisciplinarity research and scientific publishing (Woiwode & Froese, 2020). Although international rankings are beginning to evaluate SDG-related research, university managers are currently seeking technologies and tools to visualise and quantify the related scientific production.

In light of the need for such collaboration at HEIs, measuring interdisciplinarity has become crucial. However, studies have offered little more than anecdotal evidence on the topic (Leahey & Barringer, 2020). Previous scholars have proposed various ways to approach the question. Porter, Cohen, Roessner and Perreault (2007) and Rafols and Meyer (2010), for example, propose some quantitative indices, and Shannon's entropy offers an effective indicator of interdisciplinarity (Zuo & Zhao, 2018). However, few unit-level measures have been proposed thus far. Most existing measures, moreover, refer to a specific project, department or centre rather than to the larger university to which they belong (Cheng & Liu, 2006). Indeed, scholars have largely overlooked the need for university-level measures. Cassi, Mescheba and De Turckheim, (2014) noted authors' affiliations and averaged their article-level interdisciplinary scores to the university level. Jacobs and Frickel (2009) identified interdisciplinary areas by examining the proportion of faculty members with degrees in other disciplines; their study thus assumes that working in a discipline different from the one in which one was trained is a sign of interdisciplinarity. Rafols et al. (2012) sought further to compare universities in the UK, calculating an overall measure of interdisciplinarity pooling references used in all articles published by all university researchers.

At the same time, many researchers have mapped interdisciplinarity using network theory. However, most previous research has not utilised author-based analysis because information about authors' disciplines is not readily available in most datasets (Nah & Suh, 2021). In addition, verifying authors' affiliations by reviewing their manuscripts can be tedious (Schummer, 2004).

As described in the paragraph above and summarised in Table 1, some efforts have been made to construct and validate a measure of university commitment towards interdisciplinary research using

Table 1
Comparison of some relevant works assessing the interdisciplinarity of research.

Article	Level	Network type	Fundamental units	Methodology	Topic	Short description
Novel multi-step methodology	Institutional (such as HEIs) and departmental relations	Co-authorship	Real affiliations of authors	Shannon entropy, bottom-up and top-down clustering matrix	SDGs	Evaluating strategies for research (creation of interdisciplinary centres, identifying research groups) on precise topics
Porter, Cohen, Roessner & Perreault (2007)	National, National Academies Keck Futures Initiative (NAKFI) participants	Citations	Diversity in references (*WoS* subject categories)	Rao-Stirling diversity, Shannon or Herfindahl index, percentage of citations within-field	*WoS* subject category	Mapping attendees at international conferences
Rafols & Meyer (2010)	International	Citations	Diversity in references (*WoS* subject categories)	Rao-Stirling diversity, network coherence	Bionanoscience (molecular motors)	Measuring the interdisciplinarity of authors; evaluating interdisciplinary programmes; discussing the emergence and diffusion of research topics
Cassi, Mescheba & De Turckheim (2014)	Institutional	Citations	Diversity in references (*WoS* subject categories)	Rao-Stirling diversity (within and global)	*WoS* subject categories	Providing information—via the global index—on the interdisciplinary practices of institutions in a given research domain for strategic and management issues
Na & Suh (2020)	International	Co-authorship	Self-declared interests in *Google Scholar*	Shannon entropy	Complexity science	Determining the extent to which a heterogeneous community is truly interdisciplinary

bibliometric, textual and network techniques (Cassi, Mescheba & De Turckheim, 2014; Nah & Suh, 2021). To date, however, scholars have made few quantitative efforts to measure interdisciplinarity in SDG-related scientific production at the university level. Moreover, to our knowledge, no study on the SDGs has utilised author-based analysis. Such an analysis, however, has been proposed as among the easiest forms of collaboration across fields and an effective method to study social and intellectual structure (Boyack, Klavans & Börner, 2005). For instance, Bautista-Puig, Mañana-Rodríguez and Serrano-López (2021) measured interdisciplinarity in a range of green and sustainable science and technology journals without presenting data at the institutional level or using the SDGs. Only Ramirez, Romero, Schot and Arroyave (2019) found similarities regarding the use of the SDGs to detect interdisciplinary knowledge communities in Mexico, although without measuring the interdisciplinarity level of a single community. Moreover, it is becoming increasingly crucial for universities—and, in particular, public universities—to demonstrate not only to their financiers but to all stakeholders their ability to generate positive impacts on the territory through their coupling strategies. In this sense, it becomes crucial to understand how teaching generates societal outreach and, in turn, how research activities translate to societal outreach. The model presented in this research, therefore, aims to provide additional data that can contribute to HEIs' need to report not only whether but also how their research projects generate social impacts.

For these reasons, measuring the contribution of HEIs to the SDGs is both a current and complex task. Attempting to address the issue using bibliometric analysis, scholars have reached divergent conclusions (Armitage, Lorenz & Mikki, 2020;; Di Vaio, Palladino, Hassan & Escobar, 2020; Meschede 2021; El-Haddadeh, Osmani, Hindi & Fadlalla, 2021). In contrast, this study directs attention to the ways in which universities are using interdisciplinary research to address the SDGs.

2.3. *Visualising and measuring interdisciplinary SDG-related scientific production*

Measuring the interdisciplinarity of research is a multifaceted task because *collaboration* between researchers is the fundamental criterion to be considered (Milojeví, 2010; Stirling, 2007; Wagner, 2009). Scholars have studied collaboration networks using several methodologies. These include bibliometrics (Bordons & Gomez, 2000), qualitative interviews (Shrum, Genuth, Carlson, & Chompalov, 2007), surveys (Birnholtz, 2006), SNAs and centrality indices (Wagner & Leydesdorff, 2005). Among quantitative methods, citations and co-citations appear the most promising and efficient. Nevertheless, they are not exhaustive measures of interdisciplinarity. Meanwhile, SNA methods allow more detailed analyses. However, their interpretation and application are not straightforward (Bamel, Pereira, Bamel & Cappiello, 2021; Bamel, Pereira, Del Giudice & Temouri, 2020; Wagner, Roessner, Bobb & Klein, 2011). For instance, scholars have employed betweenness centrality to evaluate journals (Leydesdorff, 2007) and authors' (Schummer, 2004) interdisciplinarity. Nevertheless, authors' departmental affiliations have not been commonly utilised to analyse co-authorships networks because databases do not usually include authors' disciplines or departmental orientations (Porter, Cohen, Roessner & Perreault, 2007). The managerial side, meanwhile, requires an understanding of how the SDGs are addressed and by whom. Such an understanding may help university managers to organise collaborative groups capable of generating a greater impact (Brown, Werbeloff & Raven, 2019).

Two main approaches exist to measure interdisciplinarity. First, the structuralist approach includes knowledge transfer and researchers/papers' performances. Second, the spatial approach (Garfield, Malin & Small, 1978) typically focuses on a single object—e.g. a paper, author or journal—and takes into account the distance between nodes to measure a specific feature. In this approach, nodes, or links, are labelled. Then the collaboration network is analysed to identify interdisciplinary collaborations (Van Den Besselaar & Leydesdorff, 1996). *Diversity* is a fundamental concept among interdisciplinary research indicators (Rafols & Meyer, 2010). Stirling (2007) defined diversity as the combination of *variety* (the number of disciplines), *balance* (the evenness of distribution) and *disparity* or *similarity* (the degree of difference between disciplines). The measurement and visualisation of diversity in SDG-related scientific production thus become the focus of the proposed methodology, which is grounded in the concept of entropy.

Often applied in thermodynamics, information theory and statistical mechanics, entropy is an indicator of disorder in a system. Entropy can be used to measure the information within a system. In addition, if properly defined, it can include, by definition, the number of elements (e.g. department and disciplines) and their evenness of distribution. Hamilton, Narin and Olivastro, (2005) proposed entropy as an indicator of diversity. Using entropy in association with bottom-up approaches based on clustering algorithms or data visualisation tools (Cottafava, Sonetti, Gambino & Tartaglino, 2018) may serve to build a novel decision-making methodology (Chen, 2004). The next section presents and develops a multi-step methodology to measure and visualise interdisciplinarity for SDG-related scientific production (Singh & El-Kassar, 2019). The design process follows ISDT, which is discussed in the next subsection.

2.4. Information system design theory

Introduced by Walls, Widmeyer and El Sawy (1992) based on Dubin's theory–research cycle (Lynham, 2002), ISDT aims to design and implement an information system (IS; Gregor & Jones., 2007). Generally speaking, an IS is a system to collect, process, store and distribute information (Piccoli & Piagni, 2019). It includes five essential components: 1) hardware, 2) software, 3) data, 4) procedures and 5) people (Kroenke, Boyle & Poatsy, 2010). According to Aronson, Liang and MacCarthy (2005), ISDT focuses on the basic requirements to design specific IT architectures as knowledge management (Girard & Girard, 2015) or decision support systems (Keen, 1980). Walls, Widmeyer and El Sawy, (1992) defined ISDT as '*prescriptive theory, which integrates normative and descriptive theories*'. Meanwhile, Gregor and Jones (2007) stated that '*understanding the nature of ISDT supports the cumulative building of knowledge rather than the re-invention of design artefacts*'. Hence, ISDT as a prescriptive theory—like a normative theory—aims to define the ideal norm, artefact or system/process. This is in contrast with the objective of descriptive that is to describe an object as it is, while prescriptive theories aims to define the norm, artefact or system/process as it should or will be. Indeed, the goals and aims of design theories are intrinsically defined within the theory (Walls, Widmeyer & El Sawy, 1992). Following Dubin's theory–research cycle, ISDT is composed of two main phases. First, a conceptual framework for the theory must be defined during theory development. Second, the research operation must empirically test and instantiate the theory (Lynham, 2002). Both phases are based on various features, which must be declared and defined. Walls, Widmeyer and El Sawy, (1992), for instance, introduced several features: 1) *meta*-requirements, 2) *meta*-description, 3–4) product/process hypotheses, 5–6) product/process kernel theories and 7) design method. Each of these aspects emphasises the word *meta* because design should refer to classes of objectives/products rather than to a single objective/product. More recently, Gregor and Jones (2007) defined eight fundamental components of an IS artefact's definition: 1) purpose and scope, 2) constructs, 3) principles of form and function, 4) artefact mutability, 5) testable propositions, 6) justificatory knowledge, 7) principles of implementation and 8) expository instantiation. The first six components comprise the fundamental requirements for a new IS artefact. Meanwhile, the last two, which involve the actual implementation of the artefact, are optional. In particular, the purpose and scope defines the system's goals, scope and boundaries (the causa finalis) while the constructs refer to the basic entities of the artefact (the causa materialis). Meanwhile, the principles of form and function generally identify and describe the architecture and process adopted. Artefact mutability, the testable propositions and justificatory knowledge represent, respectively, the hypotheses, eventual change and modification to be tested and underlying knowledge and theories. Finally, the principles of implementation (the causa efficiens) and the expository instantiations are the processes required to implement the artefact.

3. Methods

This paper's design process follows the model of Gregor and Jones (2007) first to conceptualise an IS artefact and then to apply and test it. We define an IS artefact as a *design method* to support the governance of HEIs to evaluate, monitor and analyse the interdisciplinarity of academic research collaborations within a specific theme/field (e.g. within the framework of the SDGs). Such a method enables the evaluation of the overall performance of an institution as well as the identification and evaluation of individual groups of researchers. The rationale for defining an IS artefact following the ISDT principles rather than analysing the University of Turin as a case study lies in the aim of this study, which is to identify the fundamental features and processes of a generalizable IS artefact capable of assessing the interdisciplinarity of scientific publications related to SDGs (or any other topic) rather than generalizing the findings related to the case study. The IS characteristics and fundamental features corresponds to Components 1–6 while the application to the case study refers to Components 7–8.

Table 2 summarises the full declaration of the eight features required for the IS design method. The method should be robust to change (artefact mutability and testable propositions) in the selected field/topic, ISI or institution analysed and its composition (e.g. number and typology of departments). The causa formalis (principles of form and function) evaluates the interdisciplinarity of the research collaborations in an HEI at various levels (from the research group to the entire

Table 2
Component type and description of ISIs in HEIs.

n°	Component Type	Description
1	Purpose and scope (the causa finalis)	The aim is to develop an IS tool to support the governance of HEIs by evaluating, monitoring and analysing interdisciplinarity in academic research collaborations within a particular theme/field (e.g. within the framework of the SDGs). These efforts will facilitate evaluations of the overall performance of an institution and the identification of individual groups of researchers engaged in interdisciplinary research. The boundary of the analysis is the scientific production (papers, chapters, book chapters, proceedings, etc.) of the target institution.
2	Constructs (the causa materialis)	The basic entities are scientific contributions (e.g. papers, books), authors (e.g. researchers, professors) and their affiliations (e.g. departments), collaborations (e.g. co-authorships) and theme/field keywords (e.g. SDG).
3	Principles of form and function (the causa formalis)	An ISI should evaluate the interdisciplinarity of collaborations at an HEI within a theme/field by comparing the academic affiliations of authors with emerging bottom-up clusters of various sizes (from a single research group to entire departments).
4	Artefact mutability	The artefact can be adapted for any HEI with precise department subdivisions and any field/theme requiring investigation. The artefact is capable of evaluating any—and any number of—departments and fields/themes of study.
5	Testable propositions	The artefact should be robust to changes in interdisciplinarity indicators, fields, cluster sizes or institutions analysed.
6	Justificatory knowledge	The artefact derives from previous interdisciplinarity indices (Stirling, 2007) and relevant discussions. The relevance of interdisciplinarity in education, research and innovation is well supported in the extant literature (Hicks & Katz, 1996; Klaassen, 2018; Leahey & Barringer, 2020)
Additional components		
7	Principles of implementation (the causa efficiens)	The overall process consists of at least three sub-processes: 1) labelling scientific contributions and authors (ranking process), 2) unveiling emerging clusters of authors (interdisciplinarity matrix) and 3) evaluating interdisciplinarity. Fig. 1 offers a detailed depiction of the specific process for the instantiation.
8	Expository instantiation	An initial experiment was conducted on the database (DB) of the University of Turin by evaluating the 17 SDGs (17 fields/themes) across the university's 27 departments. The robustness to index change was assessed via two interdisciplinarity indicators.Although no test has been conducted on different institutions or cluster sizes, the former can be deduced from the basic units and boundaries defined (if an institution has a department subdivision, it is possible to identify the authors' affiliations, which is necessary to evaluate interdisciplinarity) . Meanwhile, the latter simply depends on the clustering algorithm employed and its resolution.

institution). The basic constructs are the scientific contributions, the authors and their affiliations and information on collaborations—for instance, co-authorships in the case of papers and the keywords necessary to select relevant scientific contributions.

The next two sections focus on the final two components required for an initial implementation, i.e. the principles of implementation and the expository instantiation.

3.1. Principles of implementation

To evaluate interdisciplinarity, we adopt a spatial approach (Garfield, Malin & Small, 1978), which focuses on a single object (in our case, the author). With *diversity* (Rafols & Meyer, 2010) as the fundamental concept to be measured, we utilise Stirling's (2007) three components: 1) *variety* (the number of disciplines), 2) *balance* (the evenness of distribution) and 3) *disparity* or *similarity* (the degree of difference between disciplines). Thus, because the Interdisciplinarity Sustainability Index—defined in Fig. 1 and the paragraphs below—considers local density, it is intrinsically based on the spatial distance between nodes.

Fig. 1 depicts the overall flowchart and methodology for building an Interdisciplinarity Sustainability Index (ISI). The implementation of the IS method consists of three main processes: 1) a scoring, ranking and labelling process, 2) the construction of an Interdisciplinary Collaboration Matrix and 3) the evaluation of an ISI. The following subsections describe these three processes in detail. Finally, we apply and test the design method on an initial case study, i.e. the University of Turin's research products related to the 17 SDGs. Through this case study, we aim to validate the method's robustness to changes in interdisciplinarity indicators, fields/themes, recognisable cluster sizes or institutions analysed.

The proposed methodology involves three main steps:

(1) *Scoring, ranking and labelling:* A QTA (Jockers & Thalken, 2020) of the database of an HEI's scientific contributions to label and assign each research contribution and the corresponding authors to one or more fields/themes based on a list of keywords for each field;
(2) *Interdisciplinary Collaboration Matrix*: An SNA of the co-authorship network (Wagner & Leydesdorff, 2005) of the selected database aimed at identifying emerging bottom-up clusters via their high interconnectedness and density;
(3) *Interdisciplinarity Sustainability Index*: A statistical analysis of the emergent clusters to quantify the interdisciplinarity of each bottom-up cluster and thereby rank the entire body of an HEI's research production for each field/theme.

Scoring, ranking and labelling. A score must be assigned to each research contribution based on a set of keywords related to the selected field/theme (in our case, the 17 SDGs). The score of the contribution j depends on three weights w_x and is quantified via the following formula:

$$K_{ij} = k_i\left(\sum_{x=1}^{3} w_x n_{x,ij}\right) = k_i\left(w_1 n_{1,ij} + w_2 n_{2,ij} + w_3 n_{3,ij}\right) \quad (1)$$

where K_{ij} is the total score for the contribution j and keyword i, k_i is the weight for keyword i, w_x is the weight for the parameter x and $n_{x,ij}$ is the occurrence of the keyword i within the text of the parameter x for contribution j. The three parameters $x = 1, 2, 3$ are (1) the journal/conference name or the title of the book, (2) the title of the contribution and (3) the text of the abstract and the author's keywords. To assign a different score according to the occurrence of a keyword within the three texts separately and independently, we adopted three weights: $w_1 = 10; w_2 = 5; w_3 = 1$. As an initial hypothesis, we set an identical weight $k_i = 1$ for each keyword. Finally, by summing the corresponding score for each keyword i, we obtained the total score $K_{SDGx,j}$ for each contribution j for *SDGx* as follows: $K_{SDGx,j} = \sum_{i=1}^{N_{SDGx}} K_{ij}$, where N_{SDGx} is the total number of keywords for *SDGx*. Subsequently, we evaluated a preliminary ranking. To properly select the contributions related to one SDG and set a logical flag $\theta \in [TRUE, FALSE]$ for each contribution related to each SDG, we set a threshold δ as follows:

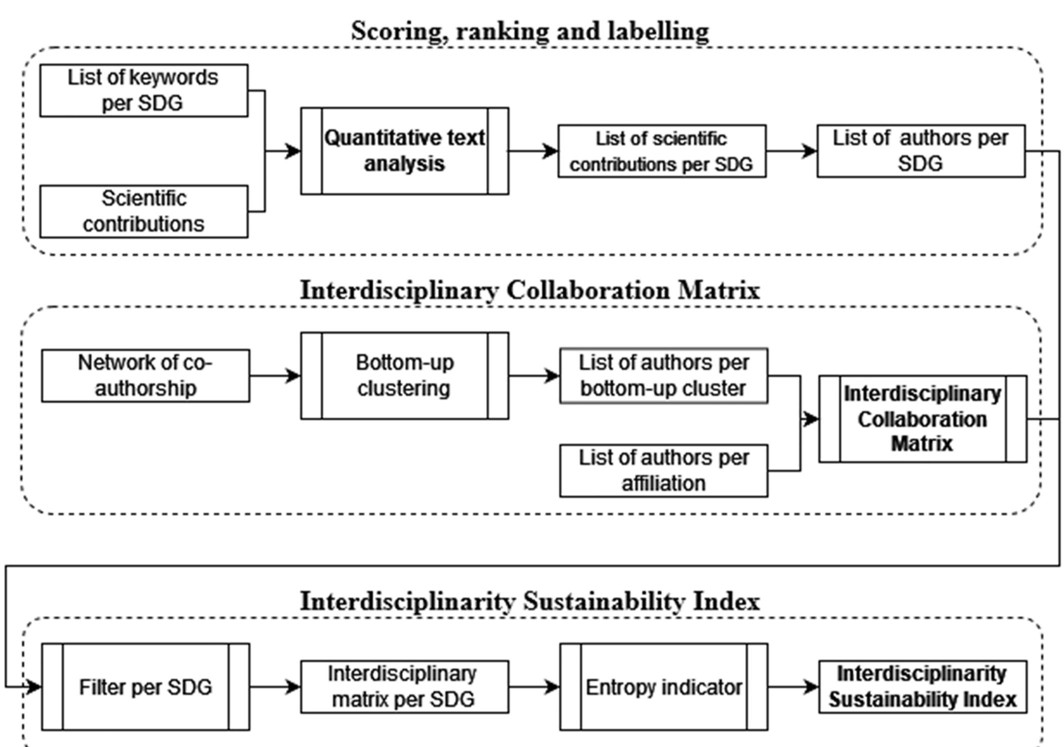


Fig. 1. Overall flowchart to build the Interdisciplinarity Sustainability Index.

- if $K_{SDGx,j} \geq \delta \rightarrow \theta = TRUE \rightarrow$ 'contribution *j* belongs to *SDGx*';
- if $K_{SDGx,j} < \delta \rightarrow \theta = FALSE \rightarrow$ 'contribution *j* does not belong to *SDGx*'.

A threshold of 5 with the three weights (1, 5, 10) led us to automatically select the contribution *j* if a keyword occurred in the journal name ($w_1 = 10$) or in the contribution title ($w_2 = 5$).

We then assigned the same score to the corresponding co-authors for each scientific contribution. Finally, we computed the total author score by adding the scores for all scientific contributions attributed to the author for a particular field/theme.

Interdisciplinary collaboration matrix. The following step involves assessing the collaboration network (in our case, the co-authorship network) by selecting the contributions and identifying the emergent clusters—based on a high density of collaborations—using a clustering algorithm (in our case, the modularity algorithm [Blondel, Guillaume, Lambiotte & Lefebvre, 2008] with a resolution of 1.0 [Lambiotte, Delvenne & Barahona, 2008]).

Interdisciplinarity Sustainability Index. According to Stirling (2007), interdisciplinarity primarily depends upon the number of disciplines, the evenness of distributions and the degree of difference between disciplines. Lacking a standard method to evaluate the difference between disciplines and avoid disputable results, this work focused solely on the number of disciplines and the evenness of their distribution within the bottom-up clusters. We adopted three indices: 1) N_i, the number of departments within cluster *i*, 2) σ_i^2, the variance within cluster *i* and 3) S_i, the information entropy of Shannon (Witten, 2020) of cluster *i*. Shannon's entropy, previously adopted as an indicator of diversity in interdisciplinarity (Hamilton, Narin & Olivastro, 2005), represents the amount of information within a particular system. It is commonly used in IS to analyse, encode and decode information within a signal. We utilised a slightly modified version of Shannon's entropy to quantify the interdisciplinarity of the cluster *i* according to the following formula:

$$S_i = -\sum_{j=1}^{N} P_{ij} log_N P_{ij} \quad (2)$$

where S_i is the entropy of cluster *i*, P_{ij} is the probability of identifying the department *j* in the bottom-up cluster *i* and *N* is the total number of departments within the analysed HEI. The base *N* of the logarithm guarantees that S_i is normalised between 0 and 1 for each cluster *i*. The three measures of interdisciplinarity—N_i, σ_i^2 and S_i—can be interpreted in a straightforward manner for every cluster *i* and *j* as follows:

(1) if $N_i \geq N_j AND \sigma_i^2 \leq \sigma_j^2 \rightarrow$'cluster *i* is more interdisciplinary than cluster *j*';
(2) if $N_i > N_j AND \sigma_i^2 > \sigma_j^2 \rightarrow$ 'cluster *i* is not comparable with cluster *j*';
(3) if $N_i < N_j AND \sigma_i^2 < \sigma_j^2 \rightarrow$ 'cluster *i* is not comparable with cluster *j*';

The above definition is grounded in the notion that a higher number of engaged departments within a cluster means that greater interdisciplinary exists in that cluster. Furthermore, the more equally distributed are the engaged departments within the cluster, the higher is the cluster's interdisciplinarity. From this definition, N_i and σ_i^2 are intrinsically connected and thus cannot be measured in isolation. Meanwhile, entropy can be assessed without additional indications as follows:

(1) if $S_i > S_j \rightarrow$'cluster *i* is more interdisciplinary than cluster *j*';
(2) if $S_i = S_j \rightarrow$ 'cluster *i* is equally interdisciplinary as cluster *j*';
(3) if $S_i < S_j \rightarrow$'cluster *i* is less interdisciplinary than cluster *j*';

3.2. Expository instantiation

We utilised the publications database of the University of Turin (UniTo) between 2015 and 2019 as a case study. The use of an internal database enabled us to overcome common problems related to the lack of data about authors' precise disciplines (Porter, Cohen, Roessner & Perreault, 2007). The entire database consists of 30,991 research contributions (papers, proceedings, books and book chapters, among others) written by 2,230 authors from the university's 27 departments. UniTo is a generalist university with departments ranging from philosophy and the humanities to physics and chemistry. Appendix A in the supplementary information (SI) provides the full list of departments. As a case study, UniTo offers an information-rich test. Thus, it may enable the analytical generalisation of findings to other generalist universities (Johansson, 2007). Although not a PRME signatory (UNGC, 2007), this university offers a relevant case study as a pioneer in placing sustainable development and sustainability at the core of its strategic mission through interdisciplinarity (Corazza, 2018). Considered a mega-university with more than 80,000 students, UniTo has received prestigious awards from the Italian Ministry for its research regarding societal outreach and public engagement. In addition, it is among the founders of the Italian Network for Sustainable Universities (RUS) and among the first Italian HEIs to be ranked by GreenMetric (achieving second place among Italian HEIs and 23rd place in the overall ranking in 2021) (Baricco et al., 2018). Furthermore, for over six years, the university has consistently provided data on its sustainability-related scientific production via its sustainability report. Thus, the case study's relevance is ensured by the necessity of providing HEI administrators with proper assessment and monitoring tools through a standardised methodology that can promote the sustainability transition (Leal Filho et al., 2018; Avelar, da Silva-Oliveira & da Silva Pereira, 2019).

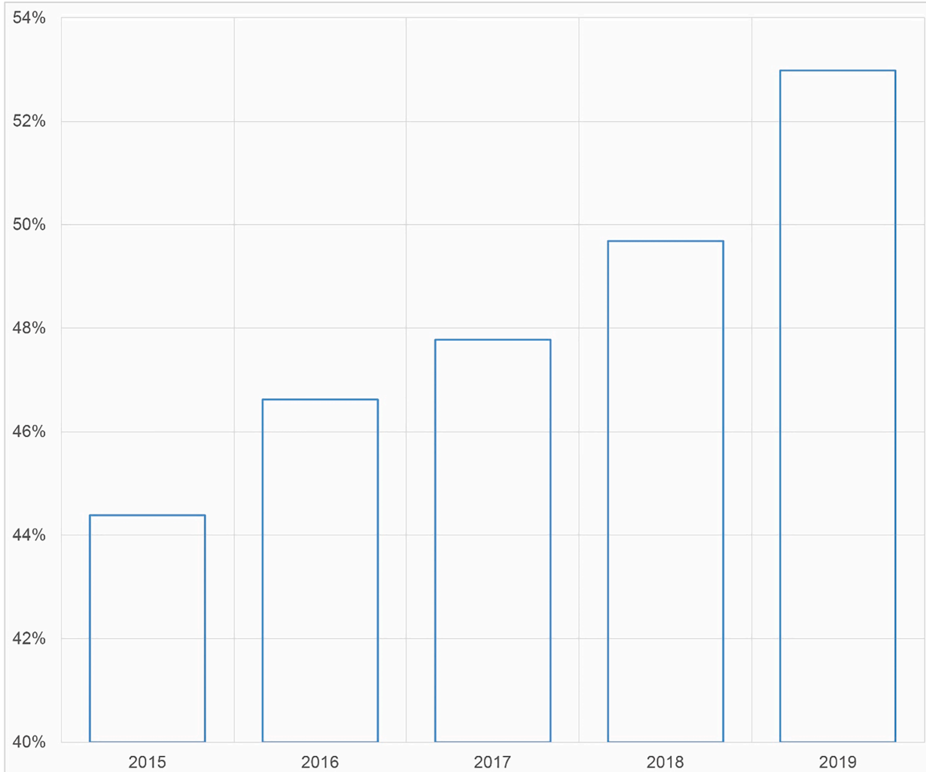
We selected the 17 SDGs as the fields to be analysed. The set of keywords used in this work, which was proposed by Körfgen et al. (2018) to evaluate Austrian research contributions, included dozens of terms for each SDG. They were directly extracted from the goals, targets and indicator texts adopted by the United Nations (2015).

4. Application to the case study

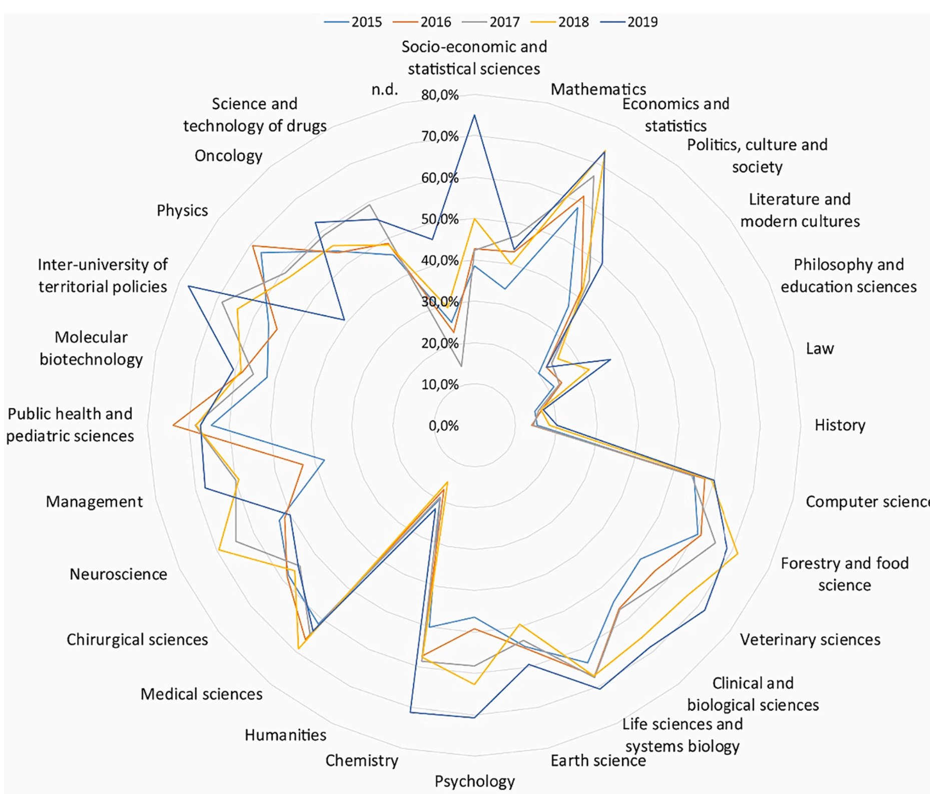
4.1. Scoring, ranking and labelling

The total number of publications related to the SDGs varied according to the selected threshold. In general, approximately one in every two publications using a threshold of greater than 3 or greater than 5 was related to one or more of the SDGs. We also observed an upward trend in recent years, as depicted in Fig. 2a. In particular, the percentage of publications related to at least one SDG increased by 6% from 2015 to 2018, reaching a peak of 53% in 2019. The Department of Economics and the Department of Management exhibited the most significant upward trend during the period studied (+36% a year of publications about SDGs), as shown in Fig. 2b. SDG 10, regardless of the threshold considered, was the most frequently addressed. This may be because, by its nature, SDG 10 requires a multidisciplinary approach, while the other SDGs are more specific to certain departments. Appendix B in the SI provides further details on the distribution of the selected contributions per SDG and department.

To better understand the first phase—the scoring, ranking and labelling process, we discuss here a few examples of selected/not selected scientific contributions and their corresponding authors. In particular, we focus on true positive (i.e. correctly selected contributions/authors), false-positive/negative (selected contributions that should not have been selected or contributions that were not selected but should have been) and true negative (correctly omitted contributions) results. In this way, we highlight the quality of the labelling process and its limitations. For instance, publications such as Paper #1—'What are the causes of educational inequality and of its evolution over time in Europe? Evidence from PISA' published in the *Journal of Education Economics* (Oppedisano & Turati, 2015), Paper #2—'Social capital dynamics and collective action: The role of subjective satisfaction in a common pool resource experiment' published in the *Journal of*



(a)



(b)

Fig. 2. Contributions related to at least one SDG per year. (a) Overall research production; (b) Percentage of contributions per department.

Environment and Development Economics (Becchetti, Castriota & Conzo, 2016) and Paper #3—'Drivers of Pinus sylvestris L. regeneration following a small, high-severity fire in a dry, inner-Alpine valley' published in *Plant Biosystems Journal* (Vacchiano, Lonati, Berretti & Motta, 2015) are true positive results. They were correctly assigned and labelled to the corresponding SDGs, i.e. Paper #1 (SDGs 4, 10 and 16), Paper #2 (SDGs 1 and 2) and Paper #3 (SDGs 10, 11 and 15). The quality of the selected results can be verified through the reported title and journal.

On the contrary, some contributions were incorrectly assigned to one or more of the SDGs (false positives). Typically, during the scoring process, the proper SDGs were identified. For instance, Paper #7—'Human capital mix and temporary contracts: Implications for productivity and inequality' (Berton, Devicienti & Pacelli, 2016)—was correctly identified as related to SDGs 1, 2, 8 and 10 but incorrectly assigned to SDG 5 due to the frequent repetition of keywords in the abstract. Similarly, false-negative cases were associated with excessively short abstracts, papers written in Italian or the use of excessively technical words not included in the adopted SDG keyword dataset. In contrast, Paper #13, written by Orsingher, Ricciuti and Toaldo (2018), exemplifies a true negative case because its title—'On semi-Markov processes and their Kolmogorov's integro-differential equations'—and its journal title (*Journal of Functional Analysis*) do not contain any keywords related to the SDGs. Once a score was assigned to a publication, the corresponding score was equally attributed to all of its authors.

4.2. Interdisciplinary collaboration Matrix

Fig. 3 shows the co-authorship network extracted. Every author received a total score equal to the sum of all scores collected for every co-authored publication for each SDG. Each network link represents a collaboration between researchers, i.e. a co-authorship, while each node represents a single author. The size of the nodes depends on the degree of the nodes (i.e. the number of links). Meanwhile, the size of the labels is proportional to the betweenness centrality degree (Brandes, 2001). In this way, we highlight the main features of the network. An in-depth analysis of the centrality degree of the network fell outside the scope of this work but may prove interesting in the future. For instance, future studies may employ centrality degrees to weight authors' scores. Fig. 3a and 3b depict the same network. In Fig. 3a, the colours and labels refer to UniTo's 27 departments (each author belongs to only one department). In contrast, Fig. 3b presents the obtained bottom-up clusters. By overlaying the two graphs, we were able to obtain the composition of each emergent cluster (Fig. 3b) in terms of the actual departments involved. For the sake of completeness, one author could have been clustered in a highly interdisciplinary group where different authors from different departments were equally involved (for a minor percentage) or in a cluster where his/her department represented the majority of the researchers involved; in the latter case, this department would be more central within the entire network (see Fig. 3). Finally, a cluster might be represented by a majority of authors from the same department (more than 50% of the total) with a few other departments also involved. Alternatively, the cluster might be represented by the case of single-authored publications that, by definition, were not considered in this co-authorship network. Overall, as briefly discussed here, this phase of the proposed methodology allowed us to easily map *knowledge communities* through co-authorship networks (Ramirez, Romero, Schot & Arroyave, 2019).

Fig. 4 depicts the composition of each identified cluster in terms of the percentage of the underlying departments. Two main aspects emerge from Fig. 1: the number of involved departments and the distribution of those departments within the bottom-up cluster (i.e. the variance). These aspects must be taken into account to measure the degree of interdisciplinarity.

4.3. Interdisciplinarity sustainability index

The results of the proposed design method are presented in terms of 1) the average number of involved departments, N_{SDGx}, 2) the average variance, σ^2_{SDGx}, and 3) the average entropy, S_{SDGx}, for each SDG. Fig. 5 first shows the results for the entire database of authors before filtering the information based on the assigned score per SDG. Fig. 5a represents the 18 bottom-up clusters (on the x-axis), the number of departments per cluster, N_i (on the left y-axis), and the variance per cluster, σ^2_i (on the right y-axis). Fig. 5b plots the trend of the entropy, S_i, rather than the variance. Similar graphs and analyses can be plotted for each SDG by filtering the author's database based on the assigned score described in the Methods section with a threshold of $\delta = 5$. Both graphs provide a way to evaluate a bottom-up cluster's interdisciplinarity and identify the most fruitful collaborations among departments. The variance σ^2_i expresses and highlights the distribution of the departments within a cluster. Indeed, a high degree of variance means that one or two departments dominate research contributions within that cluster. On the contrary, lower variance suggests equality in the contributions of the involved departments. For instance, Clusters 11 and 12 in Fig. 5a include the same number of departments, i.e. $N_i = 10$ but different degrees of variance, i.e. $\sigma^2_{12} > \sigma^2_{11}$.

The difference in variance between different clusters can be explained by examining the department distribution of the same two clusters in Fig. 4. For instance, the *forestry and food science* department accounts for approximately 70% of the total authors in Cluster 12, followed by the *life sciences and systems biology* department with 18%. All other contributions are negligible, resulting in an extremely high variance among the ten departments in the cluster. Cluster 11, meanwhile, presents a lower degree of variance due to the authors' more equal distribution. The top contributor is the *psychology* department, which accounts for 42% of the authors, followed by the *neuroscience* department (28%), the *clinical and biological sciences* department (10%) and other departments with lower percentages. As previously discussed in the Methods section, the high variance for Cluster 12 reduced its interdisciplinarity score. Indeed, by examining the variance of Cluster 8 ($\sigma^2_8 = 0.017$), for instance, which includes half of the involved departments ($N_8 = 5$), we conclude that *Cluster 12 is not comparable with Cluster 8* because $\sigma^2_8 < \sigma^2_{12} = 0.041$ and $N_8 < N_{12} = 10$. On the contrary, one can say that *Cluster 11 is more interdisciplinary than Cluster 8* because both clusters have the same variance $\sigma^2_8 = \sigma^2_{11} = 0.017$, but Cluster 11 has a higher number of departments involved, i.e. $N_{11} = 10 > N_8 = 5$.

Fig. 5b presents the same results via the information entropy, S_i, which considers both N_i and σ^2_i and clearly separates similar results in terms of variance by awarding more equally distributed probabilities. Table 3 provides the obtained values for the discussed Clusters 8, 11 and 12 for N_i, σ^2_i and S_i. As shown in Table 3, the information entropy evaluates the two cases differently. Indeed, Clusters 8 and 11 have the same variance values but different numbers of departments, N_i. The entropy, S_i, directly evaluates this difference by assigning a higher value of entropy to Cluster 11 because it includes a higher number of departments, N_i. On the contrary, entropy also allows us to compare Clusters 8 and 12. Because $S_8 = 0.406 > S_{12} = 0.319$, we conclude that *Cluster 8 is more interdisciplinary than Cluster 12*. The Discussion section will further explore these aspects.

We conducted the same analysis for every SDG by evaluating the resulting networks after filtering the authors with a threshold $\delta = 5$, as discussed in the Methods section. Finally, after determining the indices for every cluster i and every SDG, we used them to rank the entirety of UniTo's scientific production in terms of its interdisciplinarity. This involved simply averaging the indices discussed previously over all of the bottom-up clusters. Fig. 6 shows the trend of the three indices for each SDG, with the variance on the left (Fig. 6a) and the entropy on the right (Fig. 6b). As discussed for the example in Table 3, the variance is a less accurate measurement than the entropy. In terms of the entropy

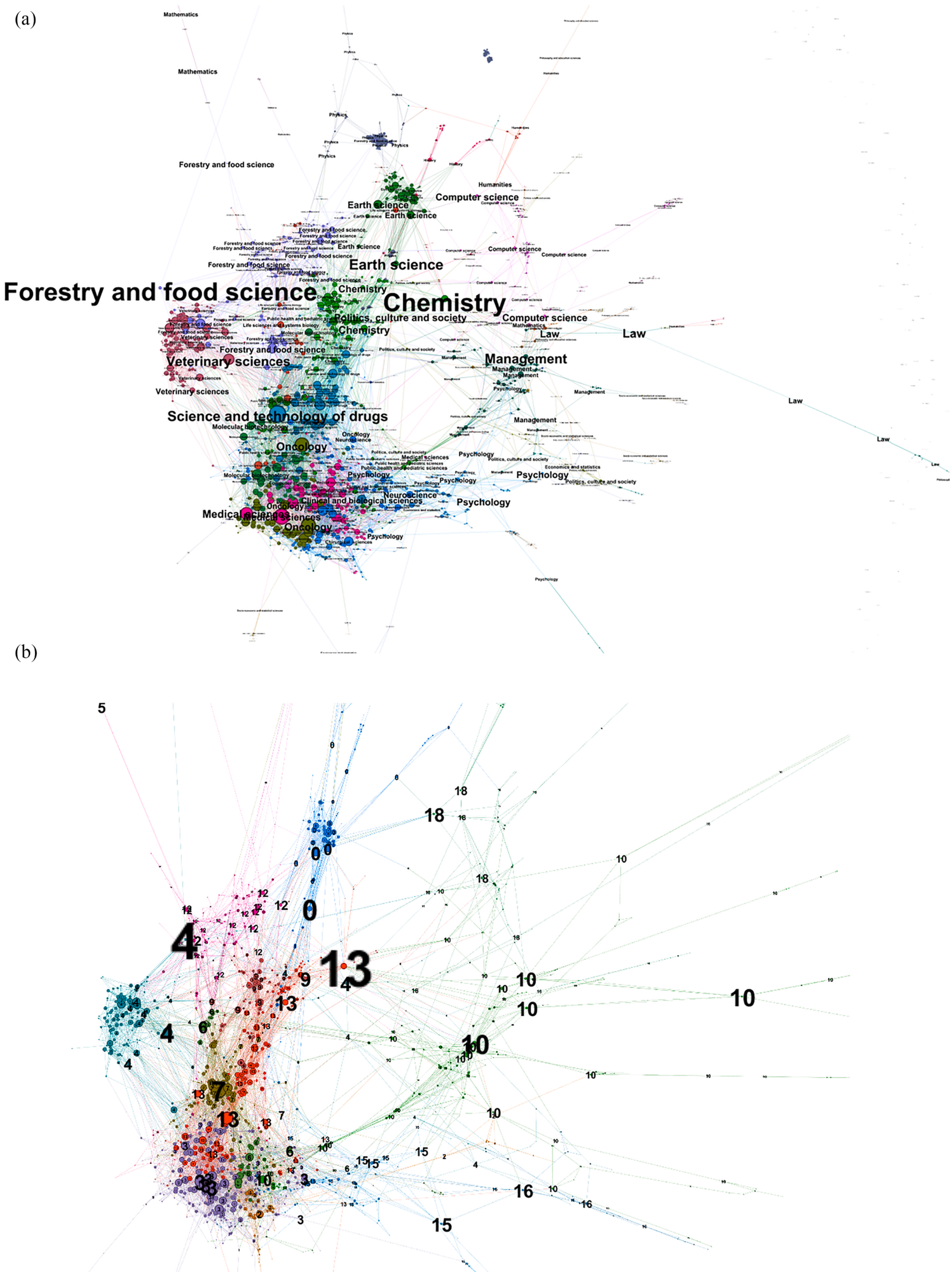


Fig. 3. Co-authorship network of the University of Turin. (a) Colours represent the departments; (b) Colours represent the emergent clusters.

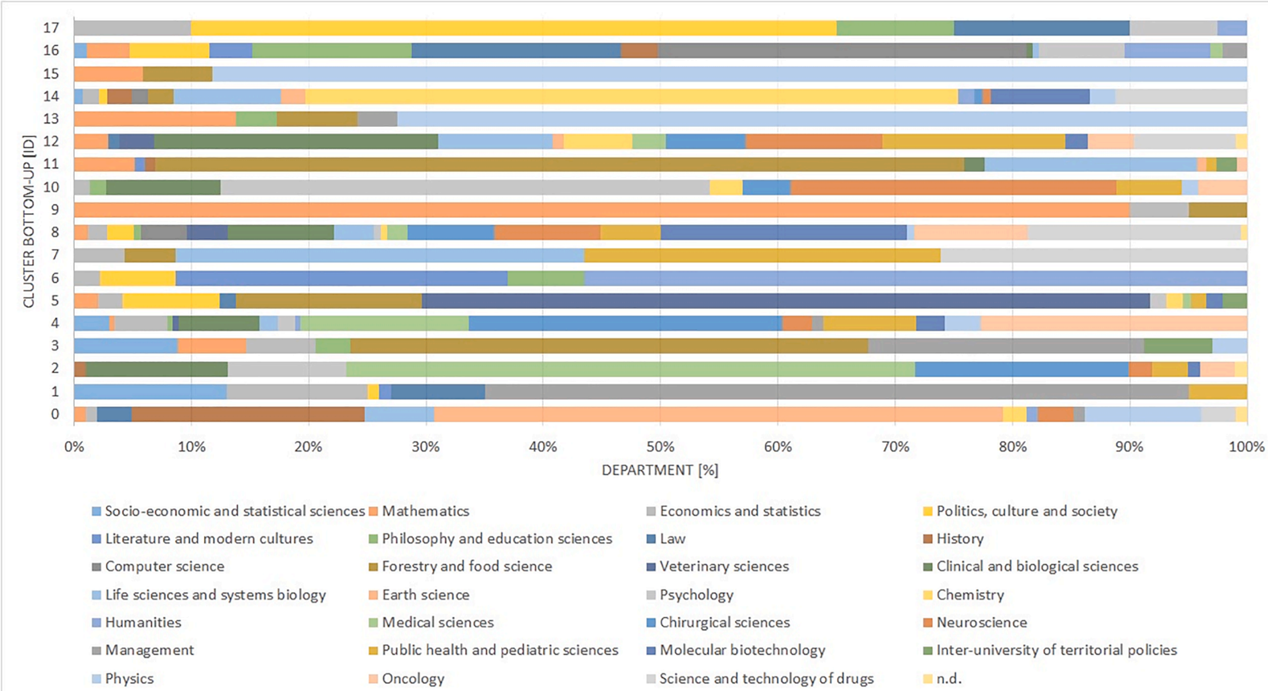


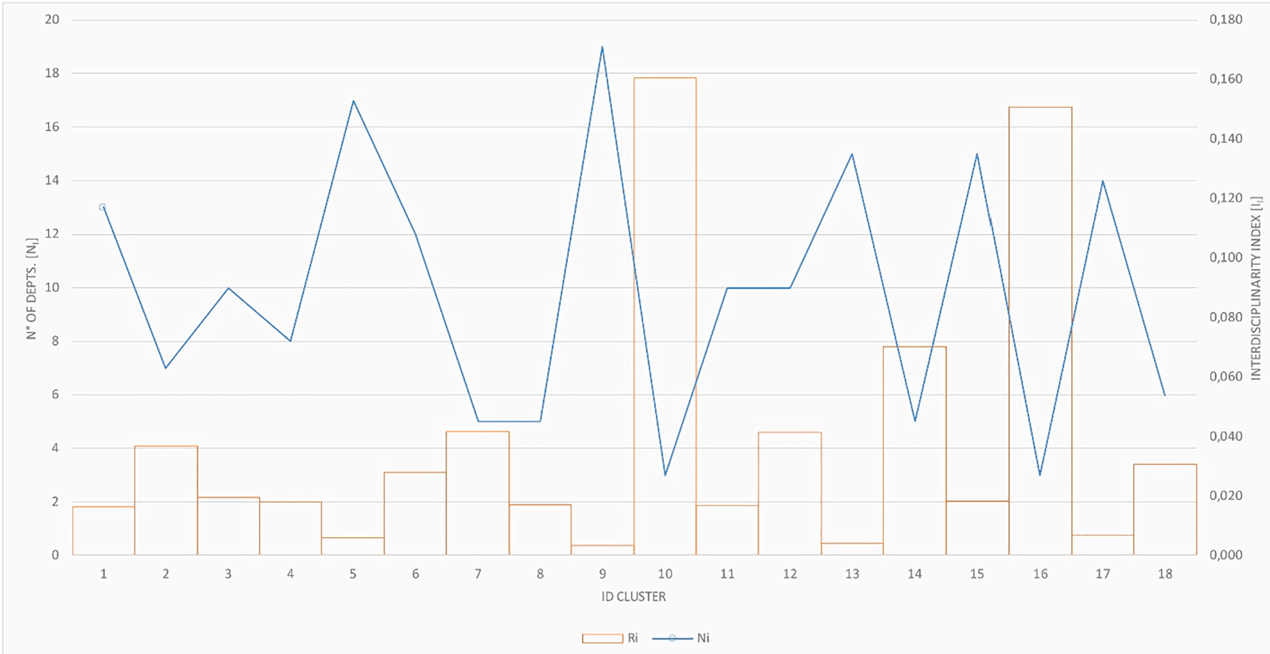
Fig. 4. Composition of each bottom-up cluster of the overall co-authorship network.

index, SDG 10 exhibits the most interdisciplinarity. Meanwhile, SDG 17 exhibits the least (likely due to a lack of specific keywords). SDGs 1 and 2 have a high number of involved departments and high entropy. SDGs 4, 5, 6 and 7 have, on average, a low number of involved departments but quite high entropy. Hence, in these cases, the departments collaborate more, and the authors' contributions are more equally distributed within the network. Finally, SDGs 13, 14 and 15 have a low N and S and thus represent less interdisciplinary fields at UniTo. SDG 13 has the lowest number of involved departments, with the exception of SDG 17. SDG 16 also has a quite low number of departments ($N = 6$) on average. However, its entropy is higher because of the heterogeneity of collaborations ($S = 0.368$).

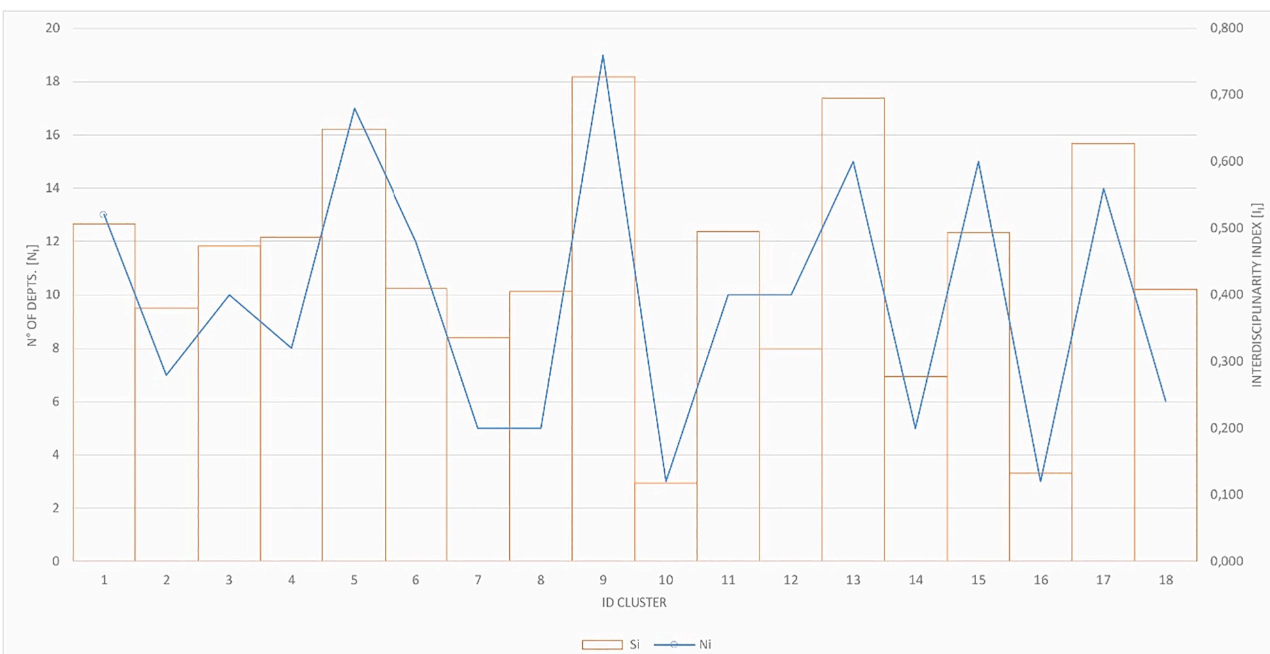
5. Discussion and managerial implications

The previous sections proposed a general and scalable IS artefact, specifically a design method, to assess the interdisciplinarity in scientific contributions of HEIs related to the SDGs. We successfully instantiated and tested the designed artefact with the University of Turin's publication database revealing how interdisciplinarity related to a certain topic (i.e. SDGs) can be assessed both at the micro (at authors' or research groups' level) and meso levels (at institution level). The initial research questions, which, in terms of IS principles, refer to Components 4 and 5 (artefact mutability and testable propositions), are satisfied by the proposed artefact as discussed in the previous section. Recalling the first research question—i.e. '*What are the main features an IS artefact should fulfil to measure the interdisciplinarity in scientific contributions related to SDGs within a HEI?',* the fundamental identified constructs are i) scientific contributions (e.g. papers, books), ii) authors (e.g. researchers, professors) and iii) their affiliations (e.g. departments), iv) collaborations (e.g. co-authorships) and v) theme/field keywords (e.g. SDG). With respect to the second research question—i.e. '*How can such an IS artefact be designed to be robust to changes in indicators, fields/topics, cluster sizes or institutions analysed?*', the structure of the artefact is extensively discussed in Fig. 1 and the corresponding description. The robustness has been detailed with the instantiation (see section 4). In fact, thanks to the modular sub-sequential design of the artefact—each module receives an input from the previous module (See Fig. 1), every aspect can be easily modified without affecting the entire structure of the artefact. In particular, if one wishes to evaluate another topic (e.g. circular economy, social innovation), one would merely need to modify the list of keywords used to initialise the scoring, ranking and labelling phase. Similarly, to vary the clustering size (from the single research group to the departmental level), one would only have to change the resolution of the clustering algorithm (or the algorithm itself) within the bottom-up clustering module (Fig. 1) in the Interdisciplinary Collaboration Matrix phase. Finally, the IS artefact is generalisable to every HEI with a clear departmental division of its academic staff. These and other specific aspects are discussed in greater detail in the subsequent section.

In terms of specific results related to the case study, the findings of this research, including observations from the case study, reveal a generally increasing trend of publications related to all 17 of the SDGs from 2015 to 2019. In the context of the examined HEI, SDG 10 appears the most popular of the SDGs across all departments. This is likely because SDG 10′s highly multidisciplinary content aligns well with the university's generalist orientation. In contrast, SDG 17 appears to be the most underexplored, likely due to the narrow range of topic-specific keywords associated with it. The application of the methodology presented here makes it possible to identify the most engaged departments with respect to all of the SDGs. Indeed, the scientific production of these departments accounts for 70% of SDG-related publications. Applying the proposed methodology, moreover, reveals another interesting aspect of interdisciplinarity. Those departments involved in exploring a wide range of SDGs via their scientific publications are the most interdisciplinary. Almost certainly, these differences can be linked to the idea that knowledge must be translated when moving from one field to another. While the need for interdisciplinary teams is undeniable, it is likewise important to note that increasing team diversity also increases the likelihood of difficulties in sharing knowledge among team members. In such cases, knowledge translation may be a useful strategy for lowering the barriers between individuals with diverse backgrounds and competencies (Dal Mas, Biancuzzi, Massaro & Miceli, 2020).



(a)



(b)

Fig. 5. Interdisciplinarity index for the entire co-authorship network. (a) Variance σ^2 VS, the number of departments *Ni* within cluster (b) Entropy *Si* VS, the number of depts *Ni* within cluster *i*.

5.1. Limitations and further research

This section discusses some limitations of and potential improvements on the proposed design method.

5.1.1. Scoring, ranking and labelling

The results obtained from the first step of the proposed methodology, i.e. the QTA, are based on keywords from Körfgen et al. (2018). The assigned scores, according to Equation (1), were thus strongly affected by the use of this dictionary and by the weight k_i of each keyword and by the field weights w_x.

First, because the score K_{ij} depends upon the number of occurrences $n_{x,ij}$ of each keyword, it may vary if researchers adopt a different dictionary. Generally, the more words used, the higher will be the score obtained. Scholars can adopt several dictionaries, and further investigations into the most appropriate dictionary for each field/theme are required. In the case of the SDGs, one possibility is to use an expanded dictionary. For example, scholars might analyse authors' keywords from relevant research contributions related to the SDGs in the *Scopus* database and thereby develop a broader and more generalised dictionary valid for all HEIs worldwide. Appendix C of the SI provides an example related to the UniTo database. Otherwise, comparing

Table 3
Example of the three indices with three representative clusters.

Cluster i	N. of depts N_i	Variance σ_i^2	Entropy S_i	Interdisciplinarity ranking (based on entropy)*
Cluster 8	5	0.017	0.406	2
Cluster 11	10	0.017	0.495	1
Cluster 12	10	0.041	0.319	3

* According to N_i and σ_i^2, cluster 11 exhibits greater interdisciplinarity than Clusters 8 and 12, but Clusters 8 and 12 are not comparable.

the filter results by adopting keywords from the SDG texts related 1) solely to the goals, 2) to the goals and targets and 3) to the goals, targets and indicators may be a way to properly calibrate the filter process.

Second, all of the weights k_i were set equal to one. To improve the model, however, each weight may be assigned differently. Indeed, scholars would generally agree that words such as *renewable energy* or *energy efficiency* should be weighted more than other more general words, such as *energy* or *environment*. Indeed, while the first two words—*renewable energy* and *energy efficiency*—represent precise selection criteria, the last two words—*energy* and *environment*—do not. With supervised training, a machine learning algorithm (Aggarwal & Zhai, 2012) may enable identification of the proper weights for each word, or n-gram (Brown, 2013). Such training may improve the scoring, ranking and labelling phase and thus eliminate or at least reduce false positives (contributions that were selected but should not be) and false negatives (contributions that were not selected but should be). More simply, assigning higher weights to certain n-grams may enable more accurate predictions (e.g. *corporate social responsibility*, *energy efficiency* or *sustainable development*).

Third, the validation process—in this case, applied to the UniTo database—must be generalised in research fields not studied at UniTo, such as engineering, architecture and the arts. The validation process—via the analysis of the author's keywords from the selected contributions (Fig. C.1 in SI)—offers a straightforward way to evaluate the

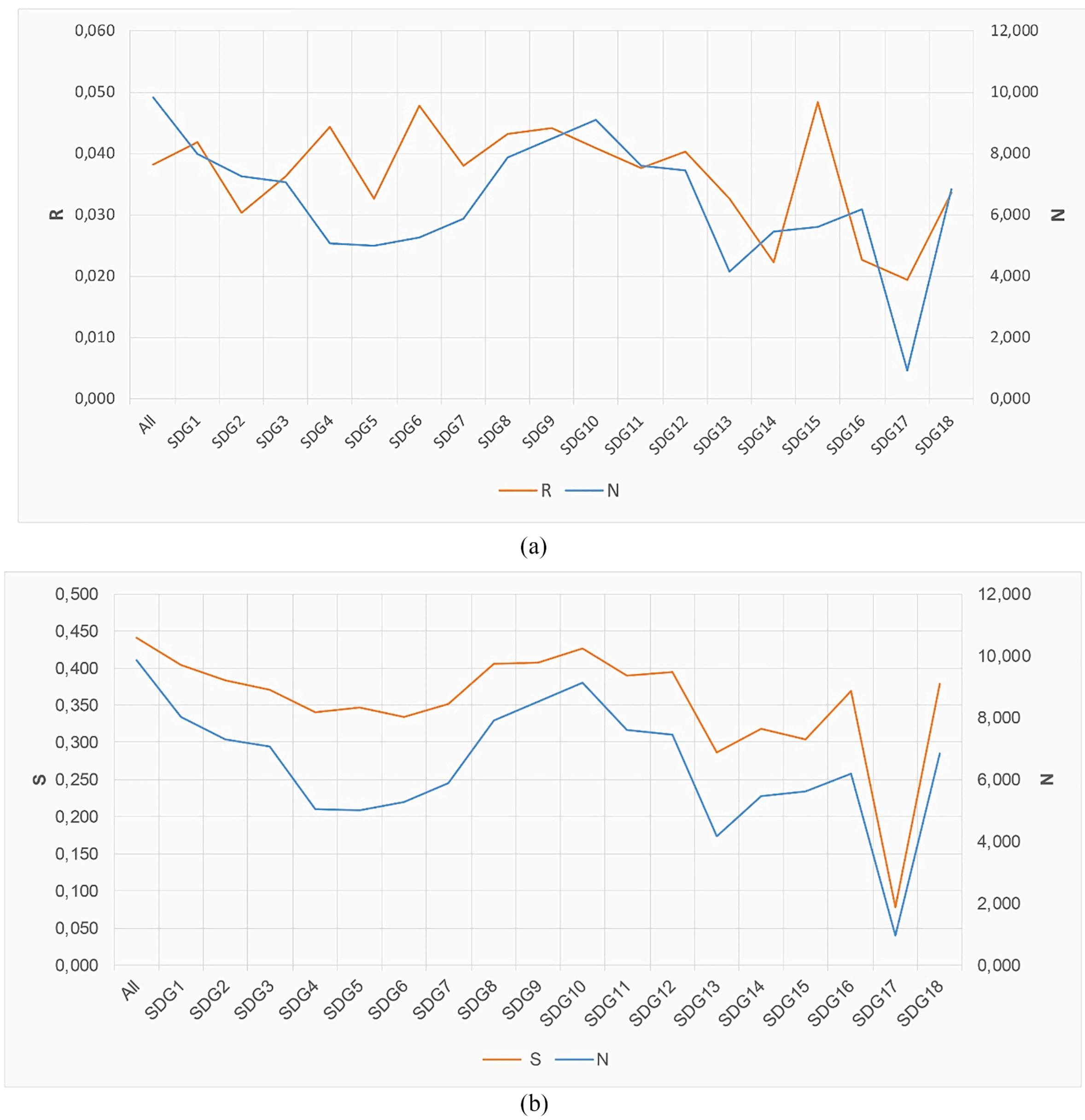


Fig. 6. Interdisciplinarity index for the entire co-authorship network. (a) Average variance σ^2 VS, number of depts N per SDG; (b) Average entropy S VS, number of depts N per SDG.

quality of the selected scientific contributions during the scoring, ranking and labelling step. Nevertheless, more robust methodologies, such as Jaccard similarity (Niwattanakul, Singthongchai & Naenudorn, 2013), are required.

Finally, future work may vary the three field weights w_x to assign different scores depending on whether a keyword occurs within the journal name, contribution title, abstract or keywords. In our case, the basic idea was to automatically select a contribution if one of the SDG-related keywords appeared within the journal name or contribution title. However, scholars may adopt other methodologies. These might include natural language processing (Indurkhya & Damerau, 2010) or simply a manual labelling process where authors must insert a new contribution within an HEI database.

5.1.2. Interdisciplinary collaboration Matrix

Several choices also affected the second step of this design method, i.e. the analysis of the collaboration (in this case, co-authorship) networks.

First, we identified the bottom-up clusters using the modularity algorithm (Blondel, Guillaume, Lambiotte & Lefebvre, 2008) with a resolution of 1.0. If scholars wish to analyse larger or smaller bottom-up clusters, this resolution can be increased or decreased, respectively. The resolution of 1.0 identified 18 bottom-up clusters out of the 27 departments at UniTo. Thus, it maintained the same order of magnitude as the current internal organisation. Decreasing the resolution parameter, however, may reveal smaller clusters and enable a more detailed microanalysis at the level of research groups. In contrast, by increasing the resolution, larger clusters emerge, and the co-authorship analysis may focus on the macro trends of collaborations. Furthermore, scholars can employ other algorithms, such as spectral clustering (White & Smyth, 2005) or min–max cut (Ding, He, Zha & Gu, 2001). In fact, research should compare the results from these and other clustering algorithms to avoid any bias due to the adopted methodology.

Second, our model can be further improved and expanded by considering various aspects, including *'when the graph is defined'* and *'when the clustering algorithms are run'*. For instance, according to the QTA of the first step, the assigned score can be used to weight each author node differently as a measure of author engagement in the analysed theme (in this case, one SDG). Similarly, centrality degree measurements, such as the betweenness (Brandes, 2001), closeness (Okamoto, Chen & Li, 2008), page rank (Brin & Page, 1998) or authority (Kleinberg, 1999), can be used to 'reward' or 'punish' an author in analyses of the composition of the bottom-up clusters (Fig. 4). In addition, the number of citations per author can be included in the model to assess the quality of the research collaborations. Moreover, the links, i.e. the co-authorships, can be weighted according to the number of co-authorships or the affinity among departments, as Stirling (2007) described. The affinity represents the proximity between research fields. For instance, *chemistry* and *science and technology of drugs* have a high affinity and thus do not represent a significant multidisciplinary collaboration. In contrast, *physics* and *philosophy* are quite distinct disciplines and thus may represent a more significant interdisciplinary collaboration.

Finally, scholars must investigate a potential limitation of the current study. The proposed methodology for the Interdisciplinary Collaboration Matrix involves 1) building the overall co-authorship network, 2) running the modularity algorithm to identify bottom-up clusters and 3) filtering the authors by the score assigned to them for each SDG. Filtering the authors based on the score K_{ij} after Steps 1 and 2, however, raises a potential issue. In fact, in some cases, e.g. for SDG 17, some bottom-up clusters appear as empty sets because no authors belong to them. By analysing the resulting network, we divided it into two or more giant components, which were no longer unique giant components in the overall network. This presents both an advantage and a disadvantage. Indeed, because some clusters were empty, the initially identified clusters did not represent actual collaborations for the analysed field (e.g. one SDG). On the one hand, this approach enables the quantification of the entropy, or variance, for the same number of bottom-up clusters (i.e. 18) and produces a meaningful result for the interdisciplinarity index at the scale of the whole dataset (Fig. 6). However, the approach does not allow the analysis of individual bottom-up clusters for each SDG (Fig. 5) because such clusters have no real meaning. On the other hand, if scholars wish to focus on analysing bottom-up clusters for each SDG, the procedure may involve 1) filtering authors by the score assigned for each SDG, 2) building the overall co-authorship network and 3) running the modularity algorithm to identify bottom-up clusters. In this way, although the number of identified bottom-up clusters may vary from one SDG to another, a meaningful analysis at the cluster scale is possible.

5.1.3. Interdisciplinarity sustainability index

Because multi-, inter- and *trans*-disciplinarity in education is an emergent and unexplored research field, few assessment tools and indicators exist. However, a few noteworthy aspects emerged from this study and were identified as relevant measures. These are depicted in Fig. 4. As described in the Methods section, the first two features to be measured and quantified are the number of departments N_i within a bottom-up cluster i and the internal distribution of those departments. The distribution was evaluated via two approaches: 1) the variance σ_i^2 and 2) the information entropy S_i. Both methodologies highlight the number of departments N_i and the internal distribution but with slightly different outcomes, advantages and disadvantages.

Fig. D.1 in SI shows the behaviour of the variance σ_i^2 versus the number of clusters N_i (Fig. D.1a) and the entropy S_i versus N_i (Fig. D.1b). The trends reveal that the variance alone is not an effective estimator of interdisciplinarity, even if a complex index, which takes into account N_i and σ_i^2, could be. Meanwhile, the entropy S_i defined according to Equation (2) could serve as a more appropriate estimator because 1) it proportionally weighs/rewards the increasing number of involved disciplines and 2) it is normalised between 0 and 1. The second feature, in particular, may allow comparisons among different HEIs with different numbers of departments.

Several other indices can also be defined. The choice to adopt one index or another primarily depends upon the behaviour that is the object of interest. For instance, Fig. D.2 in the SI shows a different definition of entropy with a variable base of the logarithm for each cluster, i.e. equal to the involved departments N_i within cluster i. The entropy with a variable base rewards clusters with a similar distribution within the cluster itself even if the number of departments involved is different. On the contrary, the entropy definition used in this study rewards the cluster with a greater N_i even if the departments within the two clusters are equally distributed.

Finally, this study did not take into account disparity or similarity as defined by Stirling (2007). Including differences and corresponding weights between theoretical fields may significantly affect the clusterisation process by changing the density and distance between nodes. Further studies testing such weights are necessary to improve the discussed model.

5.1.4. Testable propositions and first case study discussion

Although the design method presented here can be adopted as a general methodology to assess the interdisciplinarity of an HEI's research production, identifying the proper interdisciplinarity index requires further investigation. The expository instantiation fulfilled all testable propositions. Indeed, this initial case study revealed the robustness of the design method to changes in interdisciplinarity indicators (this study used two entropy-based indicators: number of departments and variance), fields (17 SDGs were analysed in this study), cluster sizes (resolution can be adjusted from the research group level to the department level) or institutions analysed (the methods are invariant to the institution analysed, and the only requirement is a well-defined affiliation for each author). Furthermore, the defined and tested design method satisfies both declared scopes and aims, i.e. identifying and evaluating groups of researchers and evaluating the overall performance of an HEI. This is because the entropy is an extensive quantity, which can be derived by adding the entropy of the smaller groups to obtain the institution entropy.

6. Concluding remarks

This study proposed a novel IS design method to assess interdisciplinary SDG-related research at HEIs. Through this paper, we contribute to the debate about SDG-related metrics at the micro level (i.e. at the organisation level) and add new knowledge regarding the organisational and strategic insights HEIs can offer to the SDG research agenda. The proposed methodology, applied here to the case of UniTo, consists of three main steps: (i) the ranking of publications through a QTA based on the occurrence of SDG-relevant keywords within those publications; (ii) the analysis of co-authorship research networks to identify emergent bottom-up and interconnected research clusters and (iii) the evaluation of interdisciplinarity indices to reveal the most interdisciplinary bottom-up clusters. These steps enable the timely and precise evaluation of interdisciplinarity for each SDG at both department and research group levels.

The results obtained here reveal interesting trends regarding interdisciplinary collaborations. Nevertheless, further investigations are required, especially to evaluate the robustness of the SDG dictionary and the generalisability of the interdisciplinarity index to other cases. Our study offers an evidence-based case on SDG research, consistent with requests from scholars in the area, such as Leal Filho et al. (2018). First, applying the multi-step methodology presented in this paper will enable university managers to organise more effective solution-oriented research groups via a bottom-up approach. Second, the methodology promotes local-level interdisciplinary research on sustainability by identifying and aligning the competencies available at HEIs with the needs of local communities. Third, by applying this methodology, university managers and governing bodies can effectively promote policies that incentivise SDG-related research and define a clear research agenda for their specific universities. Finally, the application of this methodology facilitates the communication of scientific results to various stakeholders. More specifically, it provides an explanation of the dynamics of interdisciplinary teams and incentivises knowledge translation among non-academic audiences using an interdisciplinary lens—for instance, by inviting all local researchers who are working on climate change to provide their disciplinary perspectives on that topic. Meanwhile, the proposed methodology also increases the accountability of universities in providing reliable information to ministries, private donors and other research centres regarding the contribution of the local research groups to sustainable development.

In terms of knowledge translation, future studies can improve the proposed methodology by linking the research pillar of an HEI to both the educational pillar (e.g. courses, masters) and the so-called third-mission pillar (e.g. the impact of research on society). Recently, the findings from this research were presented at a public event that included the participation of several managers and directors of UniTo. We expect this presentation to spark an internal debate regarding the role of interdisciplinarity in the achievement of the SDGs and the inclusion of an interdisciplinarity metric in UniTo's sustainability report. Hence, future studies can explore how the output of the proposed IS artefact (i.e. the interdisciplinarity of research collaborations) may influence, for instance, the creation of new interdisciplinary research centres involving external stakeholders (third mission) or the launch of new bachelor's or master's programmes (educational mission). Thus, the proposed methodology and related findings may serve as knowledge translation enablers, fostering new partnerships among multidisciplinary groups and research teams and enhancing communication with other stakeholders. Rather than a mere bibliometric exercise, moreover, this novel methodology also facilitates the linkage between science and local policymaking by matching local community managers with prominent researchers who can offer practical science-based support for local social change.

For these reasons, the proposed methodology offers a practical technological tool for university managers working to direct institutional support towards a sustainable development research agenda. These efforts align with the view of Brown, Werbeloff and Raven (2019) and Brown, Deletic and Wong (2015). In greater detail, this open technology (mainly represented by algorithms and codes) may help to identify and cultivate T-shaped researchers by nurturing a constructive dialogue, empowering researchers to work across disciplines and lending institutional support to interdisciplinary research for the sustainable development of local communities.

CRediT authorship contribution statement

Dario Cottafava: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Grazia Sveva Ascione:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Laura Corazza:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Amandeep Dhir:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbusres.2022.06.050.

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