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SMEXI – a Data-Based Approach for the Small-Scale Investigation of Sustainability Goals in Cities

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1 ABSTRACT

To address the wide range of global challenges and a more sustainable society, the UN Sustainable Development Goals (SDGs) were developed. They are a set of 17 global, interconnected goals and provide a comprehensive framework for governments, organizations, and communities to work towards common objectives. When aiming at a data-bsed approach to promote a sustainable development, it is necessary to identify for each SDG associated indicators and data sets that provide insights into the status quo or past developments. Existing approaches that aim to provide such data-based information for cities are often limited regarding the spatial resolution of the cities under consideration: they only allow the exploration and analysis of SDGs on a macro level, usually the complete city. However, cities are not homogeneous – different quarters vary a lot with regard to their population, usage, building structure, etc. Even inside of quarters, social disparities can typically be determined. Thus, to accurately identify existing problems, and to improve living conditions accordingly, an analysis at macro level is not enough. The SMEXI (Small Scale Exploration of SDG Indicators) tool presented in this work tries to overcome this limit and enables users to track the progress of SDGs in cities at a fine-grained level.

Keywords: SDG, planning, smart city, sustainability, development

2 INTRODUCTION

Cities worldwide face various complex environmental, social, economic, and governance challenges, amplified by ongoing crises such as the Covid-19 pandemic or consequences of military conflicts. It is increasingly evident that the multifaceted nature of these problems requires comprehensive, holistic approaches instead of attempts to find solutions that only focus on individual problem aspects. Ideally, the challenges are tackled by always aiming at a more sustainable development, i.e., a development that meets the needs of the present without compromising the ability of future generations to meet their own needs (United Nations 2015a).

The challenges for sustainability in cities have evolved over time, with the roots of modern concerns tracing back to works like the groundbreaking report titled "The Limits to Growth" of the Club of Rome (Meadows 1972) or the collection "Small Is Beautiful: A Study of Economics As If People Mattered" (Schumacher 1973). They highlighted the finite nature of Earth's resources and the potential consequences of unchecked population growth and industrialization. To address the wide range of global challenges and to promote a more sustainable and equitable world, the UN Sustainable Development Goals (SDGs) were developed as part of the 2030 Agenda for Sustainable Development that was officially adopted by all member states of the UN in September 2015 (United Nations 2015b). They are a set of 17 global, interconnected goals and address a range of social, economic, and environmental challenges. The role of the SDGs in promoting more sustainable cities lies in providing a comprehensive framework for governments, organizations, and communities to work towards common objectives.

When aiming to promote a sustainable development, it is critical for any type of stakeholder to first obtain a clear picture of the situation in the region of interest. Accordingly, it is necessary to identify associated indicators for each SDG that provide insights into the status quo or past developments. And last not least, these indicators can only be examined properly if data sets with information about them are available and accessible. Several approaches exist that aim to provide such data-based information for cities, e.g., the SDG tracker by Our World in Data (https://ourworldindata.org/sdgs) or the Open SDG platform (https://open-sdg.org/). Yet, these tools are often limited regarding the data sources used, but above all when it comes to the spatial resolution of the cities under consideration: they only allow the exploration and analysis of SDGs on a macro level, usually the complete city. However, cities are not homogeneous – different quarters vary a lot with regard to their population, usage, building structure, etc. Even inside of quarters, social disparities can typically be determined. Thus, to accurately identify existing problems, and to improve living conditions accordingly, an analysis at macro level is not enough.

This paper first discusses the problem context and research background. After an overview of SDGs and related indicators and data sources, the methodologies employed and the design and development of the SMEXI prototype are presented. The tool itself is then explained in detail, followed by the results of a first evaluation. The paper concludes with a summary and an outlook to future work.

3 RESEARCH BACKGROUND

Several approaches exist that offer a data-based approach to track SDGs for specific regions. It is common for them to rely on a global set of indicators for all 17 SDGs. E.g., (Arbab 2022) suggests an indicator system for measuring city sustainability based on a systematic literature review. On the one hand, this facilitates global comparisons. On the other hand, data availability for all indicators might be inconsistent across countries, regions or cities, potentially leading to biased assessments. Also, such indicators usually do not capture local nuances, variations, and disparities within countries or regions. E.g., trackers may show that a country has made significant progress on SDG 1 - No Poverty - but they may not provide the data to show that there is a significant gap between urban and rural areas. Examples of such approaches are the German SDG-Portal[1], the Eurostat SDG country overview[2], and the dashboards by the European Sustainable Development Solutions Network (SDSN)[3].

The Open SDG Platform[4] is an open data and technology framework that claims to be designed to assist in driving global action toward a sustainable and equitable future. By facilitating the collection, management, and dissemination of SDG data, the platform aims at empowering stakeholders to track progress, assess impact, and make informed decisions to drive change. The open source platform is characterized by its distinctive features, collaborative framework, and nuanced approach to data visualization. It can be customized to align with specific contexts and priorities, and allows users to create dashboards customized to their needs. However, this approach could not be used as the basis of our work as their solution works by drilling down information specific for an SDG and its dimensions for a region. One of our goals is to enable users to understand how multiple SDGs and their dimensions are related and affect each other, for example the relation between Income Distribution (SDG 8) and the Amenity Distribution in a region, where one can notice regions with higher income have access to diverse and better infrastructure than those with lower income.

In (Editorials 2018), the authors provide a comprehensive overview of the state of SDG tracking and identify key challenges and opportunities. They state that progress on the SDGs is mixed, and that progress is often uneven across countries and regions. The authors identify several data gaps and methodological challenges that need to be addressed to improve the quality of SDG data. These challenges include:

- Reliable and timely data on many of the SDGs is often scarce or unavailable, particularly in developing countries.
- Even when data is available, it is often not comparable across countries or regions. This is due to differences in data collection methods, definitions, and reporting standards.
- The quality of SDG data can be poor, due to factors such as measurement error, bias, and incompleteness.
- To address these challenges, the authors propose a number of strategies, including:
- Investing in the capacity of national statistical agencies and developing innovative data collection methods could help in analyzing data more accurately.
- Investment in data infrastructure can provide access to data and technologies that can be used to improve data quality and improve current comparison and evaluation methodologies.

[1] see https://sdg-portal.de
[2] see https://ec.europa.eu/eurostat/cache/infographs/sdg-country-overview/
[3] see https://eu-dashboards.sdgindex.org
[4] see https://open-sdg.org

- Promotion of new data sources, such as the use of satellite imagery, mobile data, and other innovative data sources to fill data gaps. An example is the usage of satellite imagery to bridge gaps in land use data in a region, such as the forest coverage.
- Techniques and processes such as developing data visualization tools and training decision-makers on how to use the SDG data effectively, can help improve the use of data for decision-making.

The authors highlight the need for greater collaboration and coordination among national governments, international organizations, and civil society to improve SDG tracking. This includes developing a common understanding of the SDGs, establishing a shared set of indicators, and developing a global monitoring system. The paper concludes by calling attention to the importance of SDG tracking for achieving the SDGs. The authors argue that by measuring progress on the SDGs, we can identify what is working, what is not working, and what needs to be changed to achieve the goals.

4 THE SMEXI TOOL

In order to examine the potentials and challenges of an approach that allows spatially differentiated analyses of SDGs within cities, the project SMEXI (Small Scale Exploration of SDG Indicators) was initiated at DFKI. Using the city of Kaiserslautern, Germany, as a first test bed, the aim is to provide an interactive and adaptable, digital platform facilitating the tracking of SDGs in cities at a small scale. Realizing such a platform entails the tasks (1) to identify indicators and (potentially) available data sets for all SDGs, (2) to examine, preprocess and integrate these data sets, (3) to determine spatial granularities that correspond to meaningful examination areas, and that can be described properly with the identified data sets, (4) to find suitable forms of presentation for the (aggregated) data on SDGs, and (5) to develop a software architecture and identify suitable components and interfaces.

A first prototype of SMEXI was realized at the end of 2023 making use of various data sets from the city administration of Kaiserslautern and other, mainly publicly available sources. It is a web-based tool that uses local districts and statistical districts as spatial units for fine-grained examinations. It offers means to compare different parts of a city, and to manually define scores for different SDGs.

4.1 Identification of indicators and data sets

The successful implementation of the SMEXI prototype hinges on a thorough understanding of the data sources and their origins, elucidating how they contribute to monitoring and tracking SDGs. We first need to identify the data we need and its dimensions, which is a challenging task. We identified that the most efficient way to tackle the challenge is through the following steps and considerations:

(1) To decide the data we need, we start by understanding the underlying intentions of the SDGs, and for each SDG discuss in detail questions we want to answer with respect to the SDG. In this step, it is very important to involve experts for specific fields such as health or education. As an outcome, a set of indicators is identified for each SDG.

(2) For each identified indicator, we need to research if data sets exist that provide respective information. Such data can come from different sources as shown in Table 1. When selecting a data source, quality characteristics such as completeness, accuracy, actuality, and being devoid of bias must be considered (Priestley et al 2023). We aimed at only using freely available, open data to foster the transferability of our approach. We were able to procure our data sets from publicly available data sources as well as from our professional networks who work with and had access to the data sets we required to present our solution. We also considered the ethics of presenting our data in the visualizations and questioned ourselves on how diverse users can interpret them, keeping in mind that visualizations can be misused to portray and focus on negativity and shortcomings (Williams 2020). It is important to have discussions and debates with diverse groups and experts on the selected approach.

It is important to be careful to not raise our expectations that every SDG and indicator that we identified in step (1) can be perfectly covered. The thought and goal is to ultimately support users and not to provide a perfect answer.

4.2 Determination of spatial units used

Since we were aiming at facilitating the tracking of SDGs on a micro level, meaningful spatial units had to be identified that allow such a small-scale examination. In our test scenario we either had the possibility to rely on existing predefined structures used in German administrations, to define spatial units on our own, or to allow end users to specify regions of interest. This decision was strongly influenced by the spatial structures for which data exists or can be merged. It turned out that, among other things due to data protection aspects, a large part of the data within our test scenario does not exist or cannot be created for freely definable regions, but only aggregated to spatial sizes established in the administration, specifically "city districts" and the smaller scale "statistical districts". These are geographical subdivisions within a city or municipality used for the collection and analysis of statistical data. Relying on these granularities allowed us to make use of the majority of data sets.

Data Set	Description
Shape Data	Our main goal is to monitor sustainability objectives at a small-scale level, achieved by dividing the city into smaller regions. The smallest regions are identified in our prototype as statistical regions which serve as the basis for our sustainability analysis, employing a bottom-to-top approach where they are grouped into larger municipality regions for comprehensive data aggregation. The data set structure includes GeoJSON data points for statistical regions, each with a unique identifier crucial for associating social data sets, while the municipality/city districts data set utilizes a mapping file to group statistical regions effectively.
Crowdsourced/ User Generated Data	In our context, such data is mainly gathered by means of volunteered geographic information (VGI). This refers to geographic data voluntarily contributed by individuals or communities, often through platforms like OpenStreetMap (OSM) to collectively create and share spatial information. They cover various aspects such as public infrastructure, transportation, amenities, and land use, aiding our analysis of diverse SDGs.
Administration Data	Refers to data gathered, maintained, and managed by municipal authorities, encompassing various aspects such as demographics, infrastructure, services, and policies, which are utilized for urban planning, governance, and decision-making processes within a city.
3rd Party Data	This fefers to collections of data obtained from organizations outside a public administration, often provided by external vendors, government agencies, research institutions, or commercial data providers. A few examples of where we use 3rd party data are in the visualizations for income distributions and educational qualifications. It is important to note that both this, and Administration Data are meticulously selected based on the important information they contain about the identified SDGs and additional criteria such as richness, reliability, and accessibility.

Table 1: A brief overview of different types of data sources used in the SMEXI prototype.

4.3 Data processing and querying

We generally receive the data from the sources shown in Table 1 in a format that requires certain preprocessing steps in order to be usable within our system. We will briefly discuss how we process this input data and rationalize our chosen storage approach, Elasticsearch.[5]

The data is received in a variety of data formats such as GeoJSON or CSV. We start by exploring the existing dimensions of the data received in order to understand and how we can leverage them within our SMEXI prototype specifically for the multiple SDGs we are tracking. Consider a scenario where we have data with information on infrastructure, we can proceed by solving for how we extract and process the information to be used in tracking for amenities and transportation by categorizing the infrastructure type and extracting supporting data from the same data source or additional data sources. To be able to do more than get the information stored in it in the current state, we wanted to be able to make queries to the data set. Among others this is realized by leveraging the technical capabilities of Elasticsearch (Gormley & Tong 2015) which has rich features such as ranking query results from which we can select the most desired results from. E.g., when we query OSM data for information on green spaces in a region, we can easily query different representations such as 'green' or 'green_community'.

[5] see https://www.elastic.co

In a further data processing step, we need to make sure that data that does not have a POI characteristic is associated with the spatial units we use in SMEXY.

4.4 Functionalities

The objective of the SMEXI prototype is to enable diverse stakeholders to track and analyze SDGs, which is possible through map visualizations, a panel with visualizations for different SDGs, data sets as well as a "Region Index Value", and through a mode that allows to compare different regions.

4.4.1 Map visualizations

The map visualization plots shapes corresponding to the selected spatial granularity (i.e., "city districts" or "statistical districts"), upon which information relevant for the examined SDGs is presented. Administrators have the flexibility to define the size and shape of these regions, enabling detailed exploration on a small scale. The map visualizations are dynamically rendered using OpenStreetMap (OSM) tiles, which are based on web maps. These tiles are meticulously crafted from a wealth of open data, including contributions to OSM, GPS information, and visual input from volunteers. The OSM tiles are flexible and can be custom crafted by users according to their need, for our prototype we utilize the standard OSM tile layer and the transport tile layer which focuses on providing all transportation-related details in a map visual. Figure 1 presents the view of the prototype on initial load, when we click on a region on the map to the right, the SDG data associated with the region is presented in the left column of the prototype.

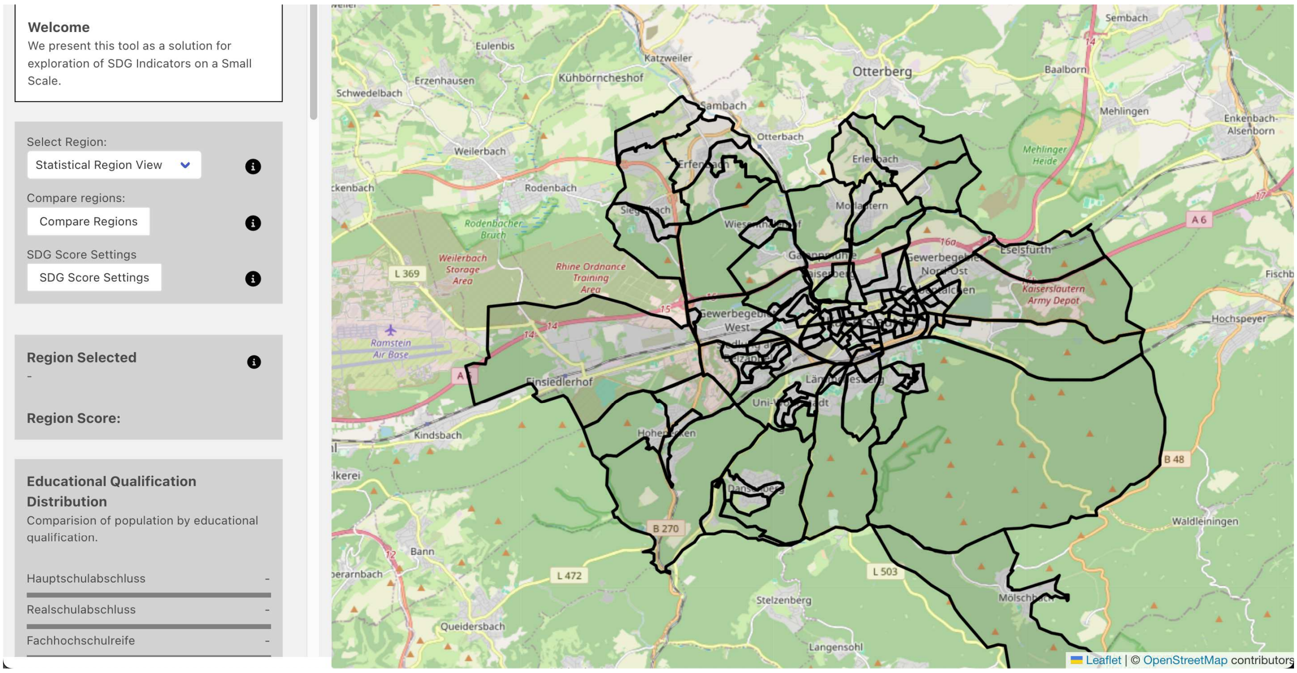

Fig. 1: Initial view of prototype on load. To the right we have a map visualization with plots of different regions. To the left we present the data visualizations specific to the region under consideration.

4.4.2 SDG/Data visualizations

On selection of a region on the map, the data associated with it is visualized to allow the user to quickly understand the information presented. As data visualization plays an increasingly crucial role in decision-making, storytelling, and communication, ethical considerations become paramount. The creation and presentation of the visualizations were discussed at length and in great detail throughout the implementation process to ensure that they are accurate, truthful, inclusive, and depict context clearly. The prototype visualizes data specific to the region which relates to various SDGs. Table 2 describes which SDG is tracked for analysis in a data visualization. As seen in Figure 1, these data visualizations are loaded in the left column of the prototype based on the region selected on the map.

4.4.3 Region Index Value

The determination of an index for tracking SDGs for each region involves a comprehensive approach, integrating insights from various research papers (Tuholske et al. 2021, Memmel et al 2021) and establishing standardized formulas (Randall & Baetz 2015). In initiating the calculation process, each setting defines an ideal value (Kurth et al. 2023), serving as the starting point for subsequent score computations. These ideal values align with standards established by relevant research papers (Grisolia & Torchio 2022), reflecting an ideal benchmark. Acknowledging the diverse nature of regions, the solution introduces sliders that allow users and policymakers to adjust values within the predefined ideal range. This flexibility ensures that regions can be accurately characterized based on their unique conditions and attributes. The aim of this technique using a weighted value for a region and comparing it with others is to bring quality to all regions as a start before moving up to a better index score.

Data Visualization	SDGs Tracked
Income Distribution	SDG 8
Educational Qualification Distribution	SDG 4
Population Age Distribution	SDG 10 and SDG 11
Population Diversity	SDG 5 and SDG 10
Amenities Distribution	SDG 3 and SDG 11
Transport Distribution	SDG 8 and SDG 11
Car Fuel Type Distribution	SDG 7 and SDG 13

Table 2: Correlation between the visualizations in our prototype and the SDGs they address.

4.4.4 Comparing Regions

This functionality is designed to establish a comprehensive methodology for comparing two regions. Through the utilization of visualizations and the computation of index scores for each region, the objective is to spotlight variations between different regions.

This information serves as a valuable resource for policymakers, offering insights into regional characteristics. By identifying specific scores and dimensions that may benefit from introduction or improvement, this approach contributes to the pursuit of greater equality between regions.

4.5 Architecture and components

The technical architecture (Fielding et al. 2000) of the SMEXI prototype is provided in Figure 2. We now briefly discuss the rationale behind choosing the technology stack. For the client side, which represents the user interface and functionality that users interact with directly, we decided to use a no-framework solution and leverage the complete functionality of JavaScript. This was done since our goal is to offer an effective long term solution, so we wanted to avoid challenges when frameworks are deprecated and no longer supported which can cause potential code rewrite. D3.js and OSM are chosen as they are open-source and have a large community of developers releasing new features for data visualization. Our data sets are stored in Elasticsearch indices, which describes our database technology. Its features of aggregating query results, retrieval speeds, and query ranked results are leveraged, as discussed in Section 4.3.

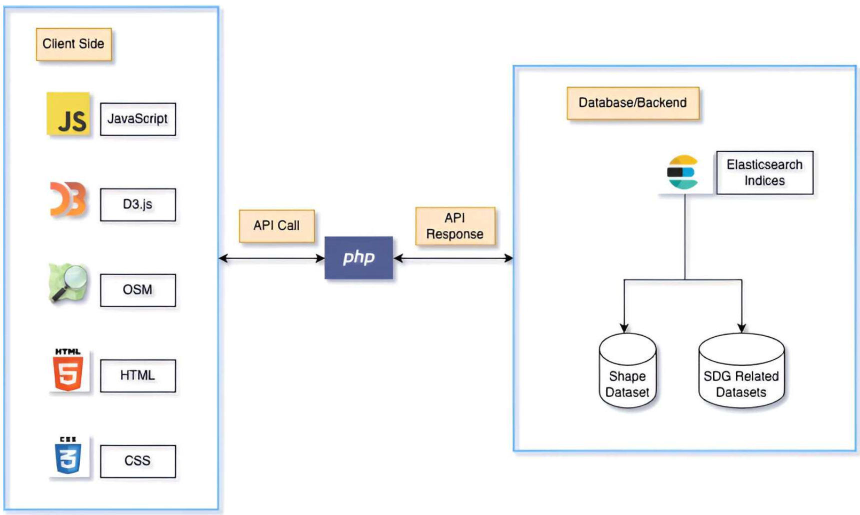

Fig. 2: Architecture diagram

We developed our code base using the Model-View-Controller (MVC) (Reenskaug 2003) chosen for its code modularity and reusability which are the most desirable principles in modern development.

We will now briefly present the controllers which are responsible for handling user inputs and managing the flow of data and control in the code in Table 3.

Controller	Responsibilities
App Controller	• Controls execution from first load to the end of life. • Manages data flow and events between the Map Controller and Region Information Controller.
Map Controller	• Query the data sets. • User click events on a region plot on the map visualization as seen to the right in Figure 1, transfers control to the Region Information Controller with the data bound to the region to be used for generating the region's visualizations.
Region Information Controller	• Instances of all the visualization models are maintained. • When data received from the Map Controller on user region selection, it transmits data to each visualization model. • Calculation of the Regional Index Score as discussed in Section 4.4.

Table 3: Overview of the responsibilities of the controllers.

Models represent the data and business logic and are responsible for storing data, performing computations, and enforcing business rules. Models encapsulate the application's state and behavior. A controller has the capability to instantiate multiple models needed as seen in Figure 3 where the Map Controller is linked to the Map Model in a one-to-one relationship, indicating a single instance of the map model. Conversely, the Region Information Controller has a one-to-many relationship with its associated models, allowing the controller to create multiple models as required.

Model	Responsibilities
Map Model	• Switching between map tiles, which are intended to provide users distinct perspectives and information layers in a map view. Our prototype has the base map and transport map tiles. • Oversees the creation, editing, and deletion of plots on the map visualization.
Donut Chart Model, Progress Bar Chart Model, & Pyramid Chart Model	• Generates and manages the state of the visualizations for the charts.

Table 4: Overview of the responsibilities of the models.

Services play a crucial role in encapsulating the logic associated with making requests to the database through API calls, handling the responses, and managing data. Services abstract the complexities of network communication and data manipulation, providing a clean interface for other parts of the solution to interact with external APIs or internal data sources.

Services	Functionalities
Elasticsearch Query Service	Encapsulates functions that support the generation of complex queries by the Elasticsearch standard and processing the response from the queries into a desirable data structure format used in the prototype.
Overpass Query Service	Interacts with the Overpass API, extracting OpenStreetMap (OSM) data. It forms queries based on Overpass API protocols, filtering options extend to various shapes via GeoJSON, enabling tailored data retrieval.
PubSub Service	Based on the Publish-Subscribe design pattern, coordinates communication between controllers or models. It handles event distribution and subscriber management, allowing communication without direct dependencies.

Table 5: Overview of the functionalities of the services.

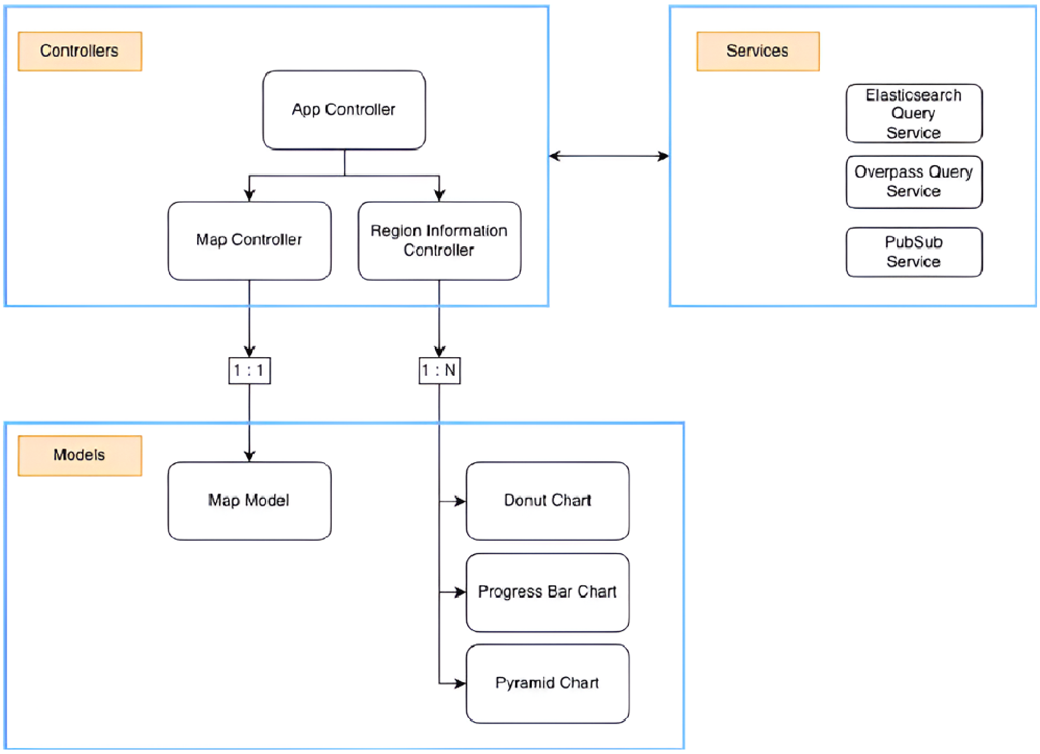

Fig. 3: MVC Design

5 PRELIMINARY EVALUATION RESULTS

As not all the data required for a complete evaluation of the SMEXI tool was available at the time of publication, the corresponding results are not yet available. However, we engaged with diverse stakeholders and sustainability experts during the development of the system. Their feedback helped us improve the solution's effectiveness, practicality, and accessibility for a broader audience. Specifically, we focused on making visualizations, regional scoring, and comparison methods quick and easy to understand within the SDG context. This aimed to prevent misinterpretations and support users in drawing meaningful conclusions from the data. Our work unfolded through iterative development stages. We continuously presented our findings to the city of Kaiserslautern, framing our solution as a potential input for ongoing initiatives. This ensured our work aligned with local context and broader development goals. Furthermore, we showcased our solution at consortium meetings of the project "Ageing Smart".[6] We demonstrated its ability to aggregate municipal data and provided interactive examples for data exploration. The positive feedback and insightful questions fueled further development, confirming the solution's effectiveness, practicality, and its potential to empower stakeholders for positive change.

6 SUMMARY AND OUTLOOK

The small-scale consideration of SDGs in cities is an important task to be able to make informed decisions for sustainable development, and to adequately consider the given diversity and heterogeneity in urban environments. The SMEXI prototype implements such an approach and uses the established geographical subdivisions of "city districts" and "statistical districts" for this purpose. This ensures that the largest possible number of available data sources can be used. In addition, these are spatial dimensions that were already considered useful for small-scale studies based on various considerations by city administrations. These spaces are therefore also particularly suitable for an investigation of SDGs.

The identification and integration of indicators and corresponding data sets for individual SDGs is a process of central importance and requires both in-depth knowledge of the goals and the availability and accessibility of data, particularly within urban administrations. In many cases, such data sets only provide information about a limited number of facets of an SDG, yet it can support decision makers and experts in an analysis

[6] see https://ageing-smart.de/

process and serve as a motivation to carry out further investigations, or to contribute with further information that can be integrated into the system.

In the future, we plan to publish the SMEXI software as open source and to realize further use cases in order to learn more about potentially relevant data sets, and about further configuration means that are required to adapt the tool to specific local settings.

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