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The Science of Tooling – Design Framework for Digital Tools in Support of Socio-Spatial City Analysis

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Abstract

In the context of the digital transformation of cities, the application of data-driven tools has become a common practice in urban studies and metropolitan research. Beyond their appropriate utilisation, their targeted design poses challenges as well. Unlike established practices in the engineering and design domains, there are only few processes established that support the targeted creation of analytical or synthetic instruments for the processing of urban data. Therefore the paper outlines a framework for a design science of digital tools that address the socio-spatial complexities of urban systems. It does so by discussing four key aspects whose investigation and integration is requisite for devising instruments applicable for urban research, planning, and decision making. The outlined methodology provides a systematic approach for the design of digital city tools as well as an educational blueprint to enable next-generation digital city scientists to understand the structure of such instruments as well as their implications for practical work. The consolidation of digital tooling thus forms a central component in data-driven urban planning and analysis i.e. Digital City Science.

Keywords: Digital City, Software Development, Design Science, User Interaction, Urban Data

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1. Introduction: Digital City Science

To understand complex urban phenomena such as social activity unfolding in urban spaces or sustainable development of human settlements, advanced scientific theories and models are necessary. Acknowledging this demand, approaches summarized as "city science" have been established since the 1970s that describe urban systems by way of mathematical and communication models [1], [2], [3]. The digital transformation of urban environments over the recent decades has fueled this scientific stream in urban studies [4]. It enabled the development of city models that rely on the gathering and interpretation of large amounts of digital data representing spatial structures and environments. In the wake of this evolution, new scientific challenges emerged. Computational models and processes needed to be established that not only translate the complex qualities of urban environments and their mechanisms of development into numerical representation but also generate new insights and intelligence for urban planners, designers, and developers. To address such challenges in City Science – which can also be seen as a byproduct of the swift evolution of digital ("smart") technologies in the urban context – and to investigate the principles of urban data processing with digital tools, Digital City Science was established as a dedicated field of research [5]. It´s specific approach may be broken down into three levels of research and study:

1) *Models and Principles*: Digital City Science seeks a fundamental understanding of how new digital technologies – such as environmental sensing or real-time traffic monitoring – relate to existing socio-material urban systems, and how the production of vast urban data may change the nature of urban production and management. The comprehensive analysis of urban data, for example, may lead to models that provide insights about future development trajectories, thus enabling anticipatory assessments of potential urban futures [6]. Investigations with such theoretical impulse may be termed "*Fundamental Digital City Science*".

2) *Tools and Applications*: A second stream of investigation within Digital City Science concerns itself with the practical application of digital instruments and methods. Effective means and procedures need to be established in order to generate benefits and added value from the growing stock of urban data – for the urban communities as well as for the professional practitioners in planning and design. Digital tools, for example, allow a significantly greater outreach in participatory planning and multi-stakeholder collaboration – thus ushering in new paradigms in co-creation and co-design [7]. These value- and user-oriented investigations form an "*Applied Digital City Science*".

3) *Digital Tooling*: A third "instrumental" aspect of Digital City Science focusses on the creation of new tools that enable the aforementioned scientific investigations. Understanding the fundamental principles and processes of digital cities on the one hand, and acknowledging user demands and application potentials on the other, systematic knowledge needs to be established about the conception, design, and implementation of digital tools that are capable of exploiting urban data [8], [9]. Targeting digital tools for processing digital data generated in digital cities, this explicit tooling approach may be termed "*Instrumental Digital City Science*".

The present article focusses on the third aspect. The investigation of urban complexity and sustainability – not alone of digital cities – increasingly relies on the availability and application of digital tools. Their methodical creation, however, is still a highly unrecognized and undefined issue. Research labs like the Digital City Science group at HafenCity University Hamburg (HCU) have thus invested large efforts in the systematic development of data-driven tools in support of urban analysis, planning and development. A central aim here is to establish a kind of design science that provides a methodical basis for creating digital instruments that can better grasp essential socio-spatial qualities e.g. the sustainability of structures, the vitality of public spaces, or the livability of neighbourhoods.

2. Four Key Aspects of Tooling

While the application of the digital city science tools may span over a large variety of fields – from transportation planning across real estate management to urban climate analysis or participatory design [9], [10], [11] – their overall process of design can be schematized and rationalized to a large degree. The tooling practice as it is carried out by

Digital City Science @ HCU usually combines four key aspects and converges them within a creative process of conceptual and technical development into coherent technical solutions. These four aspects, however, require careful investigation as individual as well as combined factors, before an integration into a productive tool can be attempted (Fig. 1)

- *User Requirements* – the variety of needs and challenges from the user side which need to be comprehensively recorded, structured and defined;
- *Solution Types* – the inventory of existing software "modules" or toolboxes that can be used, developed and combined for the envisioned future tool;
- *Interaction Level* – the variety of interactions that a user carries out – or experiences – in the utilization of the envisioned future tool;
- *Data Provision* – the comprehensive analysis of data availability and accessibility under specific aspects such as data formats, quality, quantity etc.

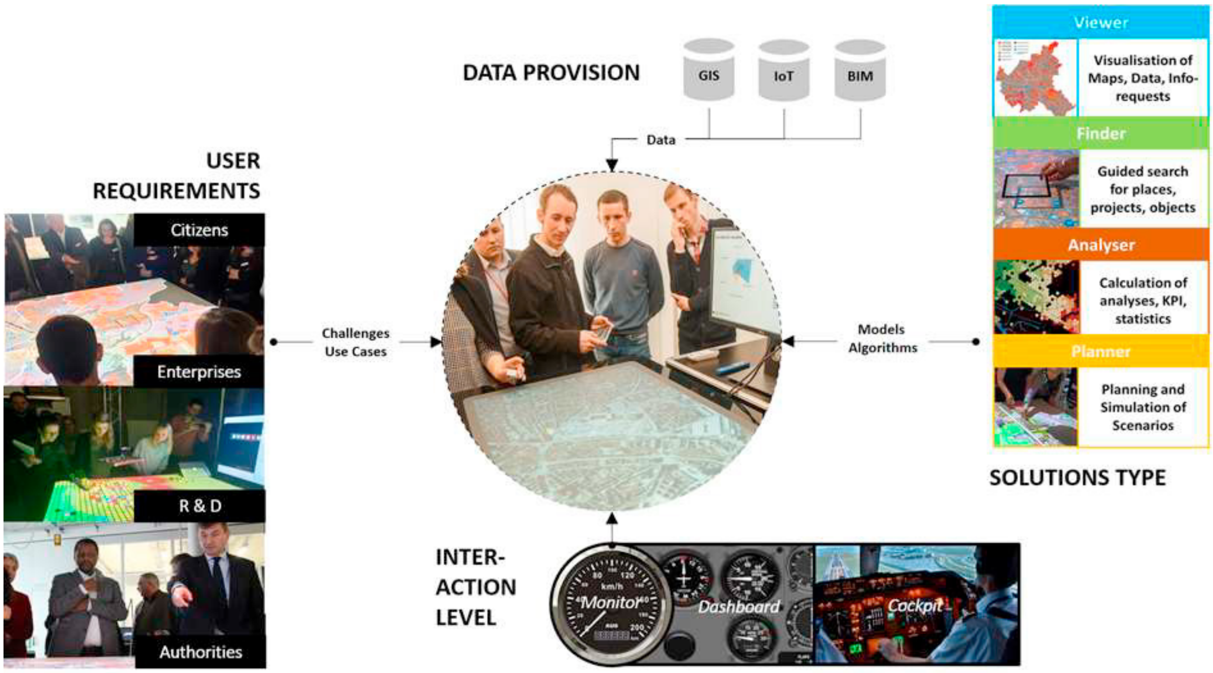

Fig. 1. Integrating four aspects for the design of digital city science tools (Source: HCU Digital City Science)

Through the integration and coordination of these four aspects, effective digital city instruments can be designed, prototyped and implemented. On such premise, Digital City Science at HCU has already devised a series of tools that found application in local urban development (cooperation project with HafenCity GmbH Hamburg and MIT "Grasbrook CityScope"), in European migration management (Horizon2020 project "MICADO Migrant Integration Dashboards and Cockpits") or in international development aid (GIZ cooperation project "TOSCA Toolkit for Open and Sustainable City Planning and Analysis"), among others.

To outline detailed procedures as how to bring above mentioned four aspects into a specific tool development process exceeds the scope of this paper. The following chapters, instead, will focus on the further explanation of the single aspects, across which various paths lead to successful integration and consolidation. Importantly, these procedures commonly do not follow a strict linear sequence, but unfold in circular and iterative pathways, thus paying attention to all aspects more or less synchronously across all development phases.

3. User Requirements: Defining Use Cases and Application Scenarios

The capacity of digital city tools to accommodate, represent, and address socio-spatial qualities – especially human factors on the collective as well as on the individual level – depends on the precise definition of user requirements. User and target groups ranging from civil society organisations to municipal or industrial corporations, from research and development actors to political and administrative decision-makers raise very different demands and expectations towards the tools they intend to use later on. These demands need to be acknowledged and accommodated by the tool design process, as they strongly determine the technical, functional, and visual design of the tools themselves. Commonly being the starting point for a tooling process, a well-structured and systematic requirement analysis is a key requisite for deriving all demanded functionalities and for an eventually successful tool.

From an application point of view, two clear-cut scenarios can be distinguished which mark the diametrically opposed outer edges of a broad range of usage contexts. From these two extremes, specific demands and requirements can be inferred which form a basis for the systematic conception of the envisioned tools from a user perspective (Fig.2).

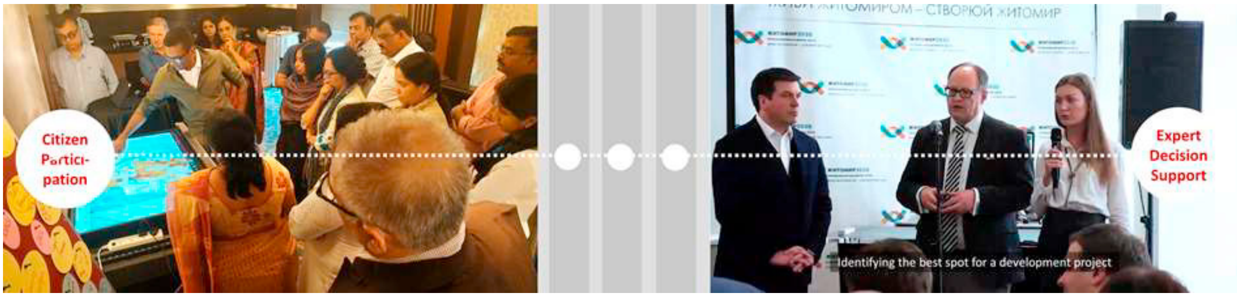

Fig. 2 Application contexts for Digital City Science tools – two extreme scenarios (Source: HCU Digital City Science)

The first scenario "Enabling Citizen Participation" aims for the broadest possible involvement of various users and stakeholder groups in participatory processes related to urban development. Here it is important to provide information and activities as low-threshold and inclusive as possible, hence large amounts of information should not be presented or processed. Instead of far-reaching decision making, the focus is rather on information provision, social exchange and interaction and an engaging multilateral communication process [9], [10]. Thus the tooling process would target features and procedures that – based on gaming approaches e.g. – create special experiences or even entertainment.

The opposite scenario "Supporting Expert Decision Making" addresses high-level decision makers in governments, administrations or enterprises who are in charge of complex tasks bearing far-reaching social, economic, political etc. consequences. Here, the application context is usually determined by small strategy groups and counselling formats in which in very limited time extensive information must be presented and digested in order to prepare a reliable decision-making [12], [13].

Between these two extremes, a range of further application scenarios can be either interpolating or combining aspects from the edge cases. By such operations, a "DNA of usage" can be defined for a variety of tools and new use cases explored (e.g. interactive planning campaigns with children, collaborative resource allocation by executive boards, co-design workshops in the urban neighbourhoods, etc.)

To determine the target applications scenario, and to consolidate the respective demands in a structured manner, formats like use case templates or users stories have been proven very useful. While use case templates comprehensively describe the operational context, expected benefits and added value in regards to the envisioned tool, user stories break down the requirements into detailed and precise definitions of the concrete features and functionalities. Commonly these activities are being carried out in co-creative workshop sessions and by way of collaborative tools (Jira, Trello, Miro etc), using pre-structured tables and manuals (Fig. 3)

Fig. 3 Requirement workshop (left); prestructured Use Cases template; (Source: HCU Digital City Science)

4. Solution Types: A Classification of Tools

While the definition of user requirements is a generative task which is highly user-specific and context-depending, the implementation of technical solutions in contrast often allows the usage of existing instruments or established toolboxes. Especially in the open source software world, a vast variety of component solutions presents itself for further usage, development and recombination. Modular approaches are well established in the software design and engineering sphere, hence a structured description of the available “modules” can brings substantial gains in development speed, efficacy, and reliability for the envisioned future tool.

Investigations by Digital City Science @ HCU have lead to a classification which differentiates the multiplicity of tools – existing ones as well as tools still under development or just in conceptual stage – into four groups in accordance to their degree of technical and scientific complexity. The distinction also reflects the level of insights and intelligence that are possible with the tools, assuming that tools of higher complexity are basically capable of generating knowledge of higher valuable than simple instruments.

"*Visualisers*" are tools that enable knowledge gains primarily by presenting available data in a more accessible visual format. The graphic translation of e.g. numerical data into diagrams, maps or dashboards makes abstract and incomprehensible information more understandable and accessible. A map display, for example, can easily convey the density and distribution of cultural facilities in a city at a glance. Visualisers are therefore particularly suitable for application scenarios where non-professionals are confronted with professional information e.g. with socio-spatial indicators. In participatory processes, for example, adequate information design is key for ensuring low thresholds and commitment by non-professional citizens. Commonly, appealing data visualization can be implemented without great effort – thus Visualisers are quick winning tools.

"*Finders*" possess a higher conceptual and technical complexity than visualizer solutions. Being basically search engines (better: "answer engines"), they are tailored to given tasks or specific questions. To clearly formulated queries, they respond with clearly formulated, unambiguous results. One well known example are navigation and routing systems that specify the shortest routes or travelling times from X to Y. While the algorithmic processes running in the background may already be complex, Finders are commonly easy to use and thus applicable also for broad public use.

As genuine instruments for research and investigation, "*Analysers*" provide knowledge about complex relationships and interdependencies in urban structures e.g. the microclima in a city district. In contrast to Finder tools, Analyzers do not necessarily output clear and simple results. They rather elucidate the complexities at stake, and prepare new and more detailed investigation. As viewing devices, Analyzers can be compared to X-ray apparatuses: They allow insight into the complex organism of the city and potentially uncover new challenges, making them visible for the first time.

As projection and prediction tools, "*Planners*" represent the most complex solution type in terms of scientific design and data technology. Extrapolating from the available knowledge about past and current states, they carry out predictions about future phenomena of urban systems e.g. by way of What-if-scenarios ("What happened to the social structure if we placed in this neighbourhood a new day care facility?"). This is fundamentally opposed to the opacity of complex dynamic systems – as cities certainly are. Urban futures can be best anticipated and planned within narrow, defined temporal and spatial boundaries. Nevertheless, projections are possible for physical-deterministic processes e.g. in mobility or resource management, insofar as validated simulation and scenario models exist [14].

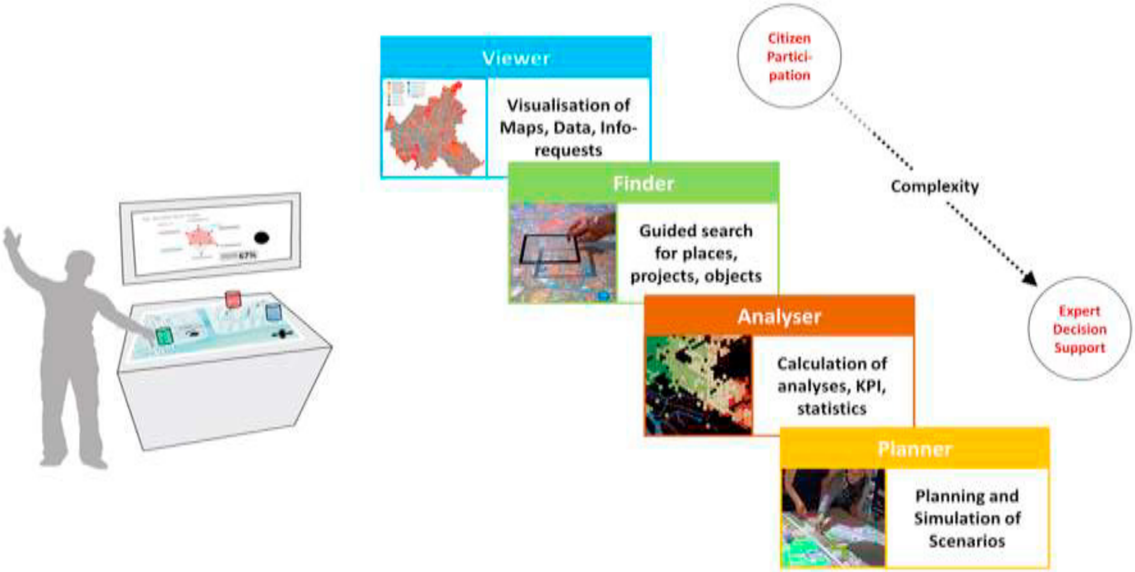

Fig. 4 Classification of tools – according to levels of complexity / application scenario

The skillful usage of this constantly growing reservoir of solutions is a central concern in the overall tooling process. Many components of new digital city tools must not be created anew; they rather need to be identified and selected from pools of already existing software solutions. In the case of Digital City Science at HCU, some of these modules are own developments while many others are drawn from third parties or from open sources.

5. Interaction Formats: Linking Users and Tools

The mere provision and availability of digital tools is not sufficient to enable users for an adequate and purposeful application. The usage process itself – that is: the interaction between tool and user – needs be meticulously designed too. Depending on the specific solution and its respective users, user interaction needs to be considered on different levels of complexity which may range from simple visual perception towards multi-step actions across different media.

For the various above-mentioned solutions, interaction intensity differs in recognition of the users and their respective application contexts. These relationships must be determined in the sense of an "interaction design"; the technical product needs to be supplied with instructions and choreographies [15]. From the research and teaching practice of Digital City Science at HCU, the following conceptual distinction into three levels of interaction intensity has been derived (Fig. 5).

A "*Monitor*" is the visual display of one selected indicator which can be comprehended by simply looking at it. The indicator "Dynamics of Socio-Spatial Development in Districts", for example, can be adequately visualized ("monitored") by way of a chloropleth map [16].

Arrangements of multiple monitors can be referred to as "*Dashboards*". Various indicators brought together in the visual context of an "armature" not only allows for a synoptic overview of complex data, but also for quick and effective conclusions and inferences. Through overviewing different yet spatially co-located contents, a cognitive synthesis is stimulated ("Look here, look there – and you will see!"). In the case of dashboards design, targeted attention management and precise guidance of the gaze are crucial [17].

Finally, monitors or dashboard arrangements which require more than visual observation but specific sequences of action are "*Cockpits*". Cockpits are based on choreographies for usage ("First this here, then that there ... then back again") which need to be designed as an integral part of the socio-technical system. When equipped with sequential guides or "protocols" for their usage, Cockpits can enable and effectively support complex knowledge and decision-making processes [8], [14], [18].

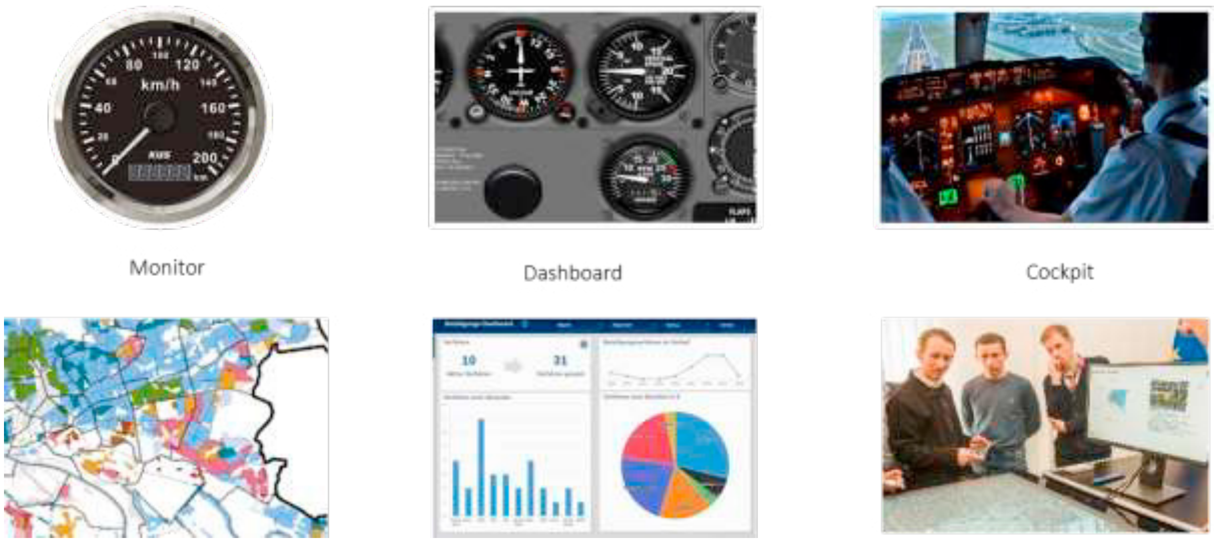

Fig. 5 Different levels of user interaction: Monitor – Dashboard – Cockpit (Source: HCU Digital City Science)

6. Data Provision: Accessing and generating urban data

Without available and accessible data, no digital tool can be useful. The existence and availability of data is the basic condition for the design and application of digital city tools. A careful analysis of the overall situation in respect to data provision is decisive. Technical decisions and definitions throughout the tooling process – such as program interfaces design, system architecture, or data bank structures – heavily depend on the existence, availability, and accessibility of data, on reliable information about data formats, ownership, quantity, quality etc.

The absence of accessible and available data thoroughly defects the tooling process. Only if ways open up to generate – with more or less effort – the requisite data, further design and development activities are meaningful. In such case, data may be generated by tapping on open sources (e.g. Open Street Map, transparency portals, Fig. 6), by purchases from data providers, digitalization campaigns or participatory citizen science formats (e.g. crowd mapping).

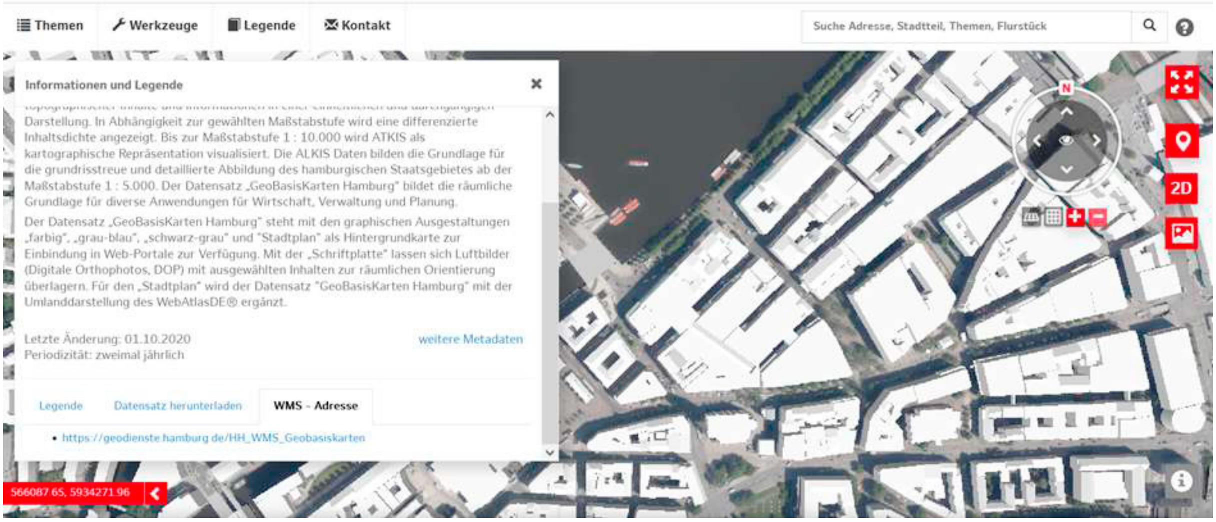

Fig. 6 Open data source: Data export via WMS from Hamburg Geodata portal (www.geoportal-hamburg.de)

The fact that useful data are existing does not necessarily imply their availability and accessibility. Data ownership, licensing and contractual factors impose constrains on data-driven digital tools – these aspects need to be investigated and clarified early on in the tooling process, to avoid wrong assumptions or later dilemmas in the implementation phase.

In the case that data are available, still their technical access e.g. via application programming interfaces (API), web services etc. needs to be clarified. The mere availability of data (e.g. in inaccessible local repositories) does not necessarily imply that they can be effectively accessed and processed. Building up additional data infrastructures may become necessary to ensure the effective transfer, processing, and valorization of the required data. The envisioned tool thus needs to embed within a suitable and effective IT architecture. The establishment of respective infrastructures and pipelines is a matter of data engineering, which shall not be addressed in this present paper, however.

4. Conclusions and outlook

The paper has indicated four main aspects to be considered in the design of data-driven tools: *User Requirements*, *Solutions Typology*, *Interaction Level*, and *Data Provision*. The integral comprehension of these conceptual components is key for the creation of new digital instruments for urban analysis, planning and decision-making. A systematic description of the qualities that derive from the linkage of these components enables a targeted tooling process, tailored to the specific purposes and tasks, users and application contexts. Before all, the juxtaposition of solution typologies ("*Visualiser*" … "*Planner*") and interaction levels ("*Monitor*" … "*Cockpit*") provides a conceptual matrix that summarises the basic design features and application potentials of digital city science tools (Fig. 7).

This classification system not only provides for precise description of digital city tools ("Planning cockpit for bicycle mobility", "Analysis Dashboard for Air Quality", or "Visual Monitor of Voter Turnout in Urban Districts" etc.) – it also defines important boundary conditions for their design and implementation process e.g. development effort, scope of necessary testing, level of the support for the productive system. In addition to supporting the research and development work, it wants to provide a methodical basis for education and training too. With such basis, students may not only use digital tools more consciously in their future practice, but also learn to design them in accordance to their tasks and needs. The capacity to design and develop digital tools in response to the complex challenges of sustainable urban development becomes increasingly important.

	Visualiser	Finder	Analyser	Planner
Monitor	Single display for the visualisation of a specific data source	Single display for answering a specific query	Single display for investigating a specific task or problem	Single display for anticipating a specific future issue
Dashboard	Composition of multiple displays for synoptic visualisation of various data sets	Composition of multiple displays for answering a complex query	Composition of multiple displays for analysing selected tasks or problems	Composition of multiple displays for enabling foresight into complex future issues
Cockpit	Complex interactive system representing complex issues	Complex interactive system querying complex data	Complex interactive system analysing complex tasks or problems	Complex interactive system modelling complex future issues

Fig. 7 Matrix of Solution Typology and Interaction Level, indicating basic features and applicability of tools

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