From Assessment to Implementation: Design Considerations for Scalable Decision-Support Solutions in Sustainable Urban Development

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Abstract. Cities have to face the challenges of steady population growth, the related increase in energy and resource demands, intensifying climate change impacts and rapid technological development. To handle these complex challenges and promote sustainable development, the smart city approach – data-driven planning based on emergent ICT technologies – has been gaining prevalence. However, the lack of shared standards, frameworks, and evidence-based decision-support tools limit the collaboration among smart city actors and the utility of the mainly business-driven technical solutions. This study explores the scalability of indicator systems into a shared framework for smart and sustainable cities by practice-based research during the development of the SmartCEPS project. SmartCEPS is an assessment system and maturity model based on key performance indicators (KPIs) for small- and medium-size European cities. In its architecture, indicators are organized in a causal network capable of capturing synergies, co-benefits and payoffs of decisions; structural metadata provides the means for a gradual customisation of the system; and finally, the indicator pool is scalable by complexity, ensuring different levels of detail in assessments. The study concludes that gradual customisation, network organisation, and open-ended scalability are the proxies for developing decision-support instruments from KPIs.

1. Introduction

The contemporary challenges that cities have to face are complex and interconnected. Constant population growth and rapid urbanization result increased energy and resource demands, and also enhance corresponding emissions that are to be handled, for which cities should be managed sustainably to meet these increased needs. Furthermore, due to the intensifying climate change impacts, cities should become more resilient to withstand stress. In addition, rapid technological development might impose further risks and challenges to cities (e.g. cyber-attacks, network overload, interruption or malfunction of services etc.) [1,2]. To handle these complex challenges and promote sustainable development, the smart city approach – data-driven planning based on emergent ICT technologies – has been gaining prevalence throughout Europe [3].
Cities are intricate and multidimensional system-networks, and due to the differences stemming from their geographic, economic and cultural circumstances, there are no one-size-fit-all urban development solutions. Therefore mindful planning and evidence-based development decisions would be needed, in which ICT technologies have a significant role due to the size and complexity of hard and soft urban infrastructures. However, the lack of common understanding of the smart city concept, shared standards, frameworks, and decision-support tools [4] limit the collaboration among smart city actors and the utility of technical solutions.

There is a gap between ICT solution providers and cities in the understanding of local needs and matching solutions, prompting the development of smart and sustainable city standards, frameworks, strategies and indicator systems. However broad frameworks (e.g. ISO37120, UN SDGs, STAR Communities etc.) are too global for practical implementation [5]; city-specific smart city frameworks that are difficult to replicate; while supplier-driven frameworks that are streamlined to boost sales of ICT products and services, do nothing to fill this gap [6–8]. Moreover only large cities can afford their bespoke framework, while smaller cities depend on standards and risk mitigation not to miss out. Yet nearly half of the EU population lives in city regions with less than a population of 500,000 [9], an upper threshold of medium-size in the European context [10].

These frameworks depend on the design of their underlying performance indicator scheme. In practice, they are siloed, steady-state lists of indicators which are either too generic [5], or too specific to a type of city [3,11], or a specific sector [12,13]. In addition, they are not able to provide common platform and shared language for stakeholders, and not able to provide assistance throughout the whole cycle from action planning to implementation and management of solutions [9]. Their application as a planning tool is severely limited by data scarcity [14], and their inability to capture synergies, complex trade-offs, or analyse different scenarios [14,15].

To be able to produce the standards that support the smart transition of small-, medium sized cities, it is necessary to investigate indicators in the context of the systems they are built in. Is there an architecture in which in which a steady-state list of indicators can function as instruments of decision-support? If so, which aspects of this architecture enable decision-support?

To answer this question, this study explores transforming indicator systems into a shared framework for smart and sustainable cities by practice-based research during the development of the SmartCEPS project. SmartCEPS is an assessment system based on key performance indicators (KPIs) for small- and medium-size European cities. A framework is developed within the project to assess the performance of these cities and to carry forward this assessment to an action plan, implementation and follow-up. Developing SmartCEPS faces the same issues that emerged from scientific discourse on performance-measurement: standardisation, participation, specificity, data scarcity, interactions – all of which hinder the ‘performance’ of performance indicators as actionable tools of decision-support. On this premise, the specific design decisions that respond to these challenges are proxies of transitioning from KPIs to KPI-based decision support, to which we can assess KPI systems and frameworks in general. As a constrained generalisation of design decisions bound to the SmartCEPS project, the proxies answer the research question, fulfilling the criteria of a practice-based research [16,17].

The article is structured as follows: section 2.1 introduces the KPI development process in SmartCEPS; 2.2 describes the methodological adjustments to bridge the gap between KPIs decision-support; part 3 showcases the what the resulting system does; and part 4 reflects on how and under what limitations did design decisions answer the research question.

2. Methodology

2.1. KPI development process

The research question is answered by identifying and generalising specific design decisions which address the shortcomings of KPI systems from a decision-support perspective. Indicator development consists of a collection of information potentially relevant for the objectives of the use-case, a selection process filtering this information pool according to use-case-specific criteria, and an organisation of the filtered pool into an analytic framework (Figure 1) [15,18,19].
Figure 1. General process of KPI system development.

In SmartCEPS, the process began with collecting a pool of over 3000 KPIs covering a wide range of topics related to the assessment of smart and sustainable cities from 34 similar international projects (e.g. CityKeys, CASBEE, ISO 37120, etc.). After cleaning the indicator pool of explicit duplicates, a top-down selection process was conducted. This meant evaluating the applicability of the KPI candidates in the context of city assessment, and a verification of conformity to project objectives. A focus group of planners, architects and economists iteratively assessed the applicability of candidates based on methods in existing criteria frameworks:

- **Usable**: KPI can be measured/calculated without excessive work on behalf of the user [20].
- **Reliable**: The result provided to the user can be trusted to support decision making effectively, minimizing the risk of high deviations in the results [20,21].
- **Comparable**: It is possible to define (conditional) benchmarks for scoring [22].
- **Relevant**: KPI should be aligned to the measured subject [20].
- **Simple**: KPI should be simple and easy to understand [20,21,23].
- **Influenceable**: KPI result can be influenced through action [21,23].

The objective of SmartCEPS is to supply an urban consulting service that builds on diagnosing and developing cities in the domains of “smart”, “sustainable”, “investment attractive” and “entrepreneurship friendly”. These domains were chosen as they reflect the interdependence of economic activity and a sustainability-oriented smart city paradigm (Table 1). Conformity was assessed by using the discourse in international agencies and industrial standards to break down these domains to the abstraction and complexity level of KPIs and cross-checking their thematic correspondence.

| Definition | References |
|------------|------------|
| **Sustainable city** | A sustainable city adopts a government model that seeks to integrate and balance its social, economic and environmental aspects to ensure its resources meet its current and future demands and aspirations. |
| **Smart City** | Smart city is an urban management approach built on the collection, generation, processing, management, storage application and promotion of information. In smart cities, awareness and informed decision making is distributed across the technical, human and organizational systems of the city to support specifying and achieving sustainability goals. |
| **Investment attractiveness** | Investment attractiveness is one type of attractiveness targeted to attract business to a specific location and act as catalyst to reach sustainability goals. Attractiveness is perceived as the available urban resources, the city’s ability to maintain them and attract the new ones, to navigate the city on an optimal development course. |
| **Entrepreneurship friendliness** | The level and quality of attention paid by cities to improve upon given and out-of-scale conditions at the local level to develop a positive and differentiated approach to attract and retain firms and corporate locators, and to support their business needs by reducing barriers, costs and risk uncertainties in all forms. |

Table 1. Main definitions for KPI selection
2.2. Methodological adjustments for decision-support
Developing a range of relevant KPIs corresponds to the level of descriptive analytics, as they are an interpretable, repeatable, comparable quantification and classification of data [38]. Decision-support systems however integrate diagnostic, predictive and prescriptive capabilities [38]. Therefore, while organising the final pool of KPIs into an analytic framework, methodological adjustments are gathered from disciplines with more mature decision-support methods.

2.2.1. Information scaling. To be able to make inferences in a data-scarce working environment, principles of differential diagnostics (DDx) were applied, which entails systematically producing data based on initial assessments [39]. Information in the analytic framework is structured into three sets based on complexity: for the baseline, input data is statistical data readily available from public databases; for a second set, input data is produced remotely from surveys, research, and big data; while the final set of KPIs require sensors, specialists or on-field investigations to assess.

2.2.2. Relationships. To develop an assessment methodology capable of identifying synergies, co-benefits, payoffs, and other interactions among performances, the indicators are organised in a causal network. Causal chains break down linear relationships into: drivers, pressures, states, impacts, and responses [40]. Causal networks are multiple chains that interact with each other [18]. In mathematical terms, SmartCEPS will deploy its KPIs organised in a weighted, directed acyclic graph based on stochastic, causal relationships between or among performances. Edge weights will represent the impact of a change in the source indicator has on the target indicator, applied to given conditions.

2.2.3. Architectural considerations. Finally, a higher-level analytic system will involve more classes of information than just KPIs, but KPIs will roll through the whole planning and implementation process. A variety of actors—and also cities—with different stakes and language engage in urban development, and a decision-support system must be able to make sense of their actions in the context of urban performance and make sense of urban performance in the sense of their actions [15].

In SmartCEPS, KPIs and other entities are indexed with multiple types of structural metadata. A simple, hierarchic classification of KPIs allows their quick legibility for less engaged users and navigability for all users. A set of keywords used as tags for multiple entities respond to divergent user types. The themes in the hierarchy are based on the breakdown of project domains (see 2.1.), while the pool of tags are expanded together with various user groups after system release.

In addition to structural metadata, supplementary data describing the local peculiarities of cities are assigned to KPIs. These are labelled contextual metadata, which are either stable, non-KPI information on cities, such as population, or other KPIs. The role of contextual metadata is to describe conditions under which a KPI for a given city is benchmarkable, and thus comparable, making the resulting analytic framework customisable.

3. Results: the SmartCEPS analytic framework
The final pool of indicators after both selection procedures include 222 objects, of which 37 constitute the core indicator set, a baseline available for most European cities from public databases. The hierarchical classification of KPIs structure them into 8 themes and 29 topics (Table 2).

KPIs are grouped into core, advanced and premium based on their complexity outlined in 2.2.1. For core KPIs, the database was filled up from Eurostat, ESPON and OpenStreetMap, while an initial set of potential data sources were identified for advanced and premium. Investigating KPIs on the lower-complexity group can be used to identify KPIs that critical to expand upon. KPIs from the higher-complexity level that are connected to these are flagged as targets for further investigations.

Due to the causal network structure, assessments within SmartCEPS are different forms of network analysis or simulation. After the information set is complete, the systems uses high-level city goals to filter the list of KPIs of interest. In a diagnostic analysis, the system ranks all KPIs by their score and impact on this filtered network. In a predictive analysis, the impact of single measures on certain KPIs are estimated, while the impact is transmitted to all other KPIs via edge weights and an attenuation factor (via the causal network structure described in 2.2.2.).
Table 2. KPI classification hierarchy

| Themes            | Topics                                                                 |
|-------------------|------------------------------------------------------------------------|
| Mobility          | access to transport, sustainable transport systems, smart mobility     |
| Infrastructure    | access to infrastructure, smart infrastructure                         |
| Environment       | ecosystem, ambient pollution, waste                                    |
| Inhabitants       | education, health and care, innovation, civic engagement, social justice|
| Economy           | economic performance, growth potential, smart economy, international embeddedness, clustering, sustainable economy |
| Governance        | open government, e-government, safety, governance awareness, smart targets |
| Energy transition | energy and mitigation, sustainable infrastructure transition            |
| Built environment | smart building, sustainable building, sustainable urban development     |

During the planning process, tags provide the common underlying language among different actors, and from one information entity to the other. Municipalities, stakeholders and citizens use tag-based surveys to define their priorities, while solution providers classify their products with tags. Tags are bundled in groups based on the user type or their framework of origin. Given the bottom-up nature of tag development, at this stage the UN domains of sustainable development are added as tags [41].

Although the analytic framework is centred around KPIs, they are positioned in a relational database with links to other information entities, namely: solution providers, solutions, measures, projects. Entities have direct links to their neighbours: solution providers deliver certain solutions, which can be built into projects, which bundle different measures, while measures have impacts on KPIs. Additionally, all share the same framework of thematic, structural metadata that couples one entity to another in an indirect way, and contextual metadata, which describe the conditions of their applicability.

Based on the key steps taken during the development of SmartCEPS we argue that gradual customisation, causal network organisation, and open-ended scalability are the proxies for KPI design in the urban management context. (Table 3).

Table 3. Generalisation of critical design decisions

| KPI system challenges (section 1) | Methodological adjustments (section 2) | Critical design decisions (section 3) | Proxies for KPI-based decision-support |
|-----------------------------------|---------------------------------------|-------------------------------------|---------------------------------------|
| Standardisation-customisation     | Methods and metadata for mediation     | Contextual metadata                  | Gradual customisation                 |
| Standardisation-customisation     | Methods and metadata for mediation     | Common structural metadata           | Gradual customisation                 |
| Complexity of interactions        | Relationships, KPI roles, interactions.| Acyclic digraph KPI organisation     | Expressed causal relationships        |
| Practicality & solution gap       | Relationships, KPI roles, interactions.| Impact-based edge weighing           | Expressed causal relationships        |
| Aggregation losses                | Relationships, KPI roles, interactions.| Impact-based node weighing           | Expressed causal relationships        |
| Standardisation-customisation & Data scarcity | Procedure for information set expansion | Complexity and impact-based KPI phasing | Scalloptability & open-ended design   |
4. Discussion

The most difficult technical challenge for indicator systems is the standardisation-customisation conundrum, which is amplified for smaller cities given their variety [42]. In SmartCEPS the set of indicators are filterable by their keywords, which makes it so that a ranking of KPIs is practically negotiated by the wider public. This can be considered during diagnosis – certain tags pose as “symptoms”. Contextual metadata on the other hand provide automatic means customisation by excluding KPIs from comparison when necessary, and by adding weights to locally more relevant KPIs in their network. This would not be possible if the KPIs were not organised in an impact-network in the first place. To generalise, the solution is a form of customisable standard [43], providing three layers: a standardised KPI set for comparison, an automated customisation for contextual constraints, and a negotiated customisation for local constraints. It must be noted that accepting rules regarding automated customisation must rely on a consensus mechanism in a wider community of professionals.

It is the KPI network structure that makes SmartCEPS actionable: it fulfils diagnostic and predictive levels of analytics by calculating how impacts of interventions or events cascade throughout city performance. The connections afford the phasing of information as per DDx principles, and node weighing gives an impact-based method to aggregate KPI scores in indices both for the entire system, or for specific keywords. Much of the success of the KPI system hinges on the accuracy of the estimation of impact size, timeliness, and conditions. The challenges of building the blueprints for network alone is complex issue beyond the scope of this paper, but it is worthwhile to mention that filling up the blueprint with information is a task for an entire field of professionals. As mentioned before, city assessment is decades behind medicine in terms of literature that provides input for running differential diagnostics. By building a framework based on the knowledge we have, the project unlocks a vast research challenge and opportunity to fill up the library of urban diagnostics.

It must be noted that choosing the range of indicators, the topics covered, the indicator definition, the metadata, the method for weighing, scoring, benchmarking, aggregating, and displaying are all steps that introduce bias, and a black box mindset will concentrate the source of subjectivity to a few professionals [19,44]. With the more open-ended SmartCEPS framework, the system is continuously validated, but this raises the issue of generalising local solutions and projects into measures that will have to be solved by some form of consensus mechanism.

5. Conclusion

The goal of this research was to find which design decisions are necessary to upgrade KPI-based assessment schemes to mature systems of urban decision-support. By building an analytic framework, the scope of the gap in the field has become clearer: the relationships among the many dimensions describing urban performance, and the specification of how treatment delivers performance. Such a highly interdisciplinary, and complex knowledge system can be only built through co-ordinated, collaborative effort. SmartCEPS aims to be a fluid, semi-open source framework for a community of smart city professionals who are dedicated to support cities in evidence-based decision-making, and for interested citizens who partake in it.

In this wider context, data-driven solutions and indicators provide the content to talk about, while this study provides the basics for a working environment in which different actors can talk about it and accumulate our knowledge on how their cities work. It is thus important to explore a shift from the knowledge we produce to how we produce it – to be able to accelerate the resources for evidence-based decision making in urban planning and management.

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