Application of knowledge graphs for creating a library of reusable knowledge in the smart city domain

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Abstract

Knowledge reuse can increase the quality and efficiency of different activities, as well as reduce risks. The digital transformation of a city is a complex task that requires new approaches and management technologies. Knowledge reuse can reinforce city digital transformation initiatives, e.g. data integration and modeling activities can be improved via ontology reuse, design and development of digital solutions can be enhanced via reference architectures and reuse of existing methods and systems. Such reuse can speed up the work of city development managers, digital architects, and other ICT specialists, as well as decrease costs and risks. Although there are platforms for knowledge sharing and reuse within the smart city domain, they apply a traditional document-oriented approach to knowledge representation. This limits knowledge integration and the creation of intelligent services. So, knowledge graph technology was selected for collecting and curating digital city planning reusable content. The Open Research Knowledge Graph (ORKG) provided an opportunity for piloting this approach. The current paper will overview the digital city planning observatory within the ORKG, including main knowledge representation mechanisms and representative content examples, and provide the link between content and application scenarios.

Keywords

Knowledge reuse, knowledge graph, smart city, city modeling

1. Introduction

People and organizations can reuse previous knowledge when encountering new tasks and challenges. They can either take and apply documented knowledge or ask for advice from someone with relevant prior experience. Knowledge reuse situations vary: reuse by shared knowledge producers, reuse by shared work practitioners, reuse by expertise-seeking novices, and reuse by secondary knowledge miners [1]. There are also different methods and techniques for "packaging" knowledge to stimulate reuse: patterns (task patterns, ontology patterns, workflow patterns, etc.), reference models, best practice cases, and lessons learned [2; 3]. Sometimes reusable knowledge is named knowledge building blocks; for example, architecture and solutions building blocks are used within the enterprise architecture management domain [4].

City digital transformation (or digitalization) is a complex task that requires new approaches and management technologies:

- Number of tasks, stakeholders, problem-solving ways, and approaches is growing,
- Life speed is increasing: people need the newest innovative technologies and applications,
- New digital services for citizens and businesses are required.

Knowledge reuse can improve many activities (areas) within a city's digital transformation:

1. Data integration and modeling activities can be improved via the reuse of data models and ontologies,

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2. Design and development of city digital solutions and systems can be improved via reference architectures and reuse of existing solutions/systems/methods,
3. (Re-)Design of public services and processes can be improved via the reuse of patterns and reference process models,
4. Smart city management and development can be improved by reusing proven key performance indicators from existing reference models and standards or by reusing existing cutting-edge solutions for city analysis, monitoring, and control (including city digital twins).

Some initiatives and platforms support knowledge transfer and reuse in the smart city domain (see section 2). But these initiatives and platforms use traditional document-oriented formats for knowledge representations, so knowledge integration, access, and reuse are limited. It is also hard to develop intelligent services using such knowledge representation. So there is a need for semantic representation of reusable knowledge in the smart city domain.

2. Related work

There are several existing solutions and platforms for knowledge sharing and reuse in the smart city domain including platforms with a broad scope, domain-specific platforms, and platforms for the specific type of content.

1. Broad scope platforms with smart city solutions:
   - Bee smart city platform (https://www.beesmart.city/) is a database of smart city cases and solutions that is extended with elements of a social network of smart city experts. This platform also collects information about tenders and is supported by matchmaking and consulting services.
   - Bable (https://www.bable-smartcities.eu/) offers information on how to implement smart city solutions and includes a library of use cases, solutions, and products. It also provides the opportunity for communication between companies and the city's administration.
2. Domain-specific platforms:
   - Eltis – The Urban Mobility Observatory (https://www.eltis.org/) is an EU-funded platform that consists of tools, information, communication channels, and best practices to help transport planners to create sustainable mobility.
3. Platforms for the specific type of content:
   - Smartcity.linkeddata.es – a repository of ontologies about smart cities, energy, and other related fields. The repository has a list of ontologies with their attributes: availability, format, type of licenses, syntaxis, using language, domain, and link. Even though it is a unique example of this type of ontology library, the biggest problem is it has not been updated since 2015.

Although these platforms include well-structured libraries of materials, they use the "traditional" approach for knowledge representation: text documents with metadata. Such an approach has limitations in terms of knowledge access, reuse, and applicability for creating intelligent services. Smart city best practices and cases can be accumulated via knowledge graphs in order to make them more findable and reusable.

Also attempts to create a city knowledge graph were made several times all over the world. An example, a Zaragoza's Knowledge Graph [5]. The graph presents a mix of open-data and data management system. The graph was built over 15 years. As a result, there is access to city data through a catalog or open platform. The project was admitted as successful and is developing. But the existing city knowledge graph initiatives are mostly related to the collection and integration of smart city data, while we are interested in smart city knowledge reuse.

3. Information requirements within city digital transformation activities

Some examples of information/knowledge requirements within city digital transformation activities, which can be supported by knowledge reuse, are presented in table 1.

Table 1
Examples of city digital transformation information/knowledge requirements

City digital transformation activities	Questions
Data integration and modeling	What concepts, domains, layers, dimensions, and relationships can be used for describing a city?
Design and development of city digital solutions and systems	What are the examples of digital solutions/systems for improving a specific domain or solving a particular problem? Are there any reusable ones? What are the results and outcomes of a solution/system application in smart cities? What methods and approaches are used within the particular solution?
(Re-)Design of public services and processes	What digital services can be offered to a specific category of citizens or businesses within a particular context (event)? How can services be delivered and implemented? How specific processes can be organized and/or transformed using available technologies?
Smart city management and development	What indicators can we use for measuring domain X? What city ranking systems exist, and what are the differences between them? What indicators can we use for measuring outcomes, outputs, processes, and inputs in domain X? How to integrate and present city-related data for decision-making? How city digital twins can be used for city management and development?

These information/knowledge requirements arise among city development managers, their digital transformation teams, and/or solution providers.

4. The ORKG application for creating a library of reusable knowledge in the digital city planning domain

4.1. Overview of the project and ORKG

Digital City Planner company aims to support city digital transformation via knowledge reuse and application of knowledge graphs and semantic technologies. This initiative may help city development managers do the following things:

1. Have easy access to the world's best practices and experience in the smart city area,
2. Minimize hiring top/external consultants,
3. Have a holistic and evidence-based smart city development system,
4. Collect, prepare and pack knowledge for reuse and worldwide replication.

There are a lot of reference and reusable content in smart city domain, such as reference models, ontologies, data models, classifications/taxonomies (e.g. of processes or services), patterns, good practice cases, reusable methods, and systems. This content can be integrated and prepared for reuse both by practitioners and researchers. From an industry point of view, such an effort can be considered as a step toward the digital transformation of IT consulting services [6].

We decided to make a pilot project using publicly available research papers as a source of reusable knowledge for city digital transformation. So despite the existence of different platforms for managing knowledge graphs, we selected the Open Research Knowledge Graph (ORKG) platform provided by the TIB Leibniz Information Centre for Science and Technology [7, 8]. The ORKG "aims to describe research papers in a structured manner. With the ORKG, papers are easier to find and compare" [9]. The ORKG represents the next-generation digital library for semantic scientific knowledge. The ORKG envisions "the transformation of the dominant document-centered knowledge exchange to knowledge-based information flows by representing and expressing knowledge through semantically rich, interlinked knowledge graphs" [8]. Originally, the ORKG is focused on researchers and aims to help them "find relevant contributions to their field and create state-of-the-art comparisons and reviews"

[10]. But we also consider opportunities for ORKG usage by practitioners, more specifically by city transformation and development teams.
So our pilot project for creating a library of reusable knowledge resulted in the curation of the digital city planning observatory within the ORKG [11] (for more information about observatories see [12]).

4.2. Representation of smart city reusable knowledge in the ORKG

We took examples of city digital transformation information/knowledge requirements as input, searched information via Google Scholar and Scopus, collected relevant research papers (primarily reviews and comparisons), and transformed them into the ORKG format. This format includes a structured description of the paper's contributions, comparisons, and reviews (for more details about the representation format see the ORKG documentation [13]). The key elements of the ORKG representation format are described in Fig. 1.

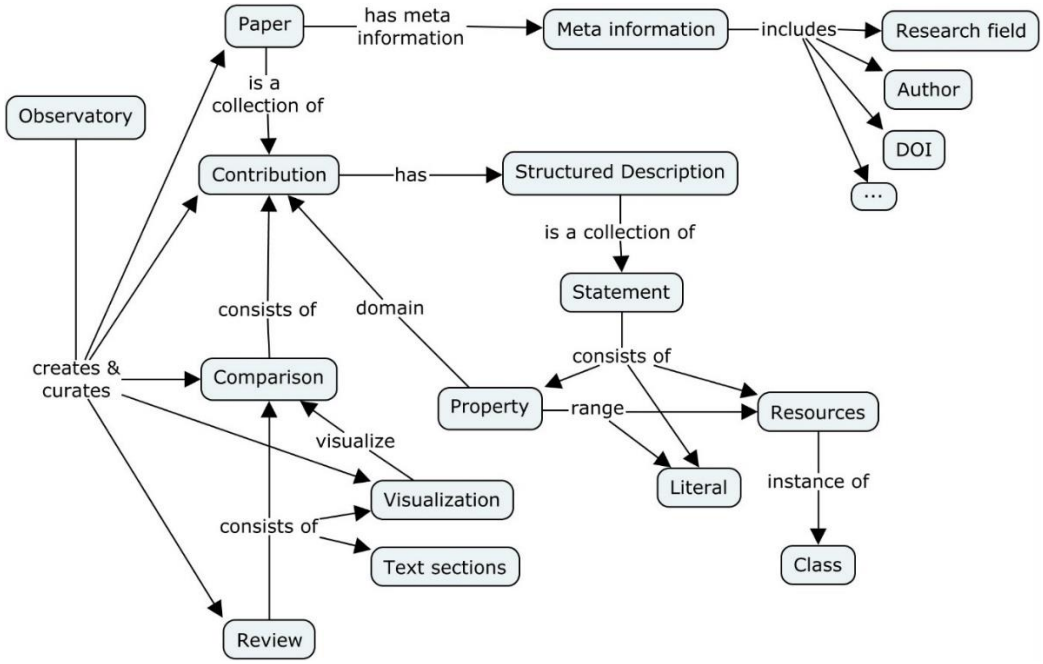
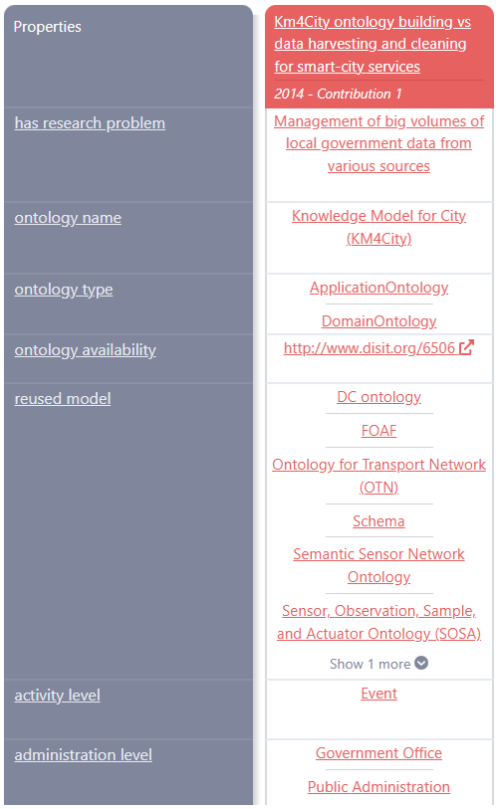


Fig. 1. Overview of the ORKG representation format [created by authors]

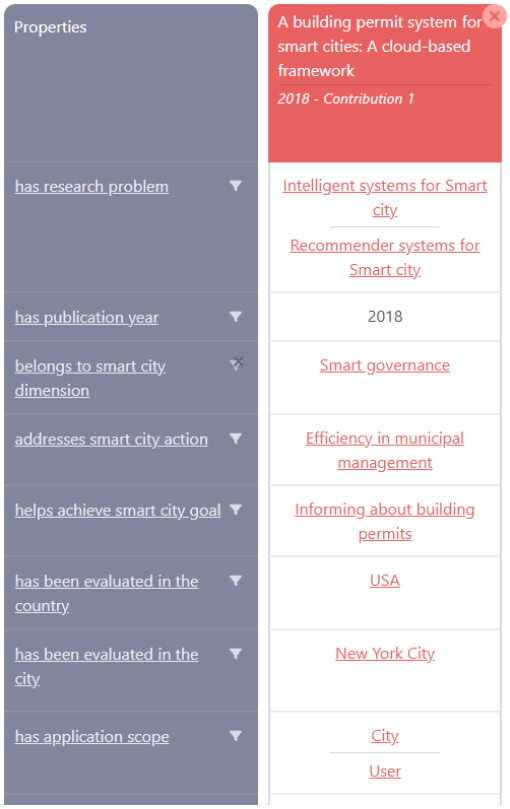
Structured Descriptions of Research papers via Contributions
In the ORKG, knowledge that is traditionally described in scholarly articles is described semantically, i.e. machine-readable. Research papers are added to the ORKG, and their contributions are described in a structured way. Typically, a research contribution describes the addressed problem, the utilized materials and methods, and the obtained result.
Our digital city planning observatory within the ORKG describes 296 research papers (for 30.07.2022). Figure 1 demonstrates two examples of structured descriptions of research papers.
Part A of Figure 2 describes the KM4City ontology (a contribution of the paper [14]). This description mostly covers classes that correspond to certain smart city modeling levels.
Every paper has a mandatory property: research problem. In addition, this property helps to categorize papers inside of the ORKG system. All other properties were chosen based on the aim of our final research. We have added properties "ontology name" and "type" to describe ontology and categorize it for feature comparison. It was important to highlight which of the existing ontologies have been reused to create current ontologies and link them with their articles (if there is one in the ORKG system).
Part B of Figure 2 describes a building permit recommender system for smart cities (a contribution of the paper [15]).
As it was mentioned before, this article has a mandatory property research problem. Other properties mainly classify the suggested recommender systems: by the smart city dimension, smart city action,

and smart city goal. Because the article includes use cases, we have added properties such as country, city, and application scope to identify use case characteristics.



https://orkg.org/paper/R138642/R138645

A) provides a structured description of a paper, which suggests smart city ontology [14]



https://orkg.org/paper/R138187/R138189

B) provides a structured description of a paper, which suggests a recommender system for smart cities [15]

Fig. 2. Structured description of research contributions within the DCP observatory

Comparisons

Comparisons are the main element of the ORKG platform, which integrates the contributions of individual papers and gives an overview of any topic. The ORKG documentation says that "comparisons are the core type of ORKG content and give a condensed overview on the state-of-the-art for a particular research question. Contributions towards the problem are organized in a tabular view and can be compared and filtered along different properties." [13].

The Digital city planning observatory within the ORKG includes 32 comparisons (for 30.07.2022). Figure 3 demonstrates a fragment of comparison "Ontologies for smart city: levels and key classes", which compares the content of 6 smart city ontologies described in the corresponding research papers [16]. It shows and compares classes of the ontologies along 18 levels (e.g. physical level, service level, safety, and risk management level).

Reviews

Reviews is the most integrative element of the ORKG. They can integrate one or more comparisons, a description of the properties used in the comparison, visualizations and text blocks including an introduction, conclusions, and links between the embedded elements. So, they give an opportunity to create a holistic overview of a specific domain. "Reviews are a novel ORKG-based method to create review or survey articles for giving an overview on research addressing a particular research question." [13].

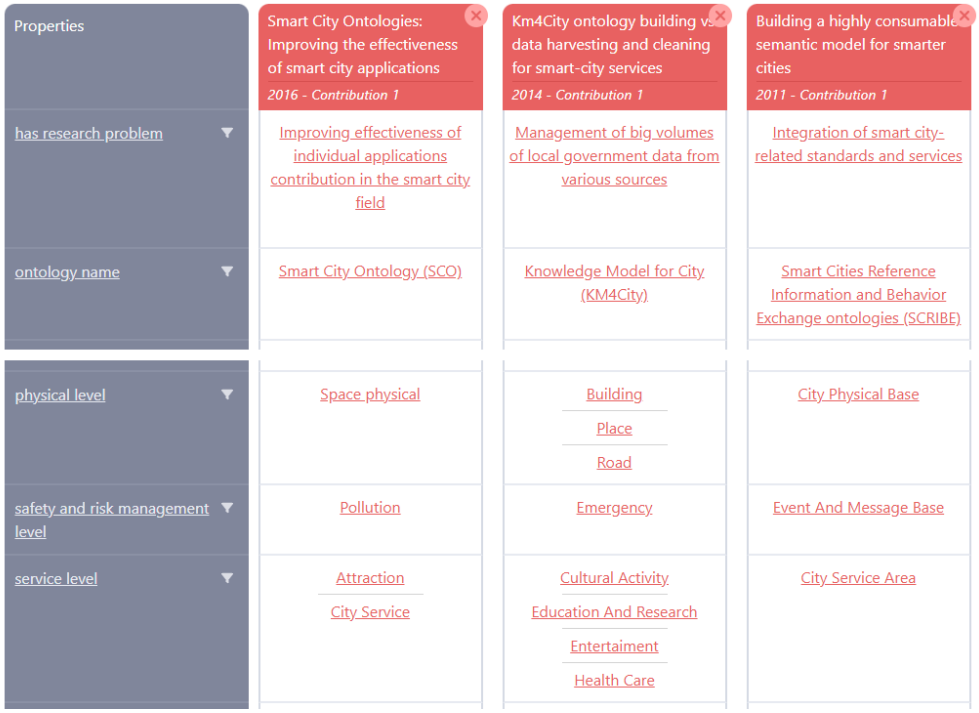


Fig. 3. A fragment of the smart city ontology comparison

The Digital city planning observatory within the ORKG includes three reviews (for 30.07.2022). Reviews can be provided with metadata (title, authors, etc.) and formally published with a DOI, they can be updated, and new versions can be published, while the archive records prior versions and can compare changes between revisions – for more details, see the documentation [13].

Figure 4 gives an overview of the Smart city's ontologies review, which integrates three comparisons (1. Ontologies for smart city: levels and key classes, 2. Domain coverage in smart city ontologies, 3. Ontology reuse in smart city ontologies). These comparisons in turn compare 18 papers described via approximately 40 contributions.

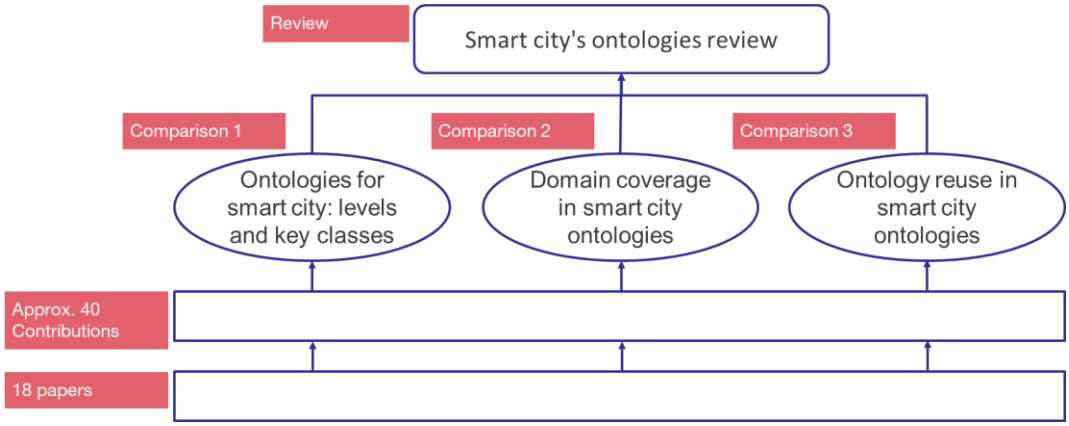


Fig. 4. Smart city's ontologies review as an integration of contributions and comparisons

4.3. Overview of the digital city planning observatory content

Totally the Digital City Planning (DCP) observatory within the Open Research Knowledge Graph (ORKG) includes 296 papers, 32 comparisons and 3 reviews.

Table 2 gives an overview of reviews and comparisons within the DCP observatory and shows how they can support various city digital transformation activities and corresponding information/knowledge requirements from Table 1.

Table 2
Overview of the Digital City Planning observatory content (fragment)

City digital transformation activities	Questions	The DCP observatory content at the ORKG
Data integration and modeling	What business / data objects exist in the domain? What are the relationships between business / data objects in the domain?	Review: Smart city's ontologies review [17] Comparisons: Ontologies for smart city: levels and key classes [14] Domain coverage in smart city ontologies [18]
Design and development of city digital solutions and systems	What are the examples of digital solutions/systems for improving a specific domain or solving a particular problem?	Comparison: Recommender systems for smart cities, Smart governance dimension [19]
Smart city management and development	What indicators can we use for measuring domain X? What indicators can we use for measuring outcomes, outputs, process and inputs in domain X? How to integrate and present city-related data for decision making? How city digital twins can be used for city management and development?	Review: Smart and sustainable city's indicators [20] Comparisons: Standardized indicators for Smart sustainable cities, by type of indicators [21] Analysis of natural environment indicators in Smart Cities' standards [22] Review: Towards a city digital twin [23] Comparisons: Thematic Identification of the City Digital Twin Potentials [24] Application areas of Digital Twin solutions in the smart city domain [25]

4.4. Knowledge curation methods and techniques

The following ORKG tools were actively used during the curation work:
Templates – they provide structure to comparisons and help to simplify entering contributions (for more details see [13]).
Classes and resources (instances) – they helped us minimize duplicates in descriptions of papers (contributions) and comparisons.

4.5. Existing application scenarios

Our pilot project and the resultant observatory within the ORKG can support city digital transformation activities via two additional knowledge services: search and visual analytics.
Faceted search for relevant contributions within the ORKG
Figure 5 demonstrates the application of property-based filters for searching relevant AI systems (recommender systems) within the comparison Recommender systems for smart cities, Smart governance dimension [19]. Properties for the current comparison were chosen based on the original research made by Lara Quijano-Sánchez et al [26].
The following filters are applied:

- Addresses smart city action = Citizen participation and inclusion AND
- Recommended items = Political candidates AND

- Application domain = Smart governance (restricted by the scope of the comparison).

This filtering results in the following two contributions:

1. A Recommender System with Uncertainty on the Example of Political Elections
2. A Fuzzy Recommender System for eElections

And what is especially important is that these two contributions are presented in a structured way, which enables one to get answers to many questions without reading the papers. For example, we see the recommendation approach and methods which were used within the suggested contributions. We also see that one paper suggested a prototype and another one – an algorithm.

Although similar attributive or faceted search is provided by existing smart city knowledge sharing platforms, their filtering properties are very limited and associated with a predefined document e.g. case description.

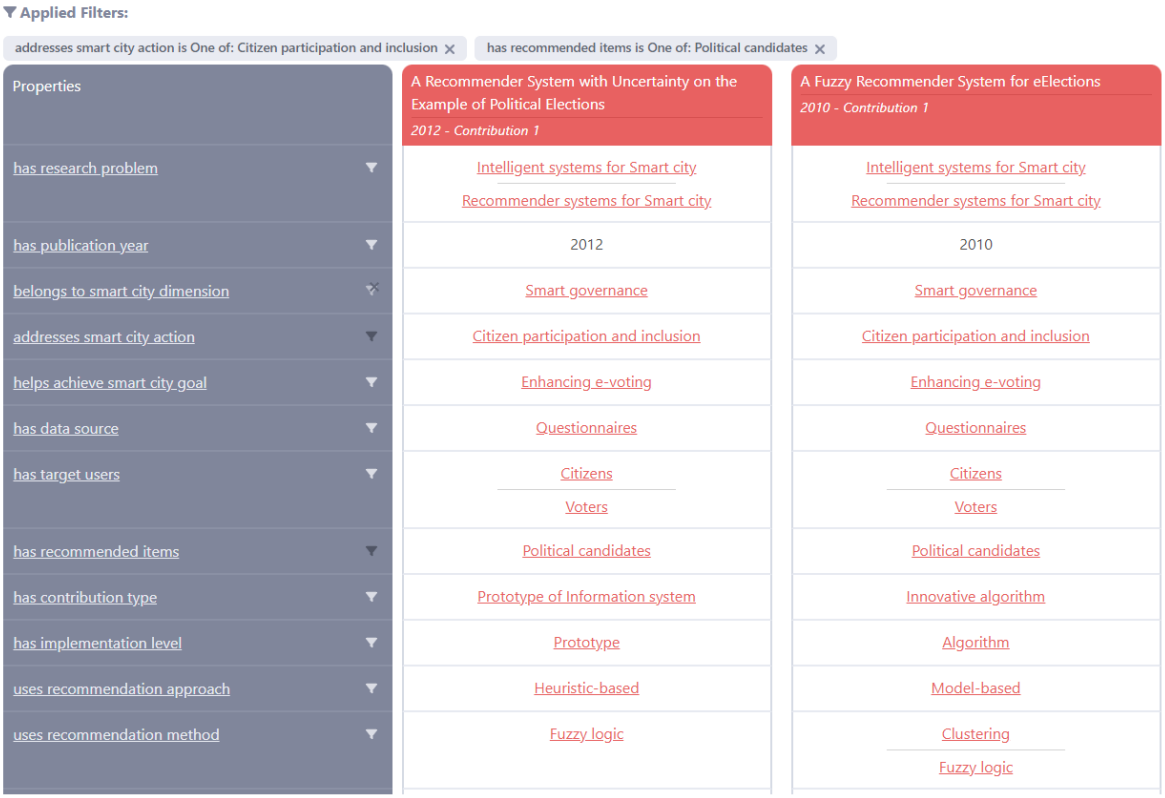


Fig. 5. Faceted search of relevant items within the DCP observatory of the ORKG

Visual analytics

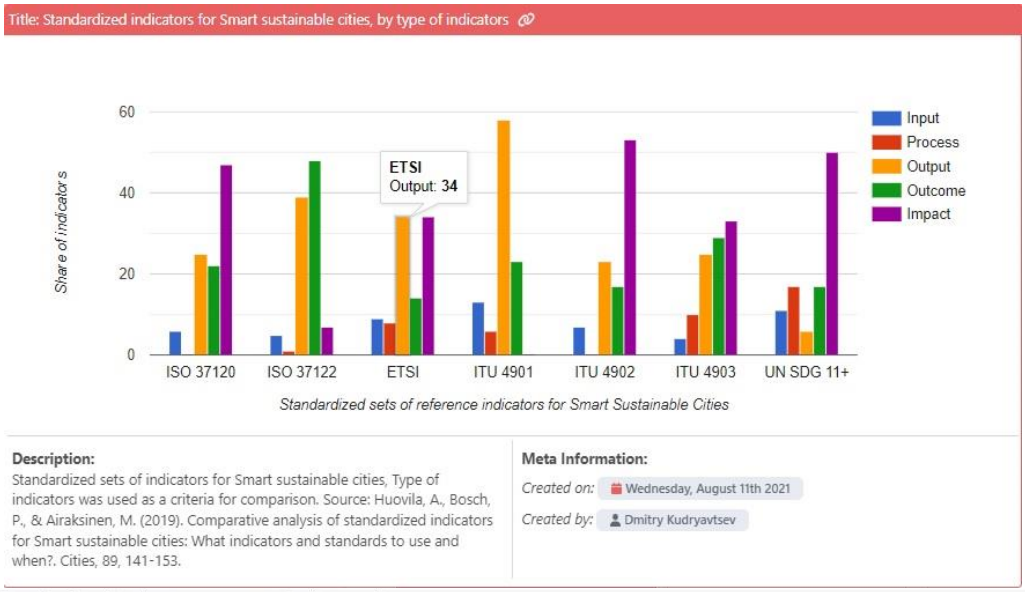
The content of the comparisons within the ORKG can be also represented in the visual format.

Figure 6 demonstrates the visualization of comparison results – several standardised sets of reference indicators for Smart Sustainable cities are compared in terms of the types of indicators they have, whether they mostly measure Input, Process, Output, Outcome or Impact aspects of the city development and transformation activities [21].

The standardised sets of reference indicators for Smart Sustainable cities are mostly reflected in international standards, which can be considered as the next step of maturity of research results.

The suggested visualization helps to identify standards which include, for example, a lot of Impact indicators – ISO 37120, ITU 4902, UN SDG 11+.

Then another comparison can be used to get access to all these impact indicators – see figure 7 [22].



Standardized indicators systems: Indicators by type

Properties	ISO 37120:2018 Sustainable cities and communities — Indicators for city services and quality of life *2018 - The suggested Types of Indicators*	ISO 37122:2019 Sustainable cities and communities — Indicators for smart cities *2019 - The suggested Types of Indicators*	ETSI TS 103 463 Key Performance Indicators for Sustainable Digital Multiservice Cities *2017 - The suggested Types of Indicators*	ITU-T Y.4901 Key performance indicators related to the use of information and communication technology in smart sustainable cities *2016 - The suggested Types of Indicators*
has contribution type	A set of Reference Indicators for Cities	A set of Reference Indicators for Cities	A set of Reference Indicators for Cities	A set of Reference Indicators for Cities
has research problem	Indicator types selection for smart sustainable cities Indicators for smart sustainable cities	Indicator types selection for smart sustainable cities Indicators for smart sustainable cities	Indicator types selection for smart sustainable cities Indicators for smart sustainable cities	Indicator types selection for smart sustainable cities Indicators for smart sustainable cities
has input type of indicators, share	6	5	9	13
has process type of indicators, share	0	1	8	6
has output type of indicators, share	25	39	34	58
has outcome type of indicators, share	22	48	14	23
has impact type of indicators, share	47	7	34	0

Fig. 6. Visualization of the comparison content

Properties	ISO 37120:2018 Sustainable cities and communities — Indicators for city services and quality of life *2018 - Indicator type*	ISO 37122:2019 Sustainable cities and communities — Indicators for smart cities *2019 - Indicator type*	ETSI TS 103 463 Key Performance Indicators for Sustainable Digital Multiservice Cities *2017 - Indicator type*	ITU-T Y.4902 Key performance indicators related to the sustainability impacts of information and communication technology in smart sustainable cities *2016 - Indicator type*
has research problem	Indicators for smart sustainable cities	Indicators for smart sustainable cities	Indicators for smart sustainable cities	Indicators for smart sustainable cities
impact indicator	Fine Particulate Matter (PM2.5) concentration Greenhouse gas emissions measured in tonnes per capita NO2 (nitrogen dioxide) concentration Number of natural disaster-related deaths per 100 000 population O3 (ozone) concentration Particulate Matter (PM10) concentration		Air quality index Change in number of native species CO2 emissions Fine particulate matter emissions (PM2.5) Nitrogen oxide emissions (NOx)	Air pollution intensity GHG emissions Perception on environmental quality

Fig. 7. Examples of city indicators for reuse

5. Future steps

The suggested Digital City Planning observatory within the ORKG can be considered as a MVP for the knowledge-based product for city digital transformation.

Next steps can be associated with two sides: knowledge consumers and knowledge producers.

We envision consumption of reusable knowledge by city development managers and their teams within different city digital transformation activities, such as design and development of city digital solutions and systems, data integration and modeling, (re-)design of public services and processes. Semantic knowledge representation enables the infrastructure for creating knowledge services for users, for example, recommendations and/or reasoning. Also, reusable smart city knowledge in the form of knowledge graph fragments can be used as building blocks for ontology-based city modeling and creating city digital twins. The ideas of knowledge graph application for these purposes are already elaborated for organizations in general [27, 28]. In order to establish effective consumption of reusable knowledge, additional marketing research and customer development should be done: clarify jobs to be done and pains of potential users, specify information requirements and possible use cases. Such market understanding will enable the creation of demanded value proposition.

The production of reusable knowledge – the development of reference city knowledge graph should also be modified. Nickel et al. [29] divided knowledge graph (KG) construction methods into four groups: (1) curated approaches, i.e., KG created manually by a closed group of experts, (2) collaborative approaches, i.e., KG created manually by an open group of volunteers, (3) automated semi-structured approaches, i.e., KG extracted automatically from semi-structured text via handcrafted rules, and (4) automated unstructured approaches, i.e., KG are extracted automatically from unstructured text. So it is necessary to move from the current curated approach (1) to a collaborative one (2) with some elements of automation (3 and/or 4). We envision the involvement of knowledge providers in this collaborative effort since reusable knowledge for city digital transformation is created by research institutes, providers of city digital solutions, universities, lighthouse cities, and associations; all these parties can participate in the knowledge graph creation. So there is a need to establish the ecosystem around the reference knowledge graph, which integrates reusable knowledge.

This approach is represented in figure 8.

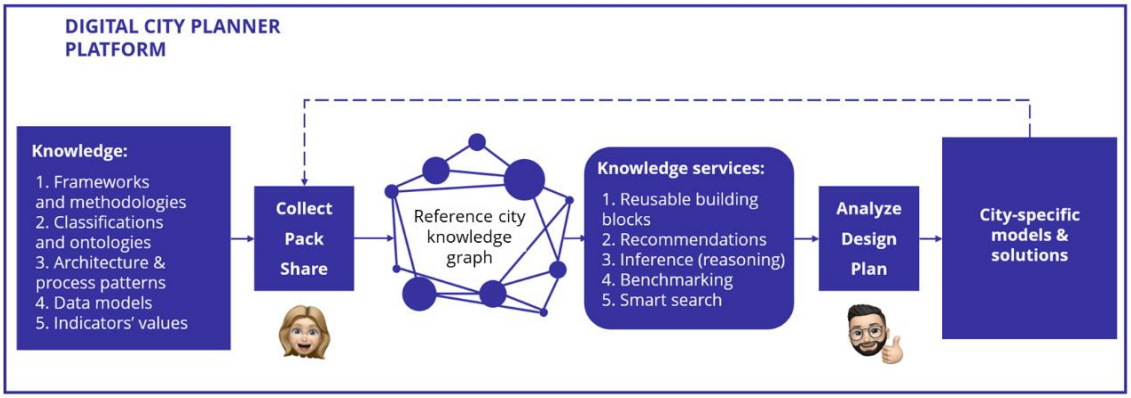


Fig. 8. Platform for creating and reusing city digital transformation knowledge

6. Conclusions

City digital transformation can be enhanced via knowledge reuse. The city development managers and their teams may do their work faster, cheaper and with low risks by reusing best practice cases, reference models, patterns (task patterns, ontology patterns, workflow patterns, etc.), and other "knowledge building blocks". Although there are several platforms for smart city knowledge sharing and reuse, they apply a traditional document-oriented approach to knowledge representation. Such an approach has limitations in terms of knowledge access, reuse, and applicability for creating intelligent services. So, knowledge graphs technology was selected for collecting and curating digital city planning reusable content. We decided to

make a pilot project using publicly available research papers as a source of reusable knowledge for city digital transformation. So despite the existence of different platforms for managing knowledge graphs, we selected the Open Research Knowledge Graph (ORKG) platform. So our pilot project for creating a library of reusable knowledge resulted in the curation of the digital city planning observatory within the ORKG. The paper described a representation of smart city reusable knowledge in the ORKG, gave an overview of the digital city planning observatory content, highlighted knowledge curation methods and techniques, and provided current and future application scenarios.

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