A LAYERED APPROACH FOR THE DATA-DRIVEN DESIGN OF SMART CITIES

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Abstract. Current approaches to smart cities have focused on implementing technologies to harvest and analyse data through sensors and artificial intelligence to improve urban performance from the top-down. However, cities are complex systems of interconnected layers that change at different speeds. More persistent layers, like networks and occupation, must have smartness embedded in them through smarter design processes. In recent years, there has been an increase in digital tools for urban design, applying computational design methods and data analytics strategies, enabling collaborative and evidence-based approaches that support sustainable urban design. A critical evaluation of their potential to inform design is necessary to aid practitioners to choose and adopt these novel strategies and tools in practice. This paper presents a critical review of selected data-driven design cloud platforms, focusing on data-driven urban design approaches that can enable the use of ICTs to steer cities into a smarter future from the bottom-up.

Keywords. Smart Cities; Data-Driven Urban Design; Computational Design.

1. Introduction

Smart cities have been defined as innovative approaches to increase the efficiency of cities. There was a general assumption that developments in Information and Communication Technologies (ICTs) would enable cities to become more equitable and sustainable (M. Batty et al. 2012). This is what Grassl and Groß's (2019, p. 25) call the "holistic smart city" discourse. Nonetheless, current practical approaches to smart cities are better identified in their definition of *"connected smart cities"*, that focus on implementing technologies to harvest and analyse data through sensors and artificial intelligence to improve urban performance, in hopes that urban development will follow.

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Hitherto, these improvements do not correlate with higher equitability and sustainability in a city, unless these questions were already being addressed before it began adopting smart technologies (Zheng et al. 2020). Thus, "holistic smart cities" are unlikely to be achieved through technological development alone, as cities behave as complex adaptive systems (Michael Batty, Bettencourt, and Kirley 2019). Over relying on private companies to propose closed technological solutions for various urban problems from the top-down, without accounting for how people's behaviour and the agency is being affected by the existing built environment and by all the devices, apps and platforms available to them, e.g. smartphones, social media or routing tools, can lead to unforeseen bottom-up social, economic and environmental consequences (Zvolska et al. 2019). There are layers of interconnected infrastructure in a city that change and are assimilated at different speeds (van Schaick and Klaasen 2011). ICTs for smart cities are but one of these layers, developing ever-evolving devices and software to harvest and analyse data in the attempt to fix urban problems from the top-down (Bettencourt 2014).

There are other infrastructural layers, e.g. the substratum with its natural resources, and the built environment, which, despite changing at slower paces, also have their own potential to embed smartness through data-informed urban design, to enable the "holistic smart city" concept to come to fruition (Grassl and Groß, 2019; Kvan 2020). This time-dependent, design-driven approach to smart cities has been understudied in existing frameworks (Yigitcanlar et al. 2018). Nonetheless, in recent years, there has been an increase in digital tools for urban design, applying computational design methods and data analytics strategies, enabling collaborative and evidence-based approaches that support sustainable urban design in early stages of the design process.

This paper aims to contribute to bridging the gap between urban design and smart city ICTs, critically reviewing urban design data-driven tools based on key evaluation criteria of interface development, data-driven flow, early stages of the design process as well as its impact on a layered understanding of the city and its alignment with an integrated and holistic view of the sustainable smart city approach. A conceptual framework for approaching smart cities as layered, time-dependent entities was developed, focusing on a data-driven urban design approach is essential to enable the use of ICTs in a non-disruptive manner, to steer cities into a smarter future from the bottom-up.

2. Context

Cities as Complex Adaptive Systems (CAS) has become a recurrent topic in the fields of urban planning and design, characterised by emergent, non-linear, behaviours that cannot be explained as the sum of their parts and should be approached as complex systems, grounded in complexity theory (Holland 2014). For Marshall (2009), urban planning for cities as CAS should apply small scale design interventions to trigger self-organisation, allowing them to evolve as ecosystems, from their internal interactions. This creates a state of indeterminacy, in which planning and design outcomes are unpredictable (Verebes 2013). Hence, urban planning and design should rely on the formulation of possible future scenarios through the observation of existing phenomena and extrapolation of existing data. Thus, generative methods can be used to create prospective scenarios to inform design decisions and improve urban development (Dovey and Pafka 2016).

The concept of smart cities in its inception was strongly related to technology-driven sustainable development. However, current practice demonstrates a great difficulty in bringing those intentions to fruition. By overfocusing on technology at the expense of the multidimensional aspects related to smart cities, e.g. community, policy, ecology and design, holistic smart cities remain out of reach (Yigitcanlar et al. 2016; Zheng et al. 2020).

We used the framework proposed by Yigitcanlar et al. (2018) as a starting point to develop a layered time-dependent framework for holistic smart cities that takes into account the concept of complex adaptive systems, in order to embed smartness into different urban systems from the bottom-up, so that technology can contribute to urban sustainability.

The framework development is based on the method proposed by Walloth (2016) to approach cities as Emergent Nested Systems (ENS). ENS are complex enclosing systems that change at a slower pace than the systems they enclose. Changes within the enclosed subsystems trigger emergence and self-organisation in the enclosing system. Therefore, predicting what individual interferences in the subsystems can trigger in the whole is a challenging task. Understanding the paces and rules with which subsystems change and how they affect emergence in the enclosing system can be a way to plan localised interventions for influencing the whole (Walloth 2016).

In the context of smart cities, by taking a layered approach to an urban system, natural systems can be understood as an enclosing system for networks, that in turn are enclosing systems for occupation. ICTs are systems enclosed by all of them, and change at the fastest pace. While they affect the enclosing systems, they do so at a slow pace. Much slower than the time they take to change themselves.

The Dutch Layers Approach (van Schaick and Klaasen, 2011) divides the physical components of an urban system into Occupation, Networks, and Substratum, according to the time they take to incur significant change. Occupation changes significantly over a generation, networks every two generations, and substratum takes over 100 years to change. For this framework to be better adapted to smart cities, other layers, understood herein as nested systems, should be added, such as those discussed by Yigitcanlar et al. (2018), i.e. community, policy and technology. Most of these layers behave as nested systems, with one system influencing the other at different temporal steps. Nonetheless, while information and communication technologies (ICT's) are influenced by them, the interaction takes a longer time to go in the other direction. In the 20th century cars completely changed urban networks and occupation patterns, but the same has still not been observed for ICT's. These technologies must become embedded in urban networks and occupation to achieve *holistic smartness* by influencing community behaviours and policy. To achieve this, design processes and urban space production must change through data-driven, empirically-based, predictive and optimisation methods.

3. Methodology

To comprehend how ICT infrastructure is impacting current urban design practice, interacting within the three urban system layers defined by van Schaick and Klaasen (2011) as well as to understand the barriers that practitioners are facing to adopt these strategies into their design process, this paper reviewed four urban design cloud-based services that aim to deliver a data-driven platform for designers, collaborators, investors, and other stakeholders that seeks an evidence-based exploratory environment. A successful platform should provide a user-friendly environment, support the collaboration between clients and designers, and integrate available public and private data into the design process to shape design decisions. While those strategies represent novel design-decision tools, they need to be critically evaluated on their potential to impact and inform design.

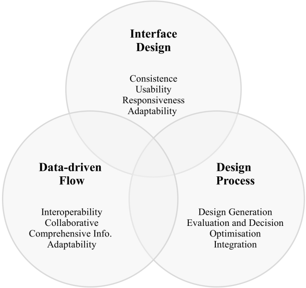


Figure 1. Diagram of relations between the three evaluation criteria.

The methodology was developed based on key evaluation criteria for interface development, data-driven flow and design process as shown in figure 1. For each key evaluation criteria, four sub-criteria were defined and, for each sub-criteria, four questions were established. These questions were formulated in order to obtain binary answers: yes or no. Each positive answer corresponds to a value of 2 or 2.5 points, without the need for computing any partial points. This means that only values 2 or 2.5 are assigned, see table 01. Subsequently, the scoring system was plotted in radar charts to assess the ability of the tool to support the design of smart territories.

According to Shneiderman et al. (2016), there are eight golden rules to measure the performance of an interface development: Consistency, Usability, Feedback, Cohesion (Design dialogues to yield closure), Error Prevention, Action Reversal, User Control, and Reduction of Short Term Memory. In this study to make the analysis more concise, we clustered the concepts in groups as follows; Consistency, Usability (Usability and User Control), Responsiveness (Feedback), Adaptability (Cohesion, Reduction of Short Term Memory, Error Prevention, and Action Reversal). The questions essentially sought to assess, respectively, whether the design of the interface seeks consistency, whether it seeks universal usability and keeps users under control, whether it offers informative feedback, and whether it designs dialogues to close errors and allow easy reversal of actions.

The data-driven flow criteria aim to assess the interoperability and collaborative potential of the design tool, as well as its availability of comprehensive and general information. The stakeholders involved in this process are clients, investors, community, and designers. The interoperability verifies whether the design tool has a common data format, whether it allows exchange information, whether it is based on an open standard and whether it is compatible with others. The collaborative process measures specifically the ability of the design tool to support a collaborative workflow among stakeholders, and the capacity of users to work on the project in real-time, with feedback and crowdsourced inputs. Comprehensive information measures the information availability for community, clients, investors and designers. Ultimately, the general information sub-criterion seeks to evaluate whether the design tool addresses social, behavioural, environmental, perception and economic information.

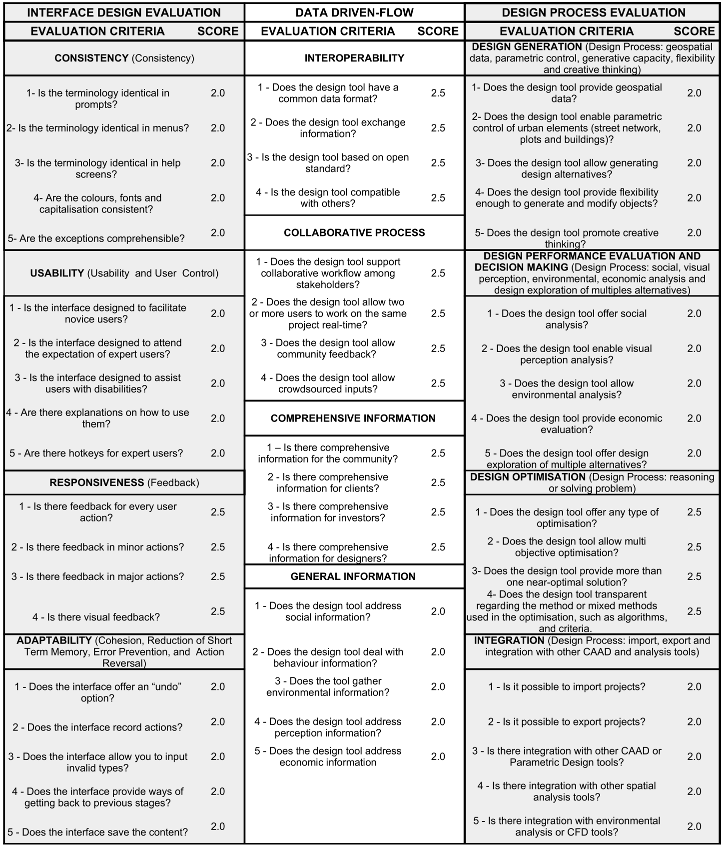
The design process assessment considered the triad: design, evaluation and optimisation. It is understood that these three criteria are essential parts of the digital design process. However, possible integration with other digital tools has also been included as a criterion especially because it would make the design process more flexible. Regarding sub-criteria, the design generation was established to first assess the availability of geospatial data (such as satellite image, topographical maps, street network, urban block perimeters and plot subdivision) as an initial database for the design conception, and second to verify the generative capacity, parametric control, and flexibility of the tool to allow creative thinking. The design evaluation sub-criterion measured the ability of the tool to offer social and visual perception, environmental and economic performance analyses, as well as to make possible the design exploration of multiple alternatives to aid the decision-making process. The design optimisation checked whether the tool provides any type of optimisation, multi-objective optimisation or even one near-optimal solution according to predefined fitness criteria. Finally, the integration evaluated the capacity of the tool to exchange information with other Computer-Aided Design (CAD) tools, such as the ease to import, export projects, as well as the integration with other analysis tools.

3.1. SELECTION CRITERIA

The selection of design tools was based on three fundamental aspects, as follows: being a cloud-based tool; focusing on urban design for smart territories, allowing street network, plots, and building volumes to be modelled, and offering free trial versions. Based on these three criteria, six cloud-based tools were identified: *Scout*, *Delve*, *SpaceMaker*, *Giraffe*, *Archistar.ai*, and *Digital Blue Foam*. These tools were identified through social media such as LinkedIn, Twitter, and Facebook in which most of them have recently been launched.

It is also important to note that all developers were requested by email to offer a trial version of the design tool so that the authors could test and evaluate their features according to the pre-established criteria. The vast majority replied to the request, except for *Archistar.ai*. In addition, the developers of *Delve* responded that, currently, it is only offering a commercial version of the tool, and they expect to make trial versions available for academia in 2021. The other four cloud-based services named *SpaceMaker*, *Giraffe*, *Digital Blue Foam*, and *Scout* offered trial versions enabling this research.

Table 1. Evaluation Criteria (Interface, Data-Driven Flow, and Design Process).



INTERFACE DESIGN EVALUATION		DATA DRIVEN-FLOW		DESIGN PROCESS EVALUATION	
EVALUATION CRITERIA	SCORE	EVALUATION CRITERIA	SCORE	EVALUATION CRITERIA	SCORE
CONSISTENCY (Consistency)		**INTEROPERABILITY**		**DESIGN GENERATION** (Design Process: geospatial data, parametric control, generative capacity, flexibility and creative thinking)	
1- Is the terminology identical in prompts?	2.0	1 - Does the design tool have a common data format?	2.5	1- Does the design tool provide geospatial data?	2.0
2- Is the terminology identical in menus?	2.0	2 - Does the design tool exchange information?	2.5	2- Does the design tool enable parametric control of urban elements (street network, plots and buildings)?	2.0
3- Is the terminology identical in help screens?	2.0	3 - Is the design tool based on open standard?	2.5	3- Does the design tool allow generating design alternatives?	2.0
4- Are the colours, fonts and capitalisation consistent?	2.0	4 - Is the design tool compatible with others?	2.5	4- Does the design tool provide flexibility enough to generate and modify objects?	2.0
5- Are the exceptions comprehensible?	2.0	**COLLABORATIVE PROCESS**		5- Does the design tool promote creative thinking?	2.0
USABILITY (Usability and User Control)		1 - Does the design tool support collaborative workflow among stakeholders?	2.5	**DESIGN PERFORMANCE EVALUATION AND DECISION MAKING** (Design Process: social, visual perception, environmental, economic analysis and design exploration of multiples alternatives)	
1 - Is the interface designed to facilitate novice users?	2.0	2 - Does the design tool allow two or more users to work on the same project real-time?	2.5	1 - Does the design tool offer social analysis?	2.0
2 - Is the interface designed to attend the expectation of expert users?	2.0	3 - Does the design tool allow community feedback?	2.5	2 - Does the design tool enable visual perception analysis?	2.0
3 - Is the interface designed to assist users with disabilities?	2.0	4 - Does the design tool allow crowdsourced inputs?	2.5	3 - Does the design tool allow environmental analysis?	2.0
4 - Are there explanations on how to use them?	2.0	**COMPREHENSIVE INFORMATION**		4 - Does the design tool provide economic evaluation?	2.0
5 - Are there hotkeys for expert users?	2.0	1 – Is there comprehensive information for the community?	2.5	5 - Does the design tool offer design exploration of multiple alternatives?	2.0
RESPONSIVENESS (Feedback)		2 - Is there comprehensive information for clients?	2.5	**DESIGN OPTIMISATION** (Design Process: reasoning or solving problem)	
1 - Is there feedback for every user action?	2.5	3 - Is there comprehensive information for investors?	2.5	1 - Does the design tool offer any type of optimisation?	2.5
2 - Is there feedback in minor actions?	2.5	4 - Is there comprehensive information for designers?	2.5	2 - Does the design tool allow multi objective optimisation?	2.5
3 - Is there feedback in major actions?	2.5	**GENERAL INFORMATION**		3- Does the design tool provide more than one near-optimal solution?	2.5
4 - Is there visual feedback?	2.5	1 - Does the design tool address social information?	2.0	4- Does the design tool transparent regarding the method or mixed methods used in the optimisation, such as algorithms, and criteria.	2.5
ADAPTABILITY (Cohesion, Reduction of Short Term Memory, Error Prevention, and Action Reversal)		2 - Does the design tool deal with behaviour information?	2.0	**INTEGRATION** (Design Process: import, export and integration with other CAAD and analysis tools)	
1 - Does the interface offer an "undo" option?	2.0	3 - Does the tool gather environmental information?	2.0	1 - Is it possible to import projects?	2.0
2 - Does the interface record actions?	2.0	4 - Does the design tool address perception information?	2.0	2 - Is it possible to export projects?	2.0
3 - Does the interface allow you to input invalid types?	2.0	5 - Does the design tool address economic information	2.0	3 - Is there integration with other CAAD or Parametric Design tools?	2.0
4 - Does the interface provide ways of getting back to previous stages?	2.0			4 - Is there integration with other spatial analysis tools?	2.0
5 - Does the interface save the content?	2.0			5 - Is there integration with environmental analysis or CFD tools?	2.0

4. Results

4.1. SOUT

Scout **interface design** is defined by parameter sliders, analysis toggle buttons, and a 3D viewport visualisation of the intervention. The range of the parameters is predefined by the creator of the algorithm as well as the analysis toggle button. The terminology in the prompts are identical, and the colours, fonts and capitalisation are *consistent*. Because of the simplicity of the interface, there are no exceptions, menus or help screens. Regarding its *usability*, the interface is easy for novice users, however, it does not offer advanced customisation options or hotkeys for expert user neither does it offer support to assist any disabilities. The *responsiveness* of *Scout* is only related to its minor action feedback. The interface *adaptability* regards its ability to record actions, accept only valid inputs and save content.

Analysing the **data-driven flow** criteria, regarding its *interoperability*, *Scout* has a common file format to save the geometry (three.js) that could be read by other platforms or software, allowing the exchange of data. Also, the file type Three.js is based on an open standard. The *collaboration* is related only to its workflow among different stakeholders, lacking real-time collaboration for a specific project, community feedback or crowdsourced inputs. Regarding *Scout comprehensibility* of the information among the different stakeholders, it is clear and comprehensible among all stakeholders (community, clients, investors and designers). In the demo version, *Scout* manages social, environmental, perception and economic information.

Scout's **design process**, regarding its *design generation*, *Scout* supports parametric control of urban elements and allows design alternative generation. In terms of *performance evaluation and decision-making*, *Scout* supports analysis tools of social, perception, environmental, and performance and offers design exploration of multiple alternatives. *Scout* does not have embedded *optimisation* algorithms. Regarding its *integration* projects can be imported and it is integrated with Rhino3D-Grasshopper allowing other analytical tools to be used through the predefined algorithms. However, there are no ready-to-go functionalities to export projects.

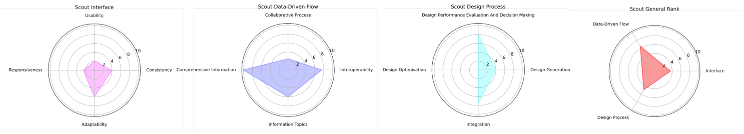


Figure 2. Scout Analysis.

4.2. DIGITAL BLUE FOAM

The *Digital Blue Foam* **interface design** is based on small icons, distributed around a circled toolbar, rather than on menus. The *terminology* is identical in the prompts and help screens. The visualisation of urban elements is schematic but *consistent*, clear and coloured. Regarding its *usability*, the generation of buildings is faster and automated, however, it is not possible to ensure that designers have systematic parametric control of building generation. *Digital Blue Foam* does not have advanced customisation options and hotkeys. Neither does it assist users with disabilities. The *responsiveness* relies on its visual feedback. Respective to its *adaptability*, it has an 'undo' option, it records actions, it is reversible for previous stages and saves the design content.

The first concept of **data-driven flow** criteria is *interoperability*. *Digital Blue Foam* is based on a common file format (three.js), allowing the exchange of data and is an open standard. Regarding its *collaboration*, workflow among different stakeholders is the only achieved sub-criteria. Nonetheless, all the criteria for *comprehension* of the information among the different stakeholders were reached.

Digital Blue Foam manages environmental and economic information in the demo version.

As for **design process** on *design generation*, *Digital Blue Foam* allows multiple design alternatives generation, supporting modification of objects and promoting creative thinking. Moreover, it allows to easily set up a mix of building functions (residential, commercial, office, leisure and education) through the Program Mixer toolbar. On *design optimisation and decision-making* it includes environmental, i.e. solar radiation and a wind rose and, and economic analyses, i.e. gross floor area (GFA). *Digital Blue Foam* does not have any *optimisation* algorithms. The *integration* in this tool meets all the set of sub-criteria. It is possible to import and export projects as well as exporting the design to other CAD tools through the SLT extension supporting posterior analysis.

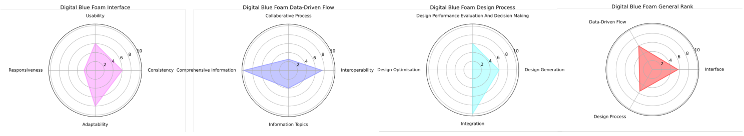


Figure 3. Digital Blue Foam Analysis.

4.3. GIRAFFE

Giraffe **interface design** is based on Mapbox which enables site search, exploration of surrounding areas and accessing geospatial data, e.g. existing street network, blocks, plots and buildings volumes. The interface *consistency* meets all criteria. Regarding its *usability*, it offers thorough explanations and is manageable for novice users. However, it lacks advanced customisation features or hotkeys. Regarding its *responsiveness*, *Giraffe* offers feedback for major actions and visual feedback. On *adaptability*. *Giraffe* records actions, does not allow inputting wrong parameters, provides ways to get back to previous stages and saves the design content.

On **data-driven flow** criteria, regarding its *interoperability*, it is based on three.js as well, which allows data exchange. Regarding its collaboration, workflow among different stakeholders in the only met sub-criteria. The comprehension of the information among the different stakeholders attends all criteria. *Giraffe* manages social, environmental, perception and economic data.

On **design process**, *design generation*, it meets all the defined criteria as well as those for *design performance evaluation and decision-making*. However, it does not include any *optimisation* algorithms in the native tool. Regarding its *integration*, *Giraffe* also attends all criteria.

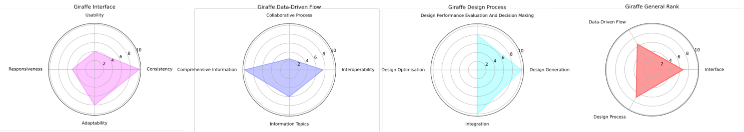


Figure 4. Giraffe Analysis.

4.4. SPACEMAKER

SpaceMaker **interface design** meets all the sub-criteria regarding its *consistency*, *responsiveness* and *adaptability*. As for its *usability*, it offers a set of tutorials on how to use the tool and is easy to understand even for beginners.

On **data-driven flow** criteria, regarding its *interoperability*, as the other tools, it is based on three.js, meeting data exchange and open standard. It also has a high level of *comprehension* among all involved stakeholders. *SpaceMaker* manages social, environmental, perception, and economic information. However, the only criterion met under *collaboration* was workflow among stakeholders.

On **design process**, regarding *design generation*, *SpaceMaker* meets all criteria. Under *Design Performance and Decision Making* the tool enables visual perception, environmental, and economic analyses and allows the exploration of multiple design alternatives. *SpaceMaker* was the only tool of those analysed that had *optimisation* algorithms embedded into its default platform. However, it does not allow multi-objective optimisation. Furthermore, it does not state what optimisation algorithm is being used, working as a black box for the users. Finally, in the demo version, projects cannot be imported. However, all the other sub-criteria are met for *integration*.

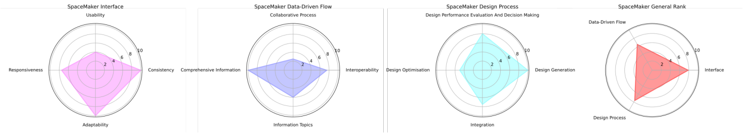


Figure 5. SpaceMaker Analysis.

5. Conclusion

This paper critically reviews urban design cloud-based and data-driven tools according to key evaluation criteria of interface development, data-driven flow and design process to understand how they can contribute to an integrated and holistic design of sustainable smart cities. In addition, the paper has introduced a conceptual framework for approaching smart cities as layered and time-dependent entities, with a focus on an urban design approach, to embed ICT in the occupation and networks layers. As can be seen, various cloud-based and data-driven urban design tools such as *Scout*, *Delve*, *SpaceMaker*, *Giraffe*, *Archistar.ai* and *Digital Blue Foam* have recently emerged as a direct impact of advances in generative design techniques and machine learning, a subset of artificial intelligence, that has contributed significantly to the automation and efficiency in the urban design process. These tools offer the ability to generate, evaluate, and optimise urban models from the early stages of design. They aid architects, planners and stakeholders to save resources, time and money, as well as to find optimal design solutions. Moreover, they promise to empower designers to design smart cities and neighbourhoods. Despite the potentialities of these new tools, a more holistic approach is still needed which should comprise social, environmental, and economic aspects, as well as behavioural and visual perception aspects of urban issues regarding the urban design interdisciplinary. Through this study, it has become clear that there has been a larger effort to develop novel tools instead of concentrating on improving their comprehensiveness. This will be crucial in further developments in order to make these tools more widely applied for urban design education and practice. Only then will this type of technology be able to achieve an impact on the more persistent urban layers and imprint a long-lasting, socially improving effect and steer cities into a smarter future from the bottom-up. However, this study is limited to the evaluation of demo versions of these tools, since the access to the full versions is still limited in most cases. The demo versions contain most of the features of full versions, but in most cases, there are resources only offered in the full versions. For instance, Giraffe offers integration with other microclimate analysis and parametric design tools which is available in its full version. A possible future step for this research is to evaluate full versions and consider more tools that were not included in this study. Furthermore, studies that apply these tools in teaching environments are needed to objectively evaluate their impact on the design process.

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