The SURE Knowledge Synthesizer: A Conceptual Tool for Urban Sustainability Research

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Abstract

The process of synthesis is key for the consolidation of new insights from existing bodies of knowledge, information, and data. In connection to other knowledge processes, e.g., inspiration, research or analysis, synthesis – as an activity of connection and convergence – is central to creating meaning and understanding. It builds upon principles of integration, unification, and generalisation as prerequisites for the inference of reliable and replicable knowledge. Synthetic processes are significant when dealing with large data sets or disparate and heterogeneous information. Especially in explorative research projects, the synthetic integration of a multitude of inputs is crucial to generating valuable and applicable knowledge output.

As a key idea, the paper puts forward the concept of a Knowledge Synthesiser as a heuristic device to shape the knowledge generated in larger research programmes. Resting on general models of information processing and knowledge life cycles, the Synthesizer is conceptualised as a system that generates meaningful knowledge output by interconnecting different functional layers and modules, e.g., for knowledge collection, structuring, or integration.

The specific case at stake is the German funding priority "Sustainable Development of Urban Regions" (SURE). Ten projects with approximately 150 partner institutions generate a large body of research about urban sustainability and innovation. The Synthesizer has been conceptualised to facilitate the convergence and integration of this knowledge and to create insights about the SURE funding priority and about future urban development in general. Specifically, the Synthesizer has various practical purposes for the research programme:

- Structuring and safe-keeping the results from the ongoing research
- Allowing easy access to the research findings
- Enabling deep analysis of the collected data and information
- Linking information to create new insights.
- Outlining future trends in urban sustainability research
- Supporting research policy-making.

In response to the overarching research programme and its purposes, a system architecture has been created to be implemented as a prototype tool for the SURE funding priority. From the variety of functional and technical requirements, an overall schematic design has been created that eventually led to a Minimal Viable Synthesiser concept – the outline for the technical implementation of the key features and functionalities the Synthesizer needs to supply to the SURE funding priority.

Keywords – knowledge synthesis; urban sustainability; digital tools; digital transformation; transdisciplinary research; complexity

Paper type – Academic Research Paper

1 Introduction

Mathematician and science philosopher A. N. Whitehead (1967) stated that "knowledge does not last longer than fish". The statement hints at one key aspect of scientific research: knowledge creation is an ever-unfinished process. Knowledge needs permanent refreshment, update, and re-organisation. Every discovery may re-arrange the entire landscape of knowledge. There is a demand for continuous efforts in searching, hypothesising, analysing, and synthesising - and for the respective methodologies and devices that can support such an open-ended venture. Besides the strenuous activities of collecting data and assembling facts, producing scientific knowledge is a task of systematisation and integration that needs creative vision. A multiplicity of often contradictory findings needs to be structured, converged, and harmonised into a new unity. A multitude of facts, events and observations must be brought into a rational structure and drawn into a comprehensive picture. This holds true, especially for large-scale research programs generating a multiplicity of knowledge around a given single topic –

which in turn need to be balanced, converged, and shaped into reliable scientific output.

The German funding priority "Sustainable Development of Urban Regions" (SURE) is such a case. The present paper revolves around the management and synthesis of knowledge in this large research programme, bringing together almost 150 partner institutions around the topic of sustainable urban development. It tackles the difficult task of creating new (meta)knowledge from the vast landscape of "pieces of knowledge" in this programme. Comprehensive knowledge synthesis and consolidation are needed. Funded by the German Ministry of Education and Research (BMBF) between 2019 - 2025, ten intercultural and transdisciplinary research projects are generating a large body of research about urban sustainability and innovation, focusing on metropolitan regions and megacities in South-East Asia and China. In concert with the need for collaborative approaches that put people first in urban and rural developments and aligned with the SDGs localisation and the New Urban Agenda, SURE targets applied research, urban-rural innovation and transformative strategies.

Accompanying the SURE funding priority is the "Facilitation and Synthesis Research project" (SURE FSR), which supports the overall evolution of the ten projects and the programme itself and is supposed to consolidate the knowledge created in them. The SURE FSR conducts qualitative and quantitative meta-studies on the projects which conceptualise and test locally implementable solutions and strategies for the sustainable transformation of fast-growing urban regions. The SURE FSR project creates conceptual, theoretical, methodological, and translational innovations that integrate and move beyond discipline-specific approaches to address the issue of sustainable urban development and contribute to transdisciplinary research knowledge. Further insights on the overall research architecture of the SURE FSR can be found in the IFKAD23 research paper (ID 231) by Katharina M. Borgmann titled “The Research Architecture for Transdisciplinary Knowledge Synthesis for an Urban Sustainability Programme – A Meta-Study Methodology”. As a creative research project, it is mandatory to invent and explore new methods and instruments to effectively facilitate and integrate the vast research knowledge of the projects and the programme. The following sections establish the theoretical background, place the paper within the SURE framework, and set the research scope and boundaries.

2 Background

2.1 Sustainability Science

The global demand for sustainable development has pressured academia to establish the field of so-called Sustainability Science. According to Komiyama and Takeuchi (2006), Sustainability Science is a comprehensive and holistic approach to identifying problems and perspectives related to the sustainability of global, social, and human systems. It is characterised as a problem-solving discipline, a transdisciplinary effort driven by the interplay of knowledge and action in environmental and social-cultural systems towards a liveable future (Kumazawa et al. 2009; Rapport 2007; Clark 2007). Sustainability Science is a "use-inspired basic research" – here, fundamental knowledge and pragmatic application are equally relevant (Clark 2007; Kajikawa 2008). Its knowledge generation rests on abduction-based synthesis, that is: new insights derive from justified assumptions or speculative hypotheses, which require validation through experiment and empirical research. The SURE Facilitation and Synthesis Research project aims to create a comprehensive and holistic knowledge synthesis approach to structure and consolidate transdisciplinary research results within the SURE framework. Yoshikawa (2008) theorises that "action based on abductive reasoning and the logic of synthesis can produce new forms of knowledge that will contribute to the creation of artefacts" – we explore and internalize this theory through the SURE FSR Knowledge Synthesis methods and conceptual tool discussed in this paper.

Sustainability Science is a problem-driven and solution-oriented field, following a transformation agenda and providing a vision and methodology (Steinfeld and Mino 2009), to deal with the complexities of sustainable development and to instigate knowledge structuring through multi-, inter-, and transdisciplinary approaches. Transdisciplinary approaches focus on the integration of knowledge from multiple scientific and societal sources through collaborative efforts. The ten projects within the SURE framework are characterized as Mode-2, transdisciplinary research projects (Slawski et al. 2022) they generate a growing pool of transdisciplinary approaches and sustainability knowledge. However, this knowledge is often based on literature and personal experiences. It still requires further consolidation and evidence-based principles to become useful and reliable for scientists and practitioners (Defila et al. 2006). Lang et al. (2012) emphasise the need for synthesising and consolidating the existing conceptual, methodological, and empirical knowledge of transdisciplinary research through qualitative and quantitative meta-studies.

2.2 Research framework and ambition of SURE

This paper and its findings feed into the meta-analysis and knowledge synthesis carried out by the SURE FSR project for SURE. Constrained by the SURE framework (limited geographical scope, number of projects, sample size for content analysis), the SURE FSR systematically examines and interprets the findings of the ten transdisciplinary projects with qualitative and quantitative approaches.

With the findings, the SURE FSR aims to consolidate the existing conceptual, methodological, and empirical knowledge of transdisciplinary research and contribute to sustainable urban development and Sustainability Science. The SURE FSR overarching synthesis research architecture is elaborated, and its goals, objectives, and methods are discussed in the accompanying IFKAD23 paper "The Research Architecture for Transdisciplinary Knowledge Synthesis for an Urban Sustainability Programme – A Meta-Study Methodology". Preliminary research findings induced the formulation of hypotheses, of which the three listed below have relevance to this paper:

- Developing new methods and practices for knowledge synthesis aided by digital technologies will improve the consolidation, integration and comprehension of the large pool of knowledge generated in urban sustainability research.
- Targeted modelling of project contents and topic evolution will help indicate future challenges and issues to be addressed in urban sustainability research and policy making.
- Cross-analysis of programme documents and project content will contribute to recalibrating funding and proposal evaluation criteria.

Although the overarching meta-study is ongoing, this paper can present initial findings and first scientific framings in support of further investigations by the SURE FSR in the future years, also reaching beyond the scope of the SURE programme. The synthesis research targets three main aspects: Scientific classification to establish a reference and impact monitoring framework. Synthesis of project contents and findings, elaboration of problems and issues to be addressed in the future. Provision of digital infrastructure for knowledge management and decision support As its central argument, this paper puts forward the design of a comprehensive IT system (Synthesizer) and discusses its potential application. The system is intended to work as a versatile environment for the synthesis of knowledge by the SURE FSR and a decision-support tool for relevant stakeholders within the community of the SURE projects. Indicating the accompanying complexities in the development process of such a system, the text explains the opportunities and challenges such an instrument can bring for urban sustainability research.

2.3 The Principle of Synthesis within the Knowledge Lifecycle

The idea of the Knowledge Synthesizer takes its point of departure from discourses in knowledge theory and knowledge management, acknowledging that the topos of "synthesis" has long been a steady concern in the scientific literature. Throughout the history of epistemology and philosophy of science, various models have been proposed to conceptualise the dynamic evolution of knowledge that commonly leads from knowledge creation to knowledge sharing and diffusion. Recent knowledge and innovation management approaches advocate so-called knowledge lifecycles that model a dynamic process of knowledge creation, consolidation, and diffusion activities (Nonaka, 1991; Nonaka and Konno, 1998; McElroy, 2003; Dalkir, 2005).

Epistemologists, however, hold that the phases of knowledge creation, especially the interplay of hypothesis creation on the one hand and knowledge integration and consolidation on the other, are essential drivers of novelty and progress (Peirce, 1878; Polanyi, 1966; Popper, 2002). Not just since Kant´s inquiry into the limits of knowledge (Kant, 1781), synthetic procedures are seen as the key to generating new insights from existing bodies of knowledge, information and data. In connection with other modes of knowledge processing, the very capacity to structure and unify the multiplicity of input data and information into a consolidated and validated "larger picture" is central to creating meaningful, usable knowledge.

Synthesis work – as an activity of integration and convergence – searches the fundamental connective principles that allow reliable expression and replicable application of gained insights. Synthetic processes gain special significance when dealing with large sets of information and data or disparate and heterogeneous knowledge bodies. Extensive explorative research programmes like SURE need to purposefully structure and integrate the variety of findings created across the programme and its individual projects. Accompanying synthesis research thus becomes essential to ensure meaningful results for future research, result application, and policy making. Knowledge structuring and organisation are essential parts of the synthesis research activities. Nevertheless, structuring methods and approaches originate from a vast domain that needs more detailing than the constraints of this paper permits. Hence, the paper highlights some of the applied guiding principles in knowledge structuring: reusability, versatility, and accessibility, that are relevant to the conceptual design of the Synthesiser.

Figure 2: Synthesis processes within the knowledge life-cycle. Adaption of the knowledge management model of McElroy (2003) and Dalkir, (2005).

With a pragmatic perspective on the requirements for the synthesis research for the SURE funding priority, this paper – and namely the synthesizer concept presented in the following sections – assumes a simplified iterative process towards the synthesis and consolidation of knowledge (Fig. 1), adapted from established models in knowledge management (McElroy, 2003; Dalkir, 2005). It connects activities of knowledge capturing, hypothesis generation and rational analysis. Leaving the creative part of hypothesis generation ("abduction") as well as the rational analysis and critical reflection on the human mind, the paper focuses on the eminent activity of knowledge synthesis, targeting its potential support with the new conceptual and technical device of the Knowledge Synthesizer. To this end, the following section is 2.3. We will line out relevant technical solutions and propose an overall conceptual design and technical system architecture in section 3.2.

2.4 Technical Solutions

Acknowledging that knowledge integration and synthesis of existing bodies of (scientific) knowledge is a cognitive activity on higher levels of complexity than data or information processing, it is still worthwhile to investigate the currently available technological means for synthetic knowledge engineering. Information technology is increasingly used in sustainable urban development to unlock insights from data, helping decision-makers and planners make informed decisions about resource use and development strategies. Platforms such as Google Big Query, Snowflake, and Azure Synapse Analytics offer large-scale data analysis services that collect and log data from various systems, including numerical and textual data. With AI's help, these platforms provide data processing and querying services and outputs from charts, diagrams, and dashboards. Understanding the interdependencies among socio-economic and environmental systems to achieve sustainable urban development is crucial. Data analysis platforms allow researchers and urban planners to collect and analyse data from multiple sources, including sensors, surveys, and administrative data, to understand urban systems comprehensively. The Urban Observatory platform, for example, enables users to compare data on various urban indicators worldwide, such as population density, air quality, and water usage. This platform provides a valuable resource for decision-makers and planners to identify areas where improvements can be made to achieve sustainable urban development. Other technologies, like Machine Learning and Artificial Intelligence, can be powerful tools to model and simulate urban systems, enabling urban planners to test different scenarios and assess the potential impacts of different development strategies. Text-based data is prominent in sustainable development, including reports, research, policies, regulations, and guidelines. In recent years, cities, governments, and academia have shown a growing interest in leveraging natural language processing (NLP) techniques to generate valuable insights and help planners and decision-makers to understand the social, economic, and environmental issues affecting urban areas. NLP can assist in analysing large volumes of textual data, extracting meaningful insights and providing a deeper understanding of urban systems. For instance, the Echobox platform offers a valuable resource for urban planners to extract and monitor public sentiment on social media. By analysing data from social media, planners can identify areas of concern and gain a deeper understanding of citizens' concerns and priorities. This information can then be used to design more effective solutions and policies better aligned with the community's needs.

Commercial NLP engines have benefits and drawbacks when creating insights from data in a specific field of research. Our preliminary study using IBM Watson or Monkey Learn for text analysis in sustainable development had good results in identifying locations and organisations and assessing the sentiment of the text; however, both platforms showed low accuracy and failed to determine field-specific information. Hence, engine training and adaptation of these platforms are crucial for meaningful information and knowledge extraction. In addition to commercial platforms, we have identified various initiatives amalgamating data science and sustainability, such as the Global System for Sustainable Development (GSSD) and open-source platforms like Apache Drill. The GSSD is an open-source database established by the Massachusetts Institute of Technology (MIT), which offers a comprehensive perspective on worldwide sustainability predicaments. The GSSD follows a rigorous knowledge structuring approach incorporating ontology engineering and collating data from multiple sources, including scientific literature, government reports, and NGO publications, to offer a holistic view of sustainability issues. A visualisation tool is also available within the GSSD, which facilitates knowledge structuring and information clustering for exploring sustainability data.

The aforementioned platforms provide powerful tools using and harmonising real-time data sets and extract insights to understand the complex interactions between urban systems and citizens, promoting more inclusive and equitable urban development. Nevertheless, data analysis platforms rely on the data's quality and accuracy, which may be compromised by missing, incomplete or inaccurate data sets leading to skewed insights. While text-based data analysis platforms may suffer from accuracy and bias issues as NLP use of unstructured data may only sometimes capture the nuances of language and context accurately. Our exploration shows an increasing trend of platforms that try to deal with information holistically and comprehensively; we highlighted only a few selected ones. We acknowledge these platforms as relevant examples for our system development to aid our synthesis research. Analysing these platforms shed light on challenges regarding knowledge structuring in sustainable urban development and existing technical solutions that can be used and incorporated into such a system.

3 Approach

3.1 Conceptual Design of the Knowledge Synthesizer

Based on the premise that technology and science are vital to enable sustainable transition, we put forward the concept of a" virtual thinking space" that provides a comprehensive visual representation of data from the SURE funding priority, projects and synthesis findings of dormant knowledge and topics in sustainable urban regions from Southeast Asia and China. As a point of departure, the idea of the synthesizer has served as a heuristic device to access, structure, and shape bodies of knowledge actively. Relating to general information and knowledge processing principles as well as platform architecture, the knowledge synthesizer represents – in the first stance – an instrument supporting the generation of meaningful insights about and from the SURE FSR. It does so by processing knowledge output from various inputs through functional modules of knowledge harvesting, structuring, analysis, and representation.

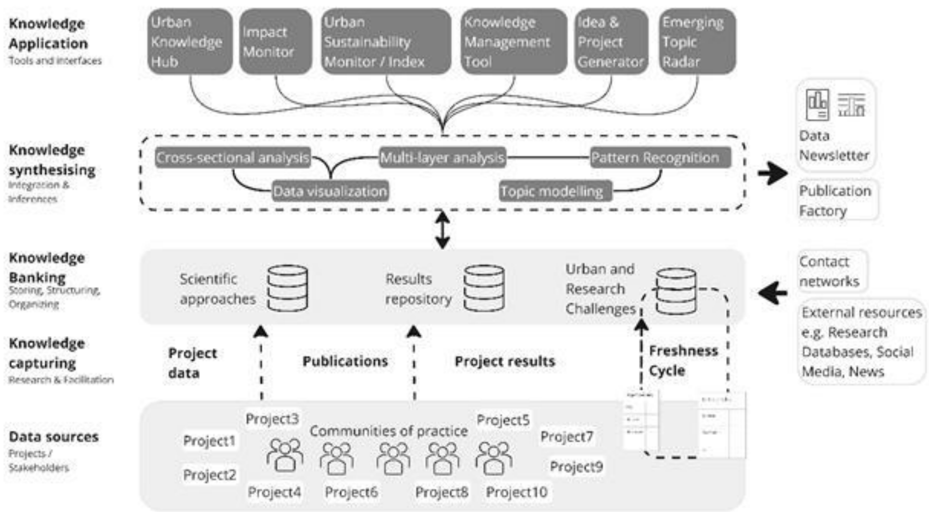

Figure 3: Maximum concept scheme of a "Knowledge Synthesizer"

Fig 2 depicts the initial conceptual design of the synthesizer – with a "Knowledge source" layer (primarily the projects facilitated by the SURE FSR), a "Knowledge collection" layer (indicating the content and input harvested and ingested in the system, e.g. qualitative and quantitative data from the research projects, their publications or through other facilitation activities, e.g. workshop, peer-to-peer meetings, project visits, interviews), and "Knowledge Banking" layer (the databases to structure, save, and make accessible the information and data gathered). A so-called "Freshness cycle" regularly updates the information and data collection as a routine task. On top of the "Knowledge Bank", the "Knowledge Synthesizer" layer processes with several "intelligent" functionalities the given input, aiming to generate new insights with the materials from the layers below. Some of these knowledge products can be automatically channelled out in the format of visual or statistic reports (e.g. "Data Newsletter"). On the top, the "Knowledge application" layer provides the specific tools and instruments to actively work and pragmatically interact with the synthetic processes and their results. This generic scheme presents a maximum concept of a "Knowledge Synthesizer" applicable to accompanying projects like SURE FSR. Given constraints and resource limitations, this initial concept needs a reduction to a pragmatic "Minimal Viable Synthesizer" (see section 3.2). However, the modular nature of this initial conceptual design provides for continuous extension and potential upgrades in future versions. Later editions of the synthesizer may incrementally scale up functionalities.

3.2 System architecture – Minimal Viable Synthesizer

The specific system architecture of the Minimal Viable Synthesizer derives from requisite key functionalities and components needed to carry out the SURE projects and programme synthesis, impact monitoring and decision support. From the primary activities of the SURE FSR team – data linkage, statistical evaluations, thematic analyses, identification of topic networks, trend analyses etc. – the required functional layers for the Synthesizer can be determined. To access and explore SURE data efficiently, a number of databases (e.g. for project results, documents and contacts) and data services (e.g. for knowledge management, communication, and collaboration support) need to be provided. User-friendly interfaces are to present the knowledge output and gained insights – here, existing solutions from the realm of business intelligence (project dashboards, monitors, interactive cockpits) may be used. The system architecture thus comprises three main component layers (see fig. 3 "System architecture of the Minimal Viable Synthesiser: Functional layers and modules"):

- Data storage (data management, database, data lake, processing flows)
- Applications (intelligent processes and tools)
- User interface (single / multi-user, web-based, on-premise).

As input, the system gathers quantitative and qualitative data, scientific and non-scientific information from multiple sources such as projects, relevant organisations, the internet, social media, or the collaborative platform SURExCHANGE.

As SURE covers a wide range of domains, good data management and organisation are required to enable a subsequent systematisation and integration of knowledge and to discover concepts hidden in the data. The data storage and management layer collects, stores, and organises the generated and used data within the SURE framework. The layer includes a database and data lake optimised for fast queries, efficient data retrieval, and handling large volumes of data. It also ensures data accuracy and integrity through appropriate data validation and quality control measures.

The application layer comprises modules for processing user requests and generating responses based on the data stored in the database. Key applications are topic modelling, content comparison, results synthesis, and thematic clustering of solutions. Three specific functional modules are foreseen for the Minimal Viable Synthesizer: 1) a synthesis assistant, 2) an impact monitor and 3) a decision-support tool.

The interface layer provides user-friendly front-ends for accessing, exploring and interacting with the data, e.g. a web-based interface optimised for desktop and mobile devices or a stand-alone application designed for touch tables. To break down the complexity of SURE´s topics, rich and intuitive user experiences are envisioned using interactive visualisations and animations.

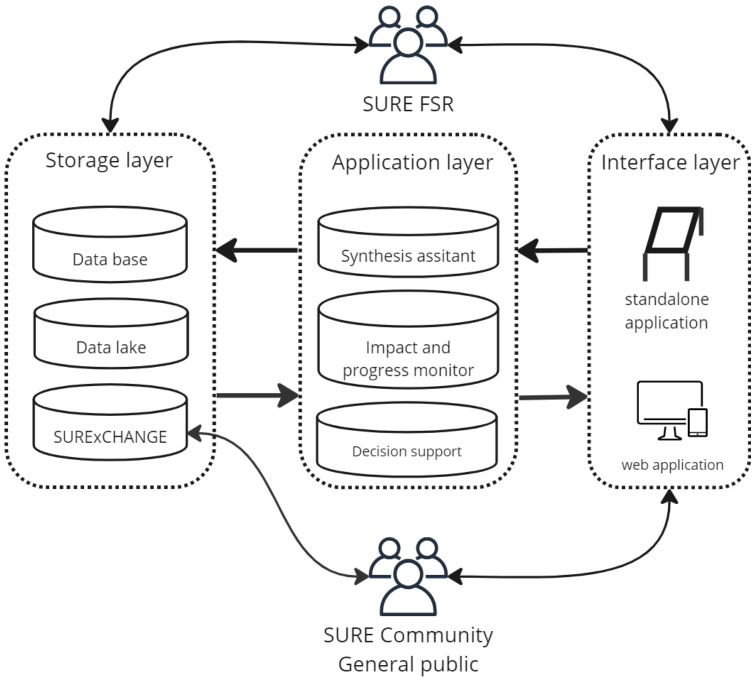

Figure 4 System architecture of the Minimal Viable Synthesiser: Functional layers and modules

3.3 Development Process of the Applications

The development process for the specific applications runs through stages of requirements definition, technical design and implementation, testing and deployment. An agile methodology is used to develop and implement all the modules, collaborate closely with stakeholders, and continuously improve the applications at every development step. This agile process is essential for creating a synthesizer that meets user requirements and expectations while ensuring that it is stable, secure, and effective.

The first step of the agile process identifies user needs and lines out concrete use cases. Collaborative workshops with the project partners and the funding agency help to outline detailed “User Stories”. So far, internal workshops have been conducted in the SURE FSR to map research needs (use cases) and identify objectives for module development. From the gathered requirements, clear and detailed design objectives and module specifications can be derived, enabling an in-depth design of the applications and functionalities in the following step, leading to a comprehensive system architecture and interface design. The technical implementation of the IT solution is followed by comprehensive testing in the next stage, where the application is thoroughly checked for mistakes and errors – first internally with the SURE FSR team and later by the entire SURE community through interactive workshops.

As a pivotal functionality to uncover and map the implicit (cross-cultural) knowledge within the SURE framework, to conduct cross-project content analysis and aid the synthesis research activities, an **NLP (Natural Language Processing) module** is envisioned. In the first stage, the NLP module will validate the list of synthetic focus topics the SURE FSR team has set up early in the project. The exploration aims to understand the text analysis and topic modelling of NLP models and train them for sustainable urban development issues. After refinement, the NLP application will assist in uncovering dormant knowledge ("Unknown Knowns"), identify open questions and problems ("Known Unknowns") and validate initial synthesis findings. The NLP module and first preliminary findings are described in more detail in a parallel paper handed in for this conference (Patel et al., 2023).

Next to the NLP module, an **Interactive Data Cockpit** is envisioned, allowing practical data exploration of the SURE funding priority. In the upcoming months, requirements-gathering workshops will be carried out with project partners and stakeholders to identify more modules to be implemented, such as a **Trend Visualiser** highlighting future development pathways or an **Impact Monitor** indicating the actual effect that SURE projects unfold in their specific context. The latter is based on the SURE Reference Picture developed by the SURE FSR partners at the Technical University of Lubeck (IFKAD23 contribution 209).

4 Conclusions

The SURE Knowledge Synthesizer is the **first conceptual and technical approach** to the ongoing challenge of integrating research findings in complex settings for urban sustainability research and to enable foresight on upcoming trends. The paper presented a conceptual design and system architecture for a Minimal Viable Synthesizer that responds to the essential requirements and functional demands deriving from such tasks. Being an ambitious venture in IT development and software configuration, however, the first technology mappings and technical explorations carried out by the FSR team suggest that solutions exist already that can effectively support knowledge management and decision-making processes in the context of sustainable urban development and policy making. Building upon existing solutions and using technology-assisted new methods and practices can facilitate the analysis and synthesis of the substantial data pool generated in sustainable urban development programmes like SURE. However, more intricate integration and in-depth research are needed to enable comprehensive knowledge synthesis in transdisciplinary urban sustainability research. On the path towards developing effective knowledge synthesis methods, the SURE FSR team acknowledges the challenges related to information organization and synthesis within an extensive research programme like SURE.

One of the significant challenges is to reduce complexity on the one hand while maintaining specificity and locality on the other. Regarding the SURE collaborative projects, region-specific topics (risk and flood management, nature-based solutions, urban planning) and culture-specific aspects remain prominent and versatile. In the process of Minimal Viable Synthesiser design, it is crucial that these aspects are reflected, and relatability by various groups of stakeholders is questioned - how to create a versatile and relatable system and generate reusable knowledge?

While the initial findings of the NLP module suggest its growing applicability in transdisciplinary research settings, the SURE FSR´s direct project interactions have uncovered the vast tacit knowledge and the eminent influence of cross-cultural sensitivity. While such aspects are difficult to grasp with technological means such as the proposed synthesizer, they still form an essential part of the SURE projects and programme. They lead to a discussion on how far tacit knowledge can be mapped, measured, and translated into tangible, transferable knowledge. For an adequate analysis of program documents and project content, recalibration of funding and proposal evaluation criteria, and improvement research policy-making, further research of respective tools and methods are needed. By exploring, testing and validating new synthesis methods, the modular synthesizer with functionalities such as the project content analyser or topic modeller may be a first step in such direction. Taking a tentative and systemic approach may uncover step-by-step the dormant knowledge and the future topics and challenges for sustainable urban research that is being inscribed in the SURE funding priority and projects already now.

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