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ABSTRACT

The development of solutions to manage or mitigate climate change impacts is very challenging, given the complexity and dynamicity of the socio-environmental and socio-ecological systems that have to be modeled and analyzed to include qualitative variables that are not so easily quantifiable. The existence of qualitative, interoperable and well-interlinked data is considered a must to support this objective, since scientists from different disciplines will have no option but to collaborate and co-design solutions, overcoming barriers related to the semantic mis-alignment of the plethora of available data, the existence of multiple data silos that cannot be easily and jointly processed, and the lack of data quality in many of the produced datasets. In the current work, we present SustainGraph, as a Knowledge Graph that is developed to track information related to the evolution of targets defined in the United Nations Sustainable Development Goals (SDGs) at national and regional level. SustainGraph aims to act as a unified source of knowledge around information related to the SDGs, by taking advantage of the power provided by the development of graph databases and the exploitation of Machine Learning (ML) techniques for data population, knowledge production and analysis purposes. The main concepts represented in SustainGraph are detailed, while indicative usage scenarios are provided. A set of opportunities to take advantage of SustainGraph and open research areas are identified and presented.

Keywords: Knowledge Graph, Sustainable Development Goal (SDG), Systems Innovation Approach, Climate Change Impact, Participatory Modeling, Graph Database

1 INTRODUCTION

The development of effective climate change mitigation and adaptation solutions is one of the most crucial challenges that we face towards the transition to a sustainable and climate-neutral way of living. To address this challenge and adopt sustainable development paths, various policies and associated targets have been specified at international and national level. First and foremost, the Paris Agreement has been adopted in 2015 (Horowitz, 2016) as a legally binding international treaty on climate change, aiming to limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels. The 2030 Agenda for Sustainable Development (Lee et al., 2016) has been also specified in 2015 by the United Nations, detailing 17 Sustainable Development Goals (SDGs) and their associated 169 targets. These high-level policies and goals have led to the development of further international and/or national policies and initiatives to support the continuous monitoring and assessment of the status per target.

Following the specification of a wide set of policies, relevant monitoring frameworks have been designed and become operational to keep track of their implementation and assessment. A wealth of data is made available (e.g., UN SDG repository, EU SDG and Green Deal targets tracking, Nationally Determined Contributions monitoring), centered mainly around the need to monitor and track the evolution of indicators for the SDG targets at national and regional level. Given that these data are collected by various organizations worldwide, semantic consistency and data interoperability among them cannot be considered as granted. Furthermore, such data are made available in many cases as data silos, while specialized software or Application Programming Interfaces (APIs) may be required for getting access to them. Lack of data quality is also a barrier, since data processing (e.g., removal of outliers, tackling of diverse assumptions during data production, use of different semantics for data description) is required in most cases to manage to transform data to formats and structure that can be considered homogeneous. Thus, the proper management of the wealth of collected information is not straightforward. There is a need for information models and information management techniques able to capture the volatility of the data, manage semantic misalignment of the denoted concepts, and facilitate the identification of hidden patterns and relationships among them. In this way, a solid, open and interoperable data infrastructure can be made available, enabling the development of innovative solutions to produce systemic changes and make economies socially, economically and environmentally sustainable.

Under this perspective, we present SustainGraph as a Knowledge Graph (KG) that has been conceptualized and developed to track SDG targets and indicators, their evolution across time and their inter-connectedness with policies and targets defined at European Union (EU) and national level. A KG is considered suitable for this purpose, since it provides a graph-based abstraction of data coming from diverse data sources and domains, while managing the semantic consistency of the detailed concepts and enabling the tracking of dynamic relationships among them (Hogan et al., 2021). A systemic nexus approach has been considered for supporting the data population processes of the KG, while taking advantage of participatory system mapping processes (Midgley and Lindhult, 2021; Matti et al., 2020). To take advantage of the wealth of available data, openness and interoperability of SustainGraph with existing databases and Application Programming Interfaces (APIs) is promoted to automate -as much as possible- the provided data population processes. Over SustainGraph, socio-environmental and socio-ecological systems participatory modeling and analysis processes can take place, aligned with the main mechanics of a Systems Innovation Approach. Specifically, the effective fusion of the collected data and their transformation to systematised nexus-coherent knowledge, can lead to novel insights (Laspidou et al., 2020), significant improvement of the participatory processes (Matti et al., 2020) and the development of collective environmental intelligence (Zafeiropoulos et al., 2021) among the engaged stakeholders and communities.

In short, it can be claimed that the main contribution of this work is twofold. On one hand, we provide the conceptualization and semantic description of SustainGraph that, as far as we know, is the first KG that considers in a holistic way the tracking of SDG targets and indicators in national and regional level, along with their relationship with specified policies and the implementation of case studies across Europe. On the second hand, by considering the mechanisms specified in a Systems Innovation Approach (Midgley and Lindhult, 2021; Matti et al., 2020), we detail the implementation of SustainGraph, the set of data population mechanisms from a plethora of open data sources and data providers, and the support of participatory modeling and analysis processes. Data population to the KG and data analysis over the KG are assisted through the exploitation of Machine Learning (ML) techniques.

2 BACKGROUND INFORMATION

2.1 Climate Change Related Policies

In this section we provide a short overview of the existing policies for addressing and mitigating the climate change impact. Focus is given on highlighting the existence of multiple policy frameworks and initiatives worldwide and the need to keep track of the relationships among the defined indicators and targets per case (e.g., similar, identical, relevant) to manage to develop an overall knowledge repository, considering the specifications provided by each framework, the applied temporal resolution and applicability area (worldwide, national, regional level).

As stated in Section 1, the Paris Agreement regards an international treaty on climate change that has been adopted by 196 parties and put into force since 2016 (Horowitz, 2016). To implement the Paris Agreement, participating countries are preparing their plans to reduce greenhouse gas emissions, as reported in climate action documents, called as nationally determined contributions (NDCs). In each NDC, a set of targets is posed for mitigating GHG emissions and adapting to climate change (United Nations, Climate Action, 2022; den Elzen et al., 2019). In parallel, within the 2030 Agenda for Sustainable Development, United Nations have specified the 17 Sustainable Development Goals (SDGs) that have to be achieved (Lee et al., 2016). The 17 SDGs are monitored based on the specification of 169 targets along with indicators to measure progress toward each target. Each goal has 8 to 12 targets, while each target can be assessed based on 1 to 4 indicators. The SDGs integrate the three dimensions of sustainable development (economic, environmental and social) and are highly related with the tracking of indicators related to the impact of climate change (Morton et al., 2019).

At European Union (EU) level, various policies are specified that are related to the achievement of SDG targets, in accordance with the 2030 Agenda for Sustainable Development (European Commission, 2016; Sachs et al., 2021). For instance, the policy areas defined in the European Green Deal and documented in terms of goals in the European Climate Law -for the implementation of actions in accordance to the Paris Agreement aiming at a climate-neutral Europe by 2050- are also related to specific SDG indicators. The relationship between the European Union’s policies established since 2020 in support of the implementation of the European Green Deal and the SDGs is also tracked in (Koundouri et al., 2022, 2021). To track progress of SDG indicators at European Union (EU) countries, Eurostat looks at the aspects of the SDGs that are relevant from an EU perspective by tracking 101 indicators (31 of which are multipurpose, i.e., are used to monitor more than one SDG). EU policy targets are considered for assessing indicator trends (Eurostat, 2022). It should be noted that the EU SDG indicator set is open to annual reviews, aiming at the alignment of the posed targets with the priorities set by the European Commission and the consideration of indicators coming from new or updated data sources (Malagó et al., 2021). Country-specific directives for promoting sustainable development are also provided at the Country Specific Recommendations (CSRs) for EU countries. Such recommendations come into play into the specification of targets that have to be achieved per country and the formulation or adaptation of national-level sustainable development policies (Rainone, 2020). The EU taxonomy has been also developed as a classification system for environmentally sustainable economic activities (Dusík and Bond, 2022). The objective is to promote sustainable investments across Europe with substantial contribution to climate change mitigation and the implementation of the European Green Deal. It has defined six environmental objectives, namely climate change mitigation or adaptation; protection of water and marine resources; transition to a circular economy; pollution control; and protection of ecosystems.

To promote a joint understanding of the classification of the set of deep transformations required in each country to achieve the SDGs, six SDG transformations are introduced as modular building-blocks of SDG achievement (Sachs et al., 2019, 2021). These regard Education, Gender, and Inequality; Health, Wellbeing, and Demography; Energy Decarbonisation and Sustainable Industry; Sustainable Food, Land, Water, and Oceans; Sustainable Cities and Communities; and Digital Revolution for Sustainable Development (Sachs et al., 2019). Each transformation is associated with specific SDGs, while targeted to suggested interventions with planned outputs.

Finally, it should be noted that various initiatives are also active on the specification of Key Performance Indicators (KPIs) for smart sustainable cities, such as the study realised by the United for Smart Sustainable Cities (U4SSC) initiative. The objective is to provide consistent and standardized methodology for cities to measure performance and progress towards the achievement of the SDGs taking advance of digital technologies (U4SSC, 2021). An overview of the relationships between the aforementioned policies and initiatives is provided in Figure 1.

2.2 Knowledge Management based on a Systems Innovation Approach

Systems innovation refers to the development of novel participatory technological solutions and breakthroughs that can lead to major transformation in national and regional economies (De Vicente Lopez and Matti, 2016). The formulation of a system is a basic concept in the systems innovation approach, where a system is formed by several elements and their relationships that can be dynamic across time. The dynamicity of a system can be attributed to changes in internal or external parameters and the influence posed to the individual elements (Matti et al., 2020). Knowledge management is a fundamental part of the systems innovation approach, since a collective understanding of the system is crucial to develop transformative solutions.

The adoption of a systems innovation approach can be considered as an enabler for the participatory formulation and development of a KG. On the other hand, the usage of a KG can be considered as an enabler for supporting knowledge management processes within a team working based on a systems innovation approach. The overall information flow in a systems innovation approach is covering the various parts of the DIKW (Data, Information, Knowledge, Wisdom) pyramid (Rowley, 2007) (see Figure 2). The first part of the flow (Data and Information parts in the pyramid) is associated with the population of the data in the KG. Through participatory processes, data collection and/or generation is taking place, considering data coming from various stakeholders. Such data can be introduced -upon processing- to the KG and populate it, creating a unique point of information management. By considering the interlinking between the denoted concepts based on the provided information, knowledge is produced.

The second part of the flow (Knowledge and Wisdom parts in the pyramid) regards the extraction of data from the KG to support participatory modeling processes. By getting access to semantically aligned

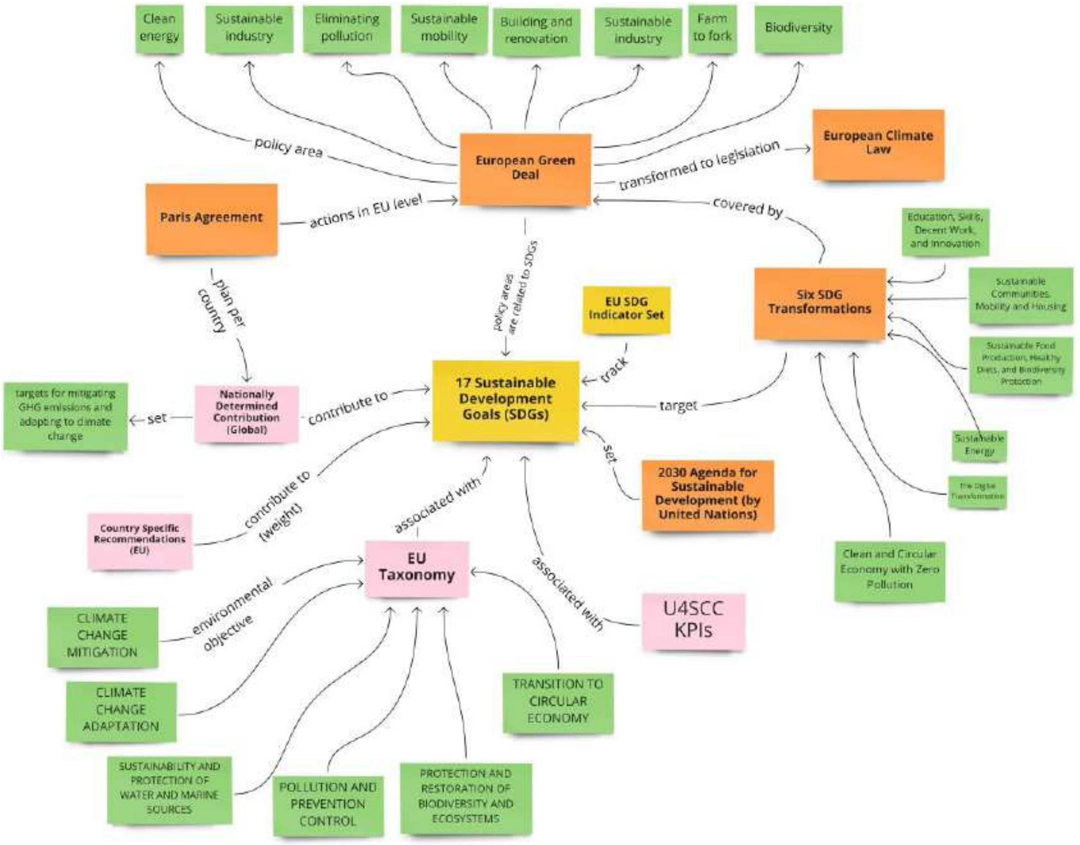

Figure 1. High level view of climate change related policies and initiatives.

and interlinked data, a participatory modeling process can be facilitated. Interdisciplinary scientists can collaborate more easily and co-create their models, given the alignment of terms coming from different scientific domains. Such modeling processes can be based on the adoption of modeling tools, such as System Dynamics Modeling, to better understand complex systems and lead to the creation of new knowledge by revealing feedback loops as well as interlinkages and cascading effects that propagate through the system (Laspidou et al., 2020). Resource nexus systems have such complexity and systemic approaches that incorporate biophysical, socio-economic and policy layers can promote knowledge elicitation and creation of new intelligence (Laspidou et al., 2019; Papadopoulou et al., 2022; Ramos et al., 2022). Resilience can be assessed successfully only through such systemic analyses (Ioannou and Laspidou, 2022). Along these lines, a KG can support the provision of input data to such models and supplement the produced intelligence through the identification of hidden relationships and/or patterns. Through the exchange and adaptation of existing information, practice-based knowledge can be co-created and applied in new contexts (Matti et al., 2020).

It should be noted that, nowadays, there are limited methods for modeling systemic changes, where there is also lack of knowledge for the processes that lead to systemic shifts in social systems (Elsawah et al., 2020). By capturing systemic changes of socio-environmental systems in the KG, such a challenge can be tackled. By getting access to visualisation and analysis results, data interpretation becomes simpler while opportunities for innovation can be identified. For instance, social network analysis and network maps can be used to analyze the system dynamics and the role of each stakeholder within a case study.

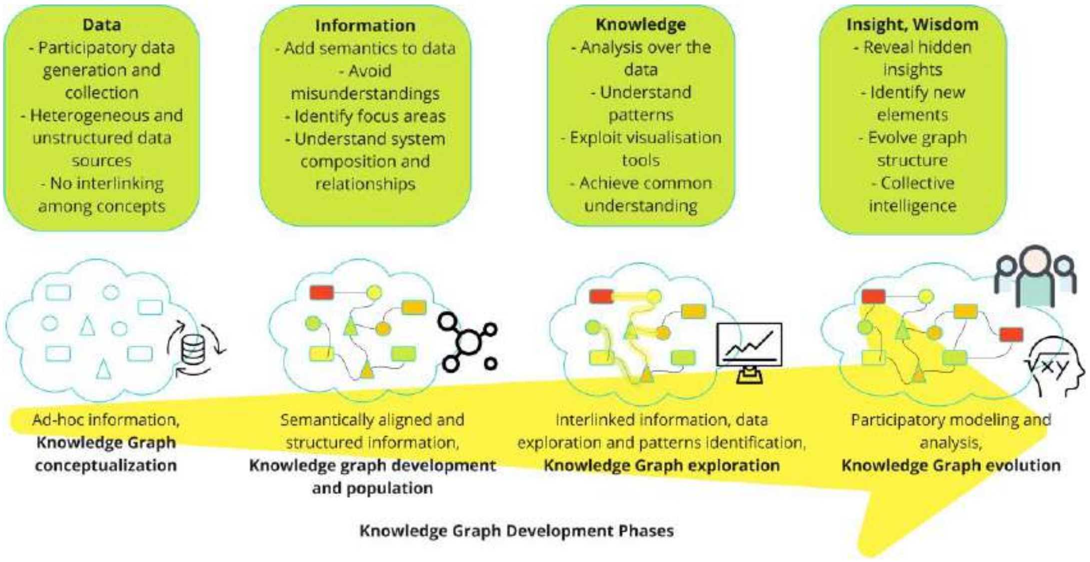

Figure 2. Knowledge Graph Development Phases.

2.3 Knowledge Graphs for Information Management

Knowledge Graphs (KGs) are emerging, since they are considered suitable to manage challenges that have arisen in modern data practices. The main challenge has to do with the existence of silos of data or dedicated software and Application Programming Interfaces (APIs) for managing such data (Sequeda and Lassila, 2021). Industry-specific data representation schemas are defined and adopted that -in many cases- may differ, even for the management of the same types of data. In parallel, dedicated software and APIs are being developed for data management in specific sectors, where the data semantics are hidden from the end users and are tackled by the internal software components. This make the software usable only for the purpose that has been initially designed and hinders its adoption, re-usability and interoperability with other data management tools (Sequeda and Lassila, 2021).

KGs are considered suitable for bridging data silos, by interlinking the concepts represented in the graphs with well-defined semantics (see Figure 3). In this way, the interconnected datasets in the KG can be enriched with meaning, misalignment of terminologies of the same concepts under different data schemas can be tackled, while relationships among concepts can be made explicit. Thus, the main motivation for the development of a KG is the usage of graphs to represent data -that can be interconnected and enriched with meaning- to explicitly represent knowledge (Hogan et al., 2021; Noy et al., 2019). Data volatility is managed, since relationships among nodes in a KG can be dynamic, making them suitable for representation of complex and dynamic systems (e.g., socio-environmental systems (Zafeiropoulos et al., 2021)). Keeping a high standard of data quality in a KG is challenging and is related mostly with the data quality of the input data. Quality management processes have to be applied to identify data quality issues (e.g., data inconsistency, data redundancy, missing values) and proceed to improvements (e.g., outliers removal) (Xue and Zou, 2022). By developing and maintaining a KG, data re-usability, extensibility and interoperability can be considered as granted, relaxing a lot the constraints posed to data scientists in existing data management practices.

Moving one step further, KGs facilitate reasoning over the available data and support analysis and complex decision-making (see Figure 3). Reasoning over KGs is required to obtain new knowledge, extract insights and conclusions from existing data (Chen et al., 2020a). Through reasoning, KG completion and evolution can be supported via the identification and prediction of new relationships among entities (Chen et al., 2020a,b; Issa et al., 2021). As already mentioned, KGs can also act as an enabler for participatory analysis of dynamic and complex systems by interdisciplinary scientists). A data scientist is able to take advantage of the interlinked data in the KG to identify transformative patterns and extract new knowledge and insights. The existence of semantically-aware and up-to-date data within a graph database enables the co-design of data management and analysis processes that can be integrated within dynamic modeling systems.

The role of Artificial Intelligence (AI) is highlighted since Machine Learning (ML) pipelines can be developed for supporting both data population and data analysis in the KG. The existence of a KG can act as a catalyst for the incorporation of a set of ML processes over a unified knowledge repository. The exploitation of ML techniques has to be carefully considered, taking into account a study that details the implications that AI may have on the delivery of all 17 SDG goals and the associated 169 targets (Vinuesa et al., 2020). It is stated that AI can act as an enabler for 134 targets, while it may also introduce negative impact on 59 targets (Vinuesa et al., 2020). With regards to the negative impact of AI, this is mostly related with the existence of biases in the data, the need for examination of the long-term impact of the applied algorithms in terms of equity and fairness and the unequal distribution of educational and computing resources throughout the world. To -at least partially- tackle these aspects, emerging technologies applied over KGs can be considered. For instance, the areas of explainable and responsible AI are emerging that can take advantage of semantic layers of knowledge provided through a KG to produce explainable and ethically-aligned decisions (Hitzler et al., 2020). The adoption of open-source and open-access policies can also reduce the barriers for the usage of the produced software by a wide community.

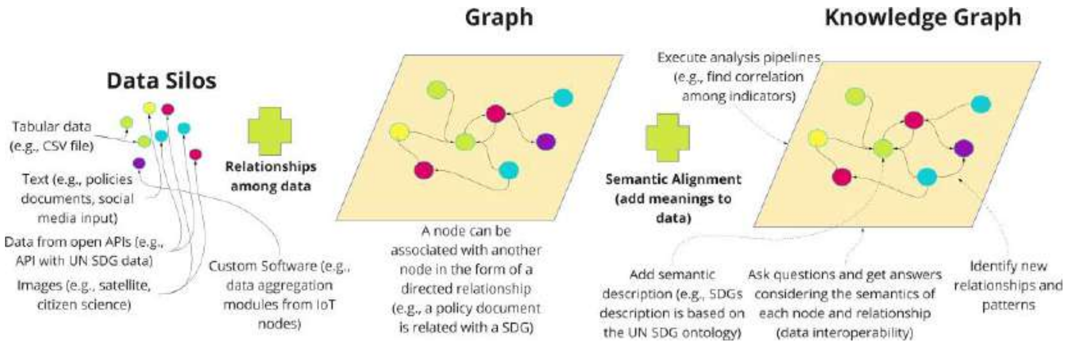

Figure 3. From data silos to a Knowledge Graph.

3 METHOD

3.1 SustainGraph Conceptualization and Walkthrough

SustainGraph is specified and developed in the form of a property graph model. In this model, a graph consists of a set of nodes (discrete objects) and relationships. Relationships are directional while both nodes and relationships can have properties to describe their characteristics. However, to properly detail the semantic information associated with each node and relationship, a SustainGraph ontology has been made available (Mandilara et al., 2022). The ontological description of the main concepts introduced in

SustainGraph can be considered as accompanying information the the structure introduced in the property graph model. A high level view of SustainGraph structure is provided in Figure 4.

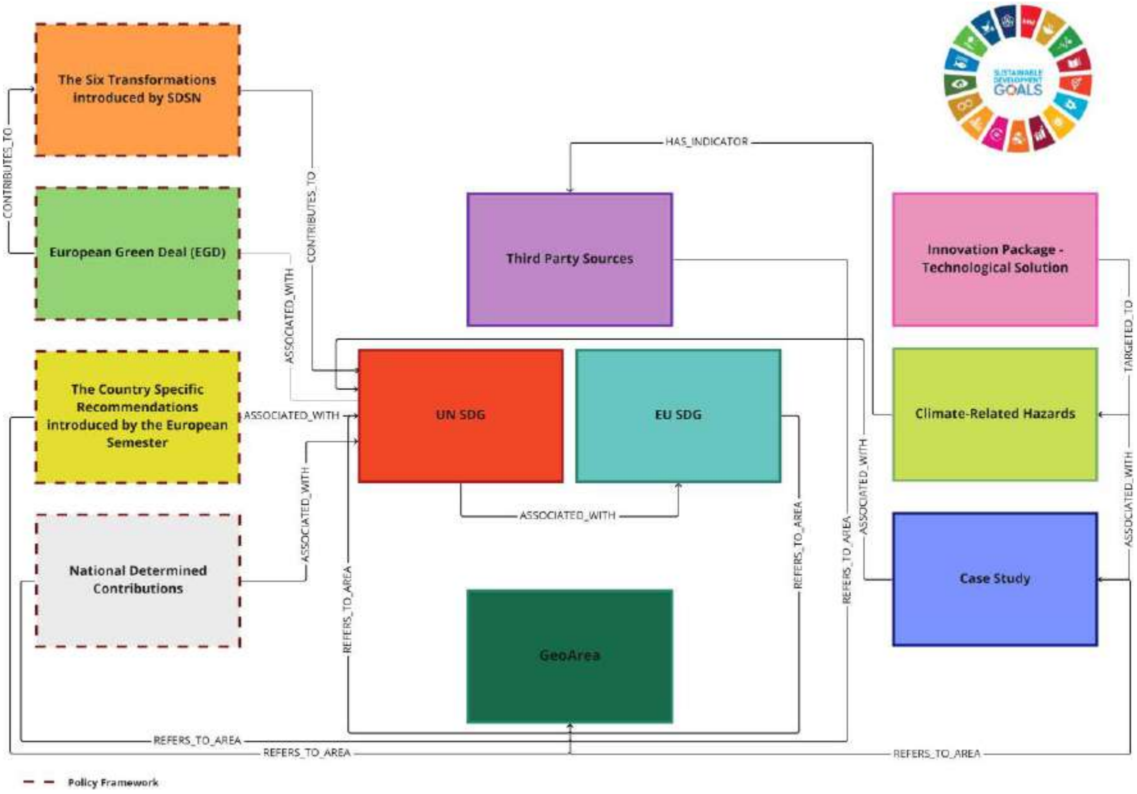

Figure 4. High level view of SustainGraph.

The main set of entities in SustainGraph has to do with the description of the structure of the UN Sustainable Development Goals (SDGs), building upon an existing formal knowledge organization system for this purpose (Joshi et al., 2021). Within SustainGraph, a *Goal* has a set of *Targets*, where each *Target* is associated with one or more *Indicators*. Each Indicator is measured based on *Series* of data. Each data *Series* is accompanied by *SeriesMetadata* where details for the metric that is measured is provided, while it includes a set of *Observations*. To support geolocation characteristics, each *Observation* refers to a specific geographical *Area (GeoArea)*.

The aforementioned structure for the representation of the UN SDGs has been generalized to support the measurement of similar indicators in EU level, as well as indicators provided from third party sources. At EU level, EU SDG indicators are provided by Eurostat and can be associated with the UN SDG indicators. Multi-purpose indicators are defined, where one EU SDG indicator may contribute to more than one goals. Data coming from third party sources are also represented, aiming at supporting interdisciplinary scientists to realise analysis over such data. This is mainly applicable in the envisaged analysis within case studies, especially in cases where the existing SDG indicators are not sufficient to properly feed the developed models for the considered socio-environmental or socio-ecological systems. The *Source* of the *Indicator* (e.g., coming from UN SDG, EU SDG or a third party source) is specified in the homonymous entity.

A main characteristic that is supported in SustainGraph regards the capability to declare relationships among *Indicators*. Each *Indicator* can be associated with any type of *Indicator* within SustainGraph. For instance, this is applicable in the case of EU SDG indicators, where each EU SDG indicator may be similar to, part of or identical to an UN SDG indicator. In this way, the relationships among indicators tracked by different monitoring frameworks are represented, enabling data interlinking and interoperability. Furthermore, a relationship is added where each EU SDG Indicator can contribute to a specific *Policy Target* defined at EU level. A view of this part of the specification within SustainGraph is depicted in Figure 5.

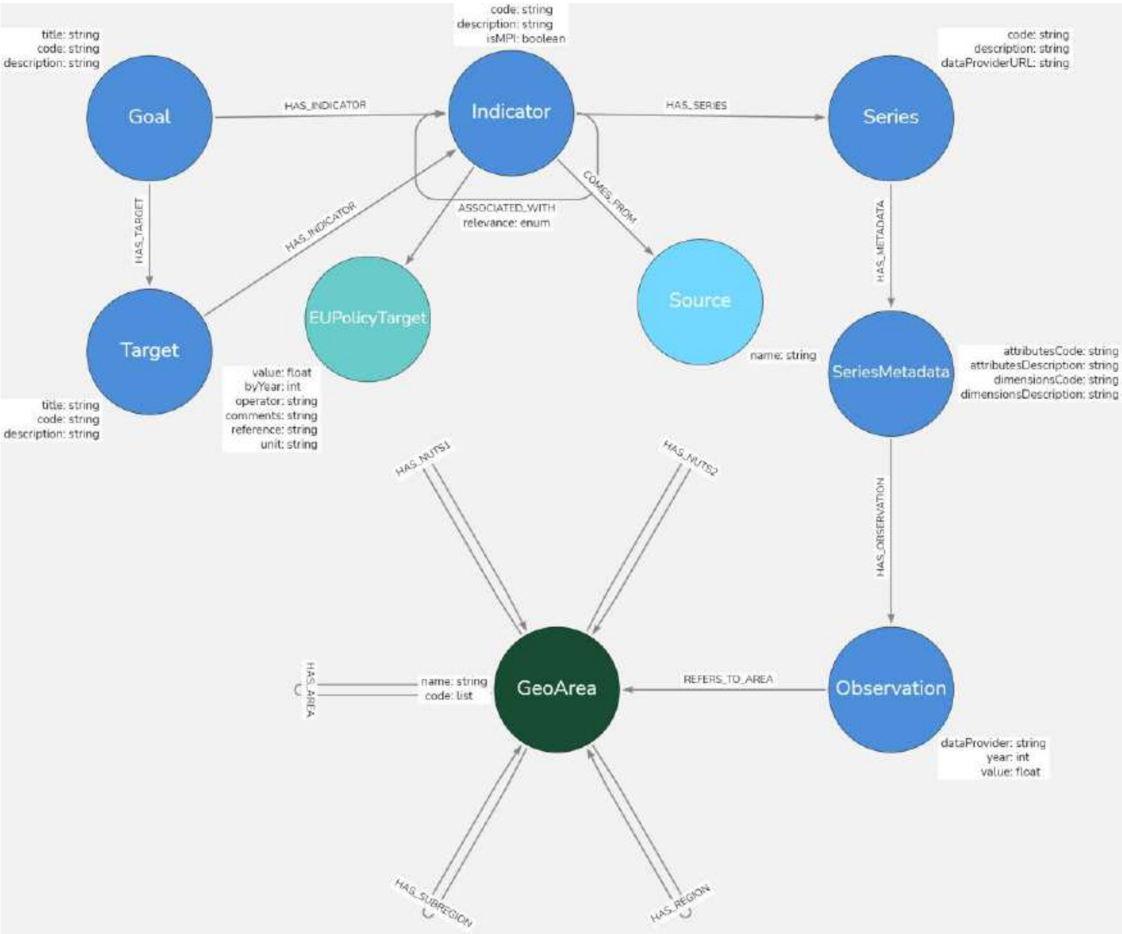

Figure 5. Sustainable Development Goals Indicators Set Representation.

By having conceptualized the way that time series data from various indicators can be represented in SustainGraph, the next step was to consider data coming from policies frameworks and directives to adapt policies frameworks. As detailed in Section 2.1, various policies are emerging at global, national and regional level. Keeping track of the targets posed on policies documents and their status of achievement or not across time is important. At the current version of SustainGraph, focus is given on the representation of concepts coming from the *European Green Deal (EGD)*, the *National Determined Contributions (NDCs)*, the *Country Specific Recommendations (CSRs)* and the *six SDG Transformations* proposed as modular building-blocks of SDG achievement (Sachs et al., 2019, 2021). For the *EGD*, the supported entities regard the defined *Ambitions* of the EGD and their implementation through specific *Policy Areas*, where each *Policy Area* can be associated with one or more SDGs. Various *EGDPolicyDocuments* are produced to implement the *EGD*, where each *EGDPolicyDocument* can contribute towards the six SDG *Transformations* detailed at (Sachs et al., 2019).

In the case of *CSRs*, once again, the *Recommendations* issued per country can be associated with one or more SDGs. These *Recommendations* are usually provided annually, thus it is important to keep track of the focus on SDGs across time. Regarding the *NDCs*, they provide action plans to cut emissions and adapt to climate impacts. An action plan is associated with specific SDG *Targets* and *Indicators* and specifies a set of targets that have to be achieved at national level by a specific point of time along with their current status, the main application sector (e.g., health, water, agriculture, energy efficiency) and the type of climate response (e.g., mitigation, adaptation) considered. With regards to the six SDG *Transformations*, per *Transformation* we consider the suggested *Interventions* that may take place through the associated ministries, as well as the expected *Intermediate Output* from the transformation. A view of this part of the specification within SustainGraph is depicted in Figure 6.

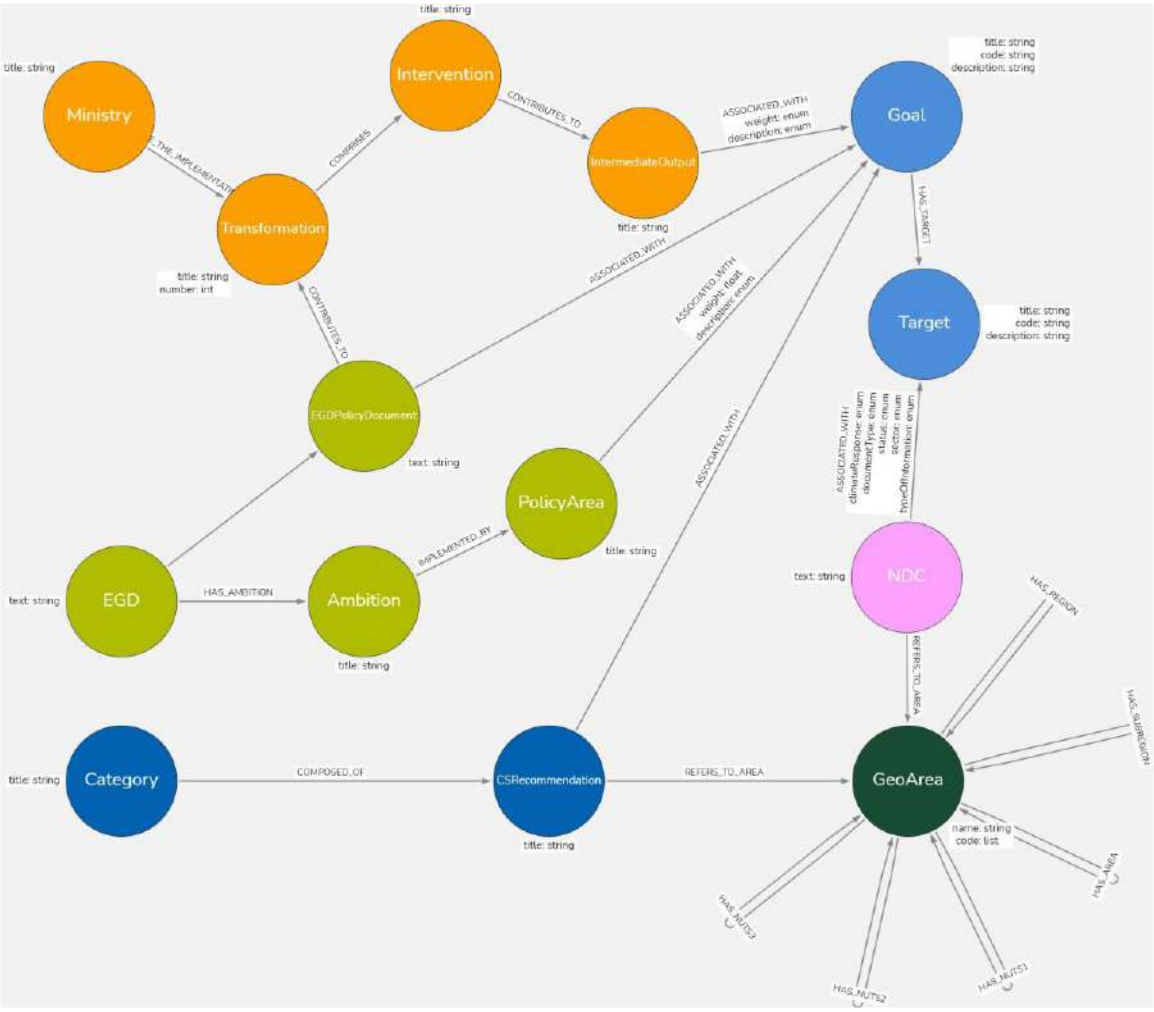

Figure 6. Sustainable Development Policy Frameworks.

Another important set of entities represented in SustainGraph is related to the implementation of *Case Studies* across Europe to develop climate-resilient regions through the adoption of systemic solutions and innovations. These entities regard the *Case Studies*, the *Climate-related Hazards* they aim to tackle and the *Innovations* that can be adopted and applied within each case study. Per *Case Study* we consider information related to a short description of the main challenges, actions and envisaged impact, the set of *Stakeholders* involved in the *Case Study* and the application *GeoArea*. Each *Case Study* is associated with

SDG *Goals*, *Targets* and *Indicators*, while it also includes information for *Indicators* defined by third-party data sources. Such information may be provided by monitoring infrastructure provided within the case study (e.g., Internet of Things (IoT) nodes, satellite images, data coming from citizen science platforms) or made available from other initiatives or monitoring frameworks (e.g., happiness index, corruption perception index). For the *Climate-related Hazards*, we have adopted the classification of hazards provided by the European Environmental Agency for tracking the Europe's changing climate hazards (Crespi et al., 2020). 32 climate hazard *Indicators* are made available, organised according to 16 hazard categories, grouped into 6 main types (heat and cold, wet and dry, wind, snow and ice, coastal, open ocean) (Crespi et al., 2020). Moving one step forward, the *Innovation* entity is introduced to represent innovative solutions that are developed to support adaptation and mitigation measures for climate change, based on the description of such innovations in the Climate Innovation Window developed by the BRIGAID project (Mintsje van Loon-Steensma, 2018). Each *Innovation* is associated with specific *Climate-related Hazards* and is applicable to specific application domains. Information related to the owner of the *Innovation* and its Technology Readiness Level (TRL) is made available. A view of this part of the specification within SustainGraph is depicted in Figure 7.

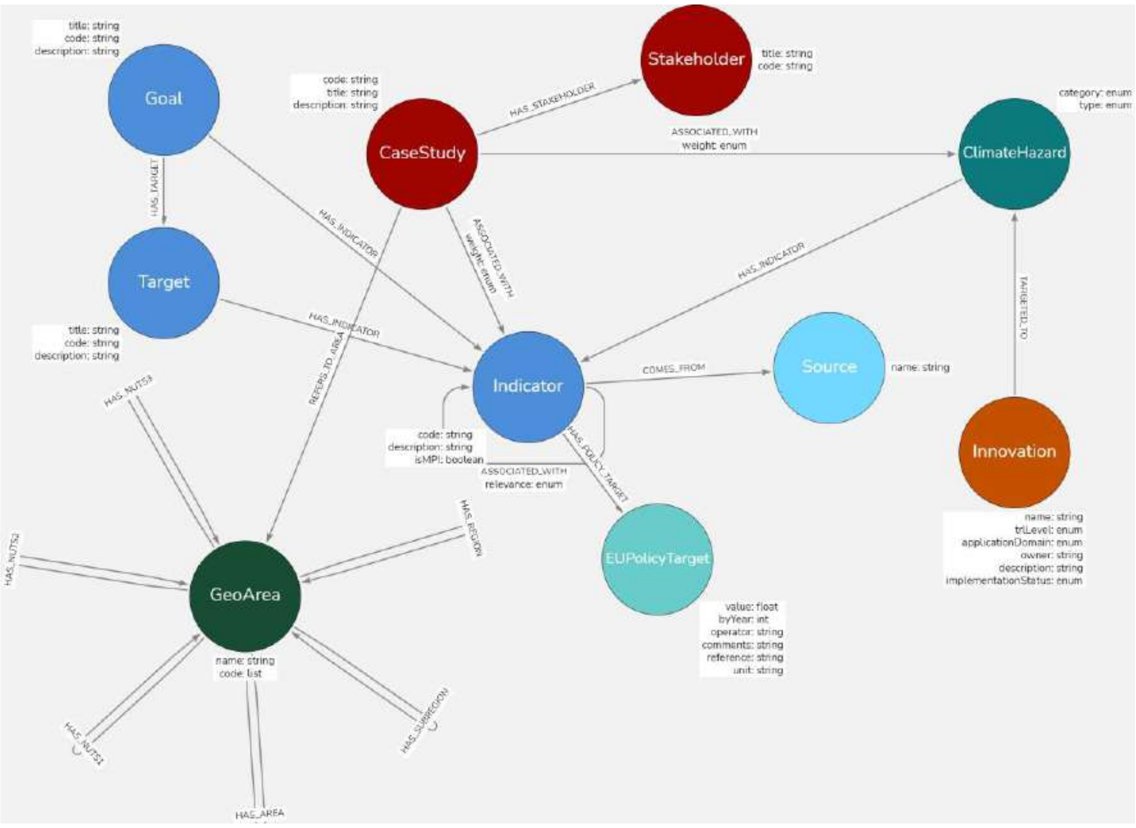

Figure 7. Case Studies.

Finally, attention is given on the proper representation of spatial information in SustainGraph. Spatial information is applicable to almost all the entities that are conceptualized in SustainGraph, given the importance to support high spatial resolution of the collected data. To achieve so, we support a hierarchical way of declaring information related to the location of the various entities. Country codes are supported based on both the International Standard ISO 3166-1 for the representation of names of countries and their subdivisions, as well as the M49 standard country or area codes for statistical use by the Statistics Division of the United Nations Secretariat. Furthermore, for EU countries, the Nomenclature of territorial units for statistics (NUTS) classification provided by Eurostat is introduced. Based on the NUTS classification, NUTS 1 areas are referring to major socio-economic regions, NUTS 2 areas to basic regions for the application of regional policies, and NUTS 3 areas to small regions for specific diagnoses. Representation of spatial geometry types is also under consideration within SustainGraph.

3.2 SustainGraph Data Population

Based on the conceptualization of SustainGraph, a set of data population mechanisms are implemented to support knowledge acquisition processes. Through the data population mechanisms, existing data provided by various sources and different formats can be transformed to knowledge within SustainGraph. The data population process is a dynamic process, where fresh data is continuously fed into the KG, enriching the available information and enabling further knowledge production and management, as detailed in Section 3.3. The main challenge faced here has to do with the development of custom scripts for automating or semi-automating the data ingestion to the KG. By making available such scripts, new releases of the considered datasets can be easily incorporated in the KG, reducing significantly the overhead posed to data scientists for continuously processing the available data to bring them into a homogeneous and interoperable format.

A wide set of data sources is considered. This set includes open data provided by international organizations, statistics authorities and public bodies in the form of tabular datasets (e.g., files in csv format) or through open Application Programming Interfaces (APIs), data coming from the monitoring infrastructure that is implemented within case studies in various regions, and data coming from the processing of policy documents and reports. For the latter, machine learning (ML) techniques are applied to support the knowledge acquisition process. The main considered ML technique is related to Natural Language Processing (NLP) mechanisms that helps understanding the content of the documents and extract information and insights from them. Data cleaning mechanisms are applied for improving data quality, while considering bias detection in terms of fairness. Data cleaning may regard -among others- removal of outliers, removal or completion of entries with missing values, and deletion of content that is not considered for inclusion in the KG.

A list of the main data sources used for populating with data SustainGraph is provided in Table 1. As already mentioned, this list should be considered as indicative, since the list of data sources is continuously evolving given the availability of further data and the emergence of new concepts within SustainGraph.

3.3 SustainGraph Knowledge Production, Exploration and Evolution

By having access to a data-populated version of SustainGraph, a set of services can be offered upon it. These services include data exploration and visualisation, data analysis, participatory modeling and analysis, knowledge production and KG completion. Following, we provide a short description of these services, while usage examples are provided in Section 4.

As already stated, SustainGraph can be considered as a knowledge repository related to the evolution of SDG indicators in national and regional level. Data exploration can take place through the submission of queries by end users. Each query is related with an open question, while the query result may provide an answer on it. Data exploration can be provided also through web-based navigation in the entities and relationships of SustainGraph. Various visualisations can be produced for depicting trends in the available data, comparing metrics based on their temporal and/or spatial resolution, and highlighting the weight of the existing relationships in the graph. In this way, end users are able to explore the existing knowledge

Data Provider	**Description**	**Data Type**
United Nations SDG API	UN SDG Indicators (SDG data reported by the United Nations Statistics Division) (UN Statistics, 2022)	Tabular (data retrieved through an API)
Eurostat Sustainable Development Indicators	EU SDG Indicators (SDG data reported by Eurostat) (EU SDG, 2022)	Tabular (CSV data processing)
National Determined Contributions	NDC data based on the Paris Agreement (time series data for specific indicators, as well as data related to the linkage between NDCs and SDGs) (Climate Watch, 2022).	Tabular and Classification (linkage) Data (data retrieved through an API)
World Happiness Report	World Happiness Index (survey data reporting how people evaluate their own lives) (SDSN - World Happiness Report, 2022).	Tabular (CSV data processing)
Transparency International	Corruption Perceptions Index (time series data for the perception of corruption levels worldwide) (Transparency International, 2022).	Tabular (CSV data processing)
European Environmental Agency	Climate Hazards Classification (data for the classification of climate hazards and the associated indicators) (Crespi et al., 2020).	Tabular and Text (data import based on a script)
Climate Innovation Window	Innovations (reference portal for innovations on climate change adaptation) (BRIGAID project, 2022).	Tabular (data import based on a script)
European Union	European Green Deal Documents (policy documents)	Text (processing based on NLP)
National Data	Country Specific Recommendations (documents with recommendations per country)	Text (manual data processing and NLP)
Research and Innovation Projects	Case Study Data (e.g., data provided in the ARSINOE project (ARSINOE project, 2022)).	Tabular and Text (csv data processing, text processing based on NLP)
6Transformation	Data from 6Transformations Report (mapping between transformations and SDGs) (Sachs et al., 2019, 2021)	Tabular (csv file produced from the report)

Table 1. Indicative Data sources for SustainGraph data population.

in the KG, achieve common understanding, get answers to specific questions and easily grasp trends and insights through visualisations.

Moving one step further, through the submission of queries to SustainGraph, the retrieved data can be fed as input to analysis pipelines. Such analysis pipelines may regard algorithms applied over tabular data or graph algorithms applied over SustainGraph or a part of SustainGraph. In the case of tabular data, algorithms such as correlation analysis, regression, descriptive statistics and classification may be applied. Tabular data can be also fed as input to developed participatory socio-environmental systems' models (e.g., based on agent-based modeling, system dynamics modeling) (Zafeiropoulos et al., 2021). Graph algorithms can be applied to support pattern identification within the KG and to evaluate the structure of the KG (e.g., examine the graph density, identify clusters, community detection). Graph ML techniques can be adopted to support link prediction and to evolve the KG with the introduction of new relationships, similarity analysis based on node embeddings, and classification analysis based on the application of node classification models. The outcomes produced by analysis pipelines can be used for the development of recommendation engines, providing insights for the design of efficient solutions (e.g., to improve the climate resilience of the considered areas within a case study).

It should be noted that the analysis results may be also fed back as information to the KG. In this way, further knowledge may be produced and made available, while results produced by different models can be compared.

4 RESULTS

4.1 Use Cases and Analysis Results

To demonstrate the applicability of SustainGraph to guide the co-design of innovative solutions for managing the impact of climate change, we detail a set of short and simple use cases. Knowledge exploration for these use cases takes place in the form of providing answers to questions, or through navigation in the information visually depicted in SustainGraph. Given the conceptualization of SustainGraph in Section 3.1, the objective is to provide some highlights on its potential usage. The provided examples can be considered as the basis for the development of advanced analysis processes in the future, binded to socio-environmental or socio-ecological models. Following, we shortly describe these use cases.

Use case #1: For a specific UN SDG indicator, compare its evolution per country in the last 20 years for countries in the Mediterranean.

In this use case, we examine the evolution of the UN SDG indicator 1.1.1 in part of the Mediterranean countries. The indicator depicts the proportion of the population living below the international poverty line and is used for evaluating the target 1.1 (by 2030, eradicate extreme poverty for all people everywhere, currently measured as people living on less than \$1.25 a day) of SDG #1. A query is submitted to SustainGraph to get time series data for a set of data series associated with this indicator for a set of countries. The produced output is visualised in Figure 8.

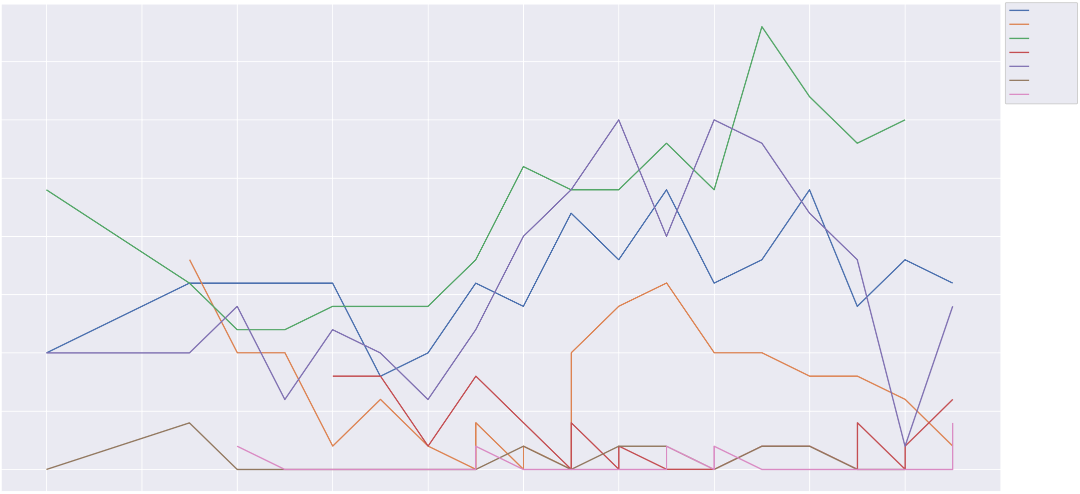

Figure 8. Monitoring of an UN SDG indicator across countries in the Mediterranean.

Use case #2: For a specific EU SDG indicator, compare the current status of the indicator across the EU countries, considering also the EU policy target to be achieved by 2030.

In this use case, we examine the current status of a specific EU SDG indicator, namely sdg_04_70 that tracks the ”Share of individuals having at least basic digital skills” across the EU countries. The current status of the indicator is compared to the posed target at EU level for 2030 that is 80%. Upon getting the relevant data through a query in SustainGraph, the visualisation depicted in Figure 9 is produced. A digital gap is noticed among the EU countries, since the indicator values range from 24 (e.g., countries in Southeastern Europe) to 81% (e.g., Scandinavian countries).

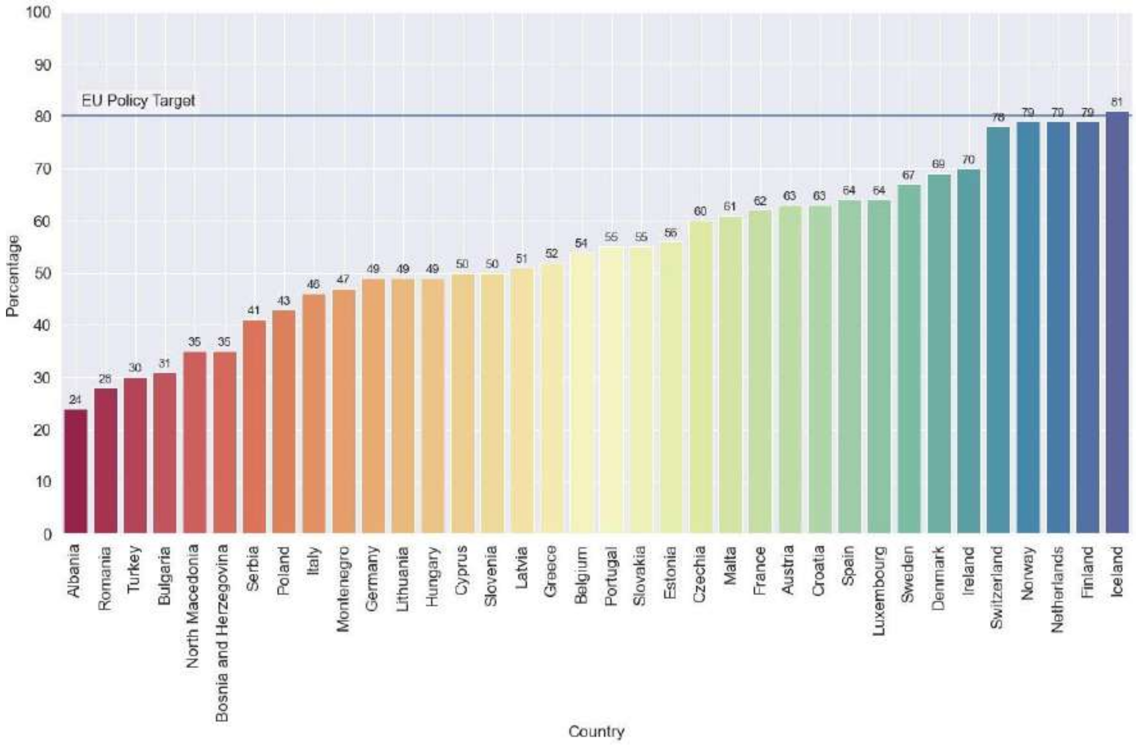

Figure 9. Monitoring of an EU SDG indicator across EU countries.

Use case #3: Which SDG targets are mostly considered in the plans for the Nationally Determined Contributions (NDCs)?

In this use case, we consider the G8 countries and we examine the importance posed in their Nationally Determined Contributions (NDCs) towards the achievement of the SDGs. The objective is to get a high level view of the priorities set by these countries, as well as identify any differences. Through a query in SustainGraph, the produced visualisation is depicted in Figure 10. For the EU countries (Italy, Germany and France) the produced distribution is identical, since the NDCs of these countries are based on the overall direction provided by the EU. The most considered SDGs regard SDGs # 7, 12 and 15. SDGs # 7 and 15 seem to be considered in the NDCs of all G8 countries with rates varying from 8-50% for SDG #7 and 13-50% for SDG #15. In the case of Russia, only these two SDGs are considered with rate of 50% per each. The most prioritized SDG is SDG #12 (with rate 23%) for Japan , SDG #7 (with rate 31%) for Canada, SDG #12 (with rate 17%) for United Kingdom, and SDGs #2 and 7 (with rate 19% each) for United States of America.

Use case #4: What is the relationship between the Outputs expected from a specific Transformation with the SDG goals?

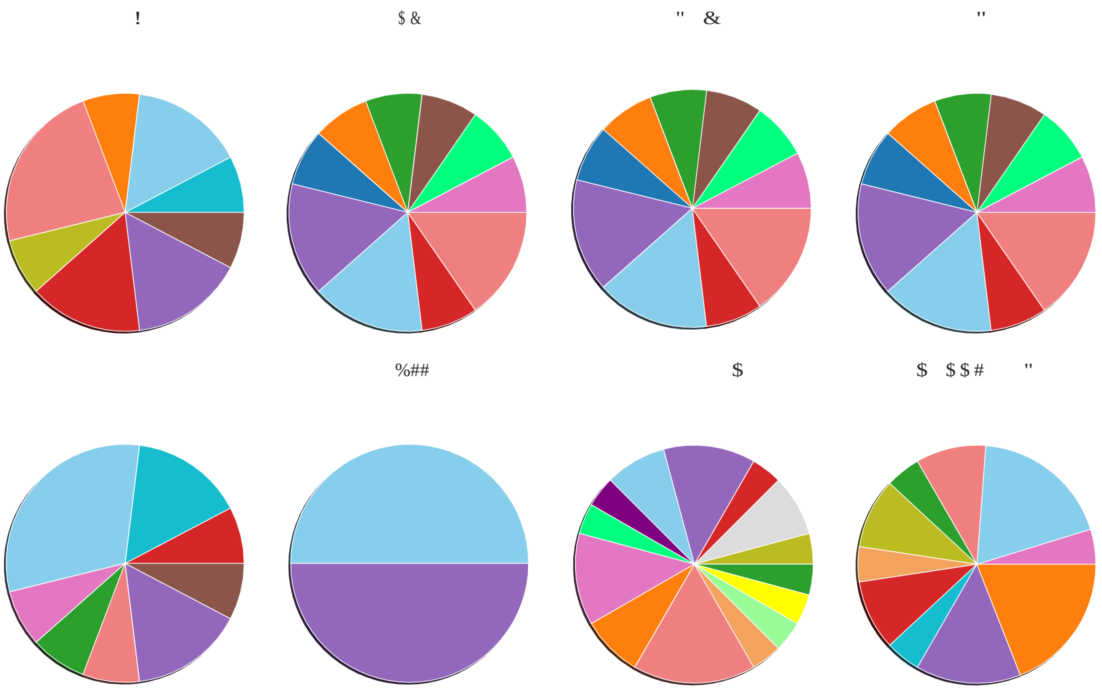

Figure 10. Association between NDC and SDGs for the G8 countries.

In this use case, we examine the association between a specific Transformation and the SDG goals, given that the Transformations are considered as modular building blocs for SDGs achievement. We have selected the ”Health, Wellbeing, and Demography” Transformation (Sachs et al., 2019). By navigating in SustainGraph (see Figure 11), it is noticed that this Transformation is mainly implemented by the Ministries of Health, while it comprises of two Interventions (development of healthy behaviours and social determinants of heal, support of universal health coverage). These interventions contribute to the Intermediate Output of providing Public Health Services that is associated with a set of SDGs (SDGs # 1, 2, 3, 4, 5, 8, 9, 10, 11, 12, 16).

Use case #5: For a specific case study, what are the associated climate hazards that are tackled within the considered geographical areas? Are there any innovations that can be adopted to tackle these hazards?

In this use case, we focus on a specific case study developed within the ARSINOE H2020 project (ARSINOE project, 2022). The case study focuses on tackling the impact of heat waves in the area of Attica in Greece. As an initial examination of the case study, we want to identify what are the main climate hazards considered in the case study and if there are available existing technological solutions to help to mitigate their impact. By navigating through SustainGraph, we can see that ”Heat and cold” is the main hazard category considered, while the associated hazard types regard the ”Extreme heat” and the ”Mean temperature” increase (see 12). For tackling these hazard types, four innovations are made available through the ”Climate Innovation Window” platform with Technology Readiness Level (TRL) levels ranging from 4 to 7.

4.2 Implementation Details

SustainGraph is developed based on the Neo4j graph data platform. It is conceptualized in the form of a property graph model (Fotopoulou et al., 2022), as well as in the form of an ontology (Mandilara et al.,

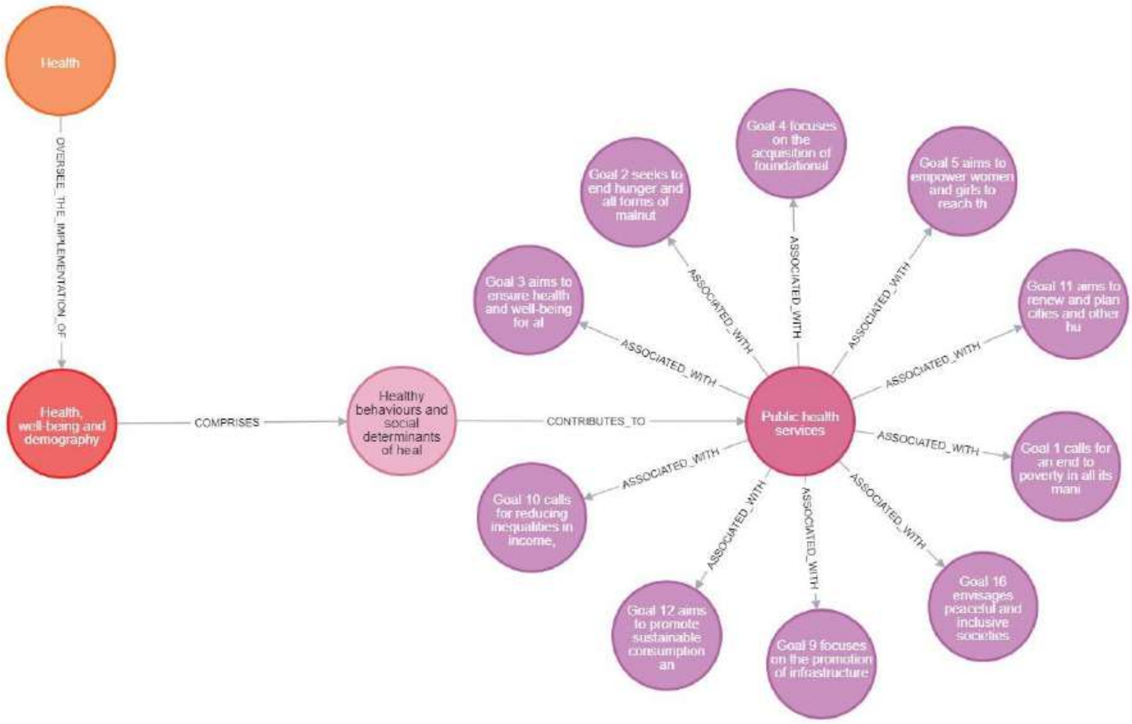

Figure 11. Association between Transformation and SDGs.

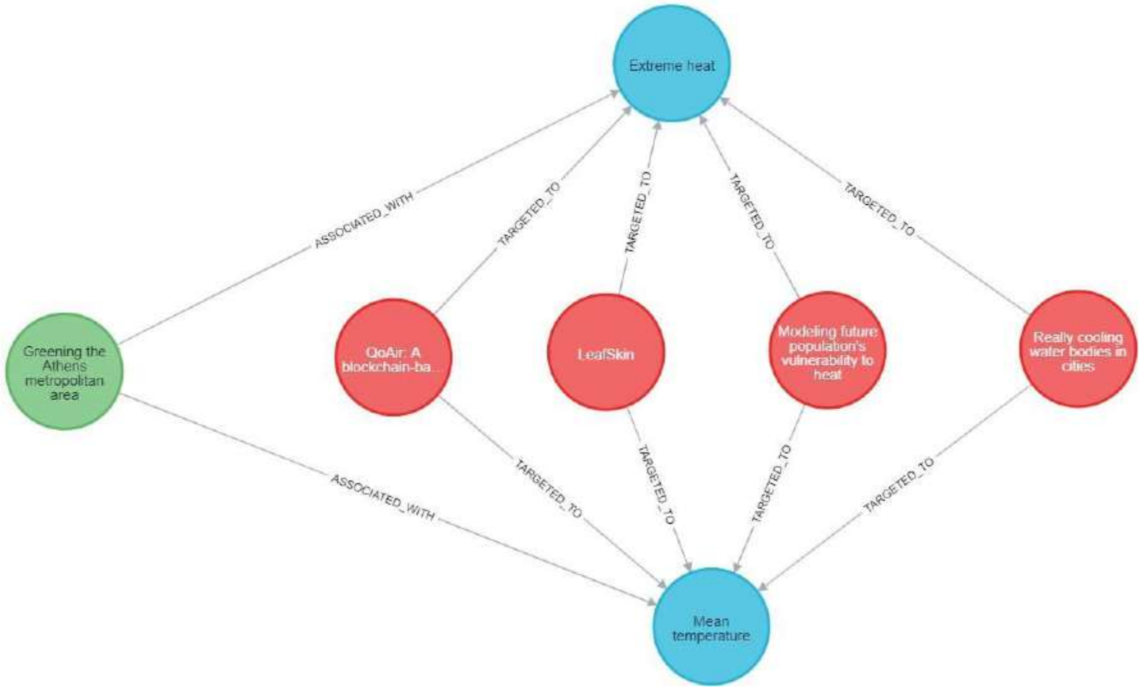

Figure 12. Climate hazards and innovation for a specific case study.

2022). The data population mechanisms are implemented through Python scripts by using the Py2neo client library and toolkit that supports to work with Neo4j from within Python applications. For the data analysis pipelines, the Neo4j Graph Data Science data analytics and machine learning platform is used.

Visualisations are produced based on the usage of the NeoDash dashboard builder for the Neo4j graph database, the Neo4j Bloom visualisation tool and SemSpect as a scalable graphical exploration interface for knowledge graphs. SustainGraph is released as an open-source KG that can be adopted and used by the scientific community.

5 DISCUSSION

In the current work, we have presented SustainGraph, as the first -up to our knowledge- Knowledge Graph that tries to holistically represent information associated with the set of goals, targets and indicators specified by the United Nations in the 2030 Agenda for Sustainable Development. SustainGraph is conceptualized by having in mind the need to track targets and indicators provided by different data providers, considering the need to represent their association based on their exact definition (e.g., the UN SDG and the EU SDG indicators are not identical). The information collected in SustainGraph includes data related to the association between the emerging policies and the SDGs, the implementation of case studies and the release of innovative solutions to tackle climate change.

The conceptualization and development of SustainGraph is the first and basic step to serve a wide set of end users, including the scientific community, policy makers and educational organizations. To achieve so, various challenges are being considered and effort is allocated to tackle them. One of the major challenges has to do with the development of mature solutions to easily populate SustainGraph with data. As already mentioned, data quality issues along with the need for harmonization of the provided datasets by different data providers hinder the ease adoption and usage of such data. A set of data population mechanisms are already into place to support the population of SustainGraph with qualitative data, however, further mechanisms have to be developed in the future, considering the volatility of the structure of the produced data and the inclusion of further data sources (e.g., data coming from initiatives related to the development of sustainable cities, data associated with the classification of activities according to the EU Taxonomy). Another challenge has to do with the development of user-friendly interfaces to make SustainGraph easily adoptable by end users without expertise in computer science. To achieve so, a set of visualisation tools are considered that make straightforward the interaction with SustainGraph, while work is in progress towards the development of user-friendly querying interfaces for submission of questions by end users.

SustainGraph aims also to promote collaboration among scientists from various domains, being aligned with the Systems Innovation Approach. Participatory modeling approaches can be applied over SustainGraph, taking advantage of the harmonization of the represented concepts in the KG and the provision of access to data that are accompanied by their meaning and can make sense to the end users. Interoperability of SustainGraph with tools that support the execution of analysis pipelines and modeling environments (e.g., multi-agent programmable modeling environments) is desirable, since it is going to further boost its usability by scientists. Furthermore, ways for ingesting the analysis results to the KG are going to be considered (e.g., the forecasting of the evolution of specific indicators can be available in the KG).

Special mention has to be given to the exploitation of opportunities provided by the emergence of ML techniques and toolkits. ML techniques can be applied in SustainGraph for supporting both data population and data analysis mechanisms. Natural Language Processing (NLP) techniques are very helpful to analyze policies documents and extract information that can be embedded in the KG. In a similar way, computer vision techniques can be applied over images (e.g., from satellite infrastructure or citizen science platforms) to further populate with data the KG. In the analysis part, various ML pipelines can be developed to support

KG evolution and completion processes, considering graph ML algorithms. Focus has also to be given on the development of explainable Artificial Intelligence (AI) solutions over SustainGraph, providing accurate and easily interpretable decisions, and facilitating the adoption of such solutions by scientists (Tiddi and Schlobach, 2022).

To be able to support the aforementioned extensions, openness and interoperability regard characteristics that are considered by design in the conceptualization and development of SustainGraph. An open-source release of SustainGraph is made available (Fotopoulou et al., 2022), while consumption of open APIs is considered -where applicable- in the development of data population mechanisms.

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

EF, IM, AZ and SP contributed to conception and design of SustainGraph. EF and IM developed SustainGraph and the set of data population mechanisms. AZ, CL, GA and PK contributed to documentation and interlinking of policies frameworks with the SDGs and the revision of the concepts and relationships detailed in SustainGraph. CL, GA and PK contributed to the description of the Systems Innovation Approach and the description of the interaction of SustainGraph with participatory modeling processes. AZ, EF, IM and SP wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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DATA AVAILABILITY STATEMENT

The release of SustainGraph is made openly available in a Gitlab repository in (Fotopoulou et al., 2022).

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