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Exploring data-driven design in landscape architecture

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Abstract
Currently, technology is growing exponentially, and with rapid urbanization, vast quantities of data are generated by the urban environment that is more spatial than before. Cities and ecological linkages become more complicated, and as the quality of the urban environment is determined mainly by how the data is used, the capacity to deal with data is becoming increasingly important in design processes and protocols. Therefore, this paper aims to introduce the data-driven design approach and distinguish the existing projects in landscape architecture based on their input and output types. Besides, it contributes mainly to bringing together the existing information in this field. The literature review process was applied to conduct potentially relevant literature on the research topic. Then, the existing projects were identified and reviewed. As the primary research outcome, most of the reviewed data-driven projects in landscape architecture received input data from environmental or human sources. At the same time, only 16% benefited from a mixed combination of environment and human-sourced data. Besides, only about 35% of the existing projects had adaptive or performative outputs, the most desirable characteristics towards environmental progress, while most were interactive. Although these projects are still in their early stages, this article illustrated the potentials of data-driven design to boost landscape performance in many ways. By unifying projects under a single framework, data-driven design can benefit more.

Keywords
Adaptive, Data-driven design, Interactive, Landscape architecture, Performative.

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1. Introduction

Technology is growing exponentially, and we have reached the "fourth industrial revolution" that deals with automation, sensing, and scanning (Melendez et al., 2020). With the presence of sensors, smart meters, social media, and mobile phones, vast quantities of more spatial and urban data are being generated in the physical environment. It has fundamentally changed our understanding of the environment and shaped our relationship with cities and the techniques we design architecture, urban, and landscape systems. Thanks to the development of these data collection techniques, we can monitor and detect even subtle changes in the environment in real time, including light, sound, temperature, energy consumption, traffic flows, pollution emissions, and communication flows. However, greater data volume only sometimes implies meaningful information (Fricker & Münkel, 2015), and the quality of the environment in which we live will be determined by how we use that data. Without any application or a critical eye, data is entirely worthless. The approach by which we gather, evaluate, and apply data matters the most. Data would be beneficial if we could interact with the information by seeing, hearing, or touching when the environment becomes a massive interface for transmitting data. When properly implemented, these environments can make our lives more pleasant and accessible and reduce resource consumption. In fact, in these environments, wireless sensor networks, transceivers, and physical actuators are combined with information systems to offer places where humans and the environment interact.

Indeed, how to better serve everyday life by embedding information and knowledge into surroundings through real-time interactions between natural or artificial environments and people has been a significant topic for data-driven design in the previous decade. Achieving this ideal infrastructure means using data productively (Batty et al. 2012). The premise is that data-driven design should create a feedback loop from concept to implementation and use (Bier & Knight, 2014).

Besides, rapid urbanization and city connectivity have resulted in increased data generated by the urban environment. Today, for the first time, we have more data than we need (Carpo, 2017). This massive amount of urban dataset has the potential to be a beneficial tool when it is made available to the public. Representing urban data or data having a contextual connection to the surrounding environment within the public, the physical environment of a city has the potential to share meaningful information with residents. This mode of transmitting information boosts our understanding of the environment and acts toward a more qualitative and environmentally sustainable urban neighborhood (Moere & Hill, 2012). This issue holds great significance because cities nowadays encounter the problem of the urban space, which is unpleasant and does not encourage residents to engage in activities and environmental changes.

2. Data-driven design

The development of data usage in design results from technological advancements that allow data to be gathered, measured, and evaluated in various ways. However, designers have always utilized data, even without being aware of it. Data of various types and sources have always been used in the design processes (Melendez et al., 2020) that enhance the design process's efficiency and meet user needs.

These data can originate from various sources: humans, senses, likes and dislikes, political views, medical records, Earth, the environment, climate, geography, oceans, companies and organizations, revenues, stock rates, and countries.

Today, although using qualitative and quantitative data (Babich, 2017) in design disciplines, architecture, the arts, and urban studies, is becoming increasingly important. How to define data-driven design is still up for debate. According to Speed and Oberlander (2016), the relationship between design and data may be approached in three different ways: "design from data", "design with data", and "design by data". "Design from data" refers to systems designed by designers inspired by measurable characteristics of the context. These designers employ various techniques to collect social, technological, and environmental data, including interviews, user observations, ethnographic methods, and contextual mapping. At the same time, design with data refers to systems designed by designers who consider data flow through systems combined with the ability to preserve and promote human values. While these methods primarily collect data and report from sources before analysis, easy access to ubiquitous computing technologies allows researchers to link with a participant or community to understand better how data-centric prototypes, products, and services affect the user. This paradigm is referred to as one in which it is possible to "design with data" because information may flow in several directions.

On the other hand, "design by data" refers to systems that are built by other systems, not designers. Vast margins of autonomy and morphologies regulate them to create information. The final area is the possibility that data, with the help of an algorithm, would become a designer.

This paper is concerned with the "design by data" category in which the input of data is generated by computational platforms like microcontrollers, environmental sensors, or virtual models and then processed and returned as output data by virtual models or actuators, which are mechanisms that operate physical devices like servos, LED lights, motors, and valves. The ability to enter input and generate a response provides the potential for responsive systems (Melendez et al., 2020) that enable real-time interaction between natural or artificial environments and users (Bier & Knight, 2014). This process consists of sensing, processing, visualizing, and feedback phases. Indeed, this concept of data-driven design is loaded with unintended ambiguity. However, vagueness can be beneficial in allowing various and competing notions to evolve (Senagala, 2006). Data-driven design covers a broad scope of subjects because the projects involve adaptability, responsiveness, and interaction through various protocols and scales, always giving a framework for data to be altered and activated as a type of exchange.

2.1. Scope and definitions

Data-driven design refers to a system comprising two or more entities that communicate with one another through data exchange. This system operates responsively, adaptively, performatively, or interactively through the utilization of smart systems. However, the distinctions between adaptive, responsive, and performative techniques in design research still need to be clarified. Several definitions exist in the literature for these concepts, and they have been used loosely and interchangeably among professionals (Barozzi et al., 2016). In order to clarify the use of these terms, the authors suggest general definitions listed in Table 1.

Adaptive techniques have long been popular in design to address sustainability and efficiency issues. They can be as essential as doors and window shutters that allow occupants to make temperature and airflow changes as needed. The main aim of adaptive systems is to make design more responsive to residents' daily requirements (Kalantari & Ghandi, 2017). On the other hand, the term responsive was first coined by Nicholas Negroponte, who pioneered the use of digital technology in the area of architecture in 1975, when spatial design challenges were first being studied, owing to breakthroughs in cybernetics, artificial intelligence, and digital technologies (Kolarevic & Parlac, 2015). Indeed, while adaptive systems deal with problems with multiple variables, responsive systems respond to individual problems. Adaptive is a much broader notion than responsive, since it aims to maximize function and waste reduction (i.e., energy usage and material resource availability) (Al-Obaidi et al., 2017). Hereafter, the term "responsive" is taken as "adaptive" for ease of use.

According to Al-Obaidi et al. (2017), two main adaptive approaches exist: adaptive behavior based on the motion

Table 1. *Definitions of the terms.*

Term	Definition	Source
Responsive system	"Responsive means that the environment which has an active role, initiating to a greater or lesser degree changes as a result and function of complex or simple computations".	(Negroponte, 1975)
	Refers to a system moving and responding from the outside based on specific factors, thus allowing interaction with a passive environment.	(Hasselaar, 2006)
	Refers to the control of environmental conditions with the use of computational algorithms, thus allowing a system to learn new concepts while educating the occupants.	(Brown & Cole, 2009)
	A system with the objective of physically reconfiguring themselves to meet changing needs with variable mobility, location or geometry.	(Pesenti et al., 2014)
	A process of feeback, a conversation between two actors.	(Cantrell & Holzman, 2015)
Responsive landscape	The environment that combine sensor networks and actuators to provide interest, beauty, comfort, and engagement for visitors, occupants, users. These sensor networks typically are controlled by some central or distributed set of algorithmic and logical (or perhaps random) controls, that generate the outputs and thereby the perceived sensation(s) of the place.	(Ervin, 2018)
Adaptive system	The ability of a system to adjust by itself in relation to a changing environment. An adaptive system, as in the case of building skins, has the ability to adapt the features, behavior or configuration of the external environment.	(Dewidar, 2013)
	Refers to a morphogenetic evolution and real-time physical adaptation of a design in relation to its surrounding environment.	(Al-Obaidi et al., 2017)
Performative system	Refers to systems that can mediate surrounding environment for user comfort.	(Turrin et al., 2012)
Interactive system	Systems with mutual or reciprocal action of influence to external stimuli.	(Ahmed, 2018)

that changes the structure by sliding, folding, creasing, expanding, rolling, hinging, fanning, inflating, rotating, or curling, and adaptive behavior based on material characteristics that directly change a material's internal structure, such as light reflection or absorption properties, or energy transfer from one form to another.

Additionally, according to Ahmed (2018), the difference between interactive and adaptive systems is that in interactive systems, users are permitted to take their path through the content, while in adaptive systems, users may enter their content and control how it is employed.

2.2. Data visualization

Our sensory-motor system allows us to interact with our surroundings. Specific senses are aroused due to the contact between our bodies and the items in our surroundings. We can see, hear, touch, and smell the tangible creatures around us. However, we require external "interfaces" to interact with digital information in the digital world since digital entities have no physical representation. Data visualization provides an appropriate mode of interaction with digital technologies (Tahouni, 2018).

Despite being fundamentally multidisciplinary, data visualization has a solid academic foundation and tradition in computer science, where the earliest computer-mediated data visualizations emerged from the study of computer graphics (Swackhamer et al., 2017). Data visualization helps a wide variety of users to grasp information hidden inside the data (Hosseini et al., 2019). Data is often represented in abstract forms in data-driven contexts to enhance understanding. Visual representations of information can aid memory, make abstract concepts visible, support problem-solving and decision-making, and make the analysis of large datasets more efficient (Myatt & Johnson, 2011).

Data may be represented in a variety of ways. While using numbers and graphs to represent data is a beneficial technique because it requires little display space and it is simple to comprehend (Consolvo et al., 2014), the use of metaphors to represent data is believed to be more engaging, inspiring, and simple to understand (Lin et al., 2006). Data representation using text, play elements by gamification techniques, and data sculptures that are defined as "data-based physical artifacts, possessing both artistic and functional qualities that aim to augment a nearby audience's understanding of data insights and any socially relevant issues that underlie it" (Zhao & Vande Moere, 2008) are among the categories of data visualization. These data are transformed into a physical form and released into the physical environment as a tangible representation of the action (Khot et al., 2020), called physical visualization. Physical media can be felt, and its physical features, such as shape, texture, temperature, or weight, may all be used to depict different parts of the received information.

In contrast, standard computer representations cater primarily to visual senses. Data physicalization has expanded in recent years, and it now encompasses a wide range of disciplines, including computer scientists, artists, designers, psychologists, practitioners in human-computer interaction, and many others (Hogan et al., 2020). Scientists, architects, artists, and designers work together to visualize data innovatively to spark and expose new connections, interpretations, and readings. When combined with three-dimensional space, a visualization can alter spatial perception skills. Furthermore, incorporating data into sculptures and installations can broaden the public's discovery and comprehension of crucial, complicated data (Jovanovic et al., 2016).

2.3. Sensors and actuators

Data-driven investigations are fueled by the advent of Arduino, Raspberry Pi, and other microcontroller kits, as well as rapid developments in sensors and smart materials (Khot et al., 2020). Today, data collection is supported by sensors. Sensors can be defined as devices that generate an output whose characteristics (amplitude, frequency, voltage) are in a known and repeatable scaled relationship to their inputs across a range of size and temporal scales or distinct segments of the electromagnetic spectrum or various electrical, physical, chemical, and other inputs (Ervin, 2018). Sensing technologies include visual, sound, motion, weather, human/health, Radio-frequency Identification Tracking (RFID), cellphone, Bluetooth, GPS, location, mobile, and environmental sensors.

Besides, actuators are electromechanical devices that turn a signal into a physical effect. It is the last part in a sequence of controls, which is in charge of the body's movement in line with the control system's directives. Every kind of sensor has a corresponding type of actuator. Visual actuators include lights, projectors, and displays/screens; auditory actuators include loudspeakers, bells, buzzers, clappers, and other similar devices; tactile actuators include pressure sensors, buttons, and 'touch panels.' Olfactory actuators are technically possible but have yet to be created or implemented, whereas gustatory actuators, also known as "taste emitters," are difficult to imagine. Interconnected sensors and actuators that can operate various devices and actions, from solenoids, valves, and motors to digital audio-visual and website contents, give new potential for monitoring environmental systems. This fundamental structure – sensor input from the environment; sensor output to actuator input; actuator output back into the environment – serves as the foundation for an indefinite number of response systems (Denardin et al., 2009).

2.4. Materials

Materiality is a fundamental part of the design process. Materials that demonstrate structural durability provide protection and shelter from external environmental conditions and affect our visual, haptic, and acoustic experiences through surface qualities such as textures, colors, and patterns that have shaped our built environment for centuries. Traditional and modern materials, such as stone and wood, as well as steel, glass, and concrete, have long been employed in the construction of present constructions and will continue to be used in the future. However, present socioeconomic, political, and environmental situations are putting traditional materials and production processes to the test, necessitating the development of new material research procedures in the design process. Working with materials, manufacturing, and data-driven processes to promote performance, optimization, sustainability, and circular design approaches are all part of these innovative methodologies (Melendez et al., 2020).

Current technical advances in material development give designers new options to develop new material systems and employ form-changing adaptive materials. According to López et al. (2015), four types of adaptive materials exist: temperature-reactive materials, light-reactive materials, humidity-reactive materials, and carbon dioxide-reactive materials. Temperature-reactive materials include thermo-bimetals, heat-sensitive plastics, shape memory alloys, thermochromic polymers, and phase-change materials. Light-reactive materials include phosphorescence pigments, light-responsive polymers, and photochromic dyes. The cellular structure of wood and hydrogel are among humidity-reactive materials, and CO2-responsive polymers and titanium dioxide are among carbon dioxide-reactive materials. These shape-changing materials can be integrated with other sensing materials, creating the programmable matter concept. The concept of programmable matter is closely tied to the idea of developing materials that embed computing. Programmable matter is "materials whose properties can be programmed to achieve specific shapes or stiffness upon command" (Hawkes et al., 2010). These materials differ from robotic materials. The critical difference is that robotic materials allow programmability by directly embedding electronic components and microcontrollers in the material. In other words, rather than depending on the physical qualities of materials and structures to give certain levels of programmability, robotic materials have a microprocessor that can be programmed in any way imaginable and can determine the overall behavior (Tahouni, 2018).

The essential factor is choosing the suitable material and technique to achieve the design's technical criteria. Designers must evaluate underlying material qualities while selecting an appropriate material for representations to serve the intended goal. The selected materials must have inherent performative and self-actuating capacities and the ability to respond to changing environmental conditions in real time. Along with the mentioned tangible materials, intangible materials such as air, scent, and light are the elements that can represent digital data in physical space (Khot et al., 2020).

3. Data-driven design in landscape architecture

Landscape architecture is a comprehensive discipline rooted in natural sciences, problem-solving, engineering, visionary imagination, social psychology, and aesthetic composition. The discipline encompasses various issues focusing on design and environments (Cantrell & Mekies, 2018). However, defining the goals and scope of the effect is a constant challenge for the discipline; with the current accelerating rate of urbanization, even more challenges are on the horizon. This rapid urbanization, climate change, and growing social inequity have all become significant issues that need landscape architects to reconsider the communities and make them more adaptable to changing environmental circumstances (Hermansdorfer et al., 2020).

Additionally, increasing urbanization has led to a surge of data generated by the urban environment. In this new context, landscape architects must understand the possibilities and transform how they analyze, design, and affect city policy decisions. Cities are now opening up vast amounts of data with the proliferation of data-collecting tools. Indeed, far more technology devices are implanted in our urban fabric than we realize. We are immersed in an interconnected ecosystem of ubiquitous communication infrastructures, which includes sensors, global positioning systems, automated systems, and locative media (Melendez et al., 2020). Most daily life elements are tracked and evaluated in real-time (Fricker & Münkel, 2015). According to McCullough (2013), modern city dwellers live in a constant cloud of ambient data and are always linked to digital information flows. Cities, urban environments, and ecological linkages become more complicated. As the quality of the urban environment is determined mainly by how the data is used, the capacity to deal with data is becoming increasingly important in design processes and protocols. In other words, the ability to sense, gather, and retrieve data provides landscape architects with new opportunities to make well-informed design decisions that are more responsive and adapt to residents, just like a biological creature adapts to its environment (Kalantari & Ghandi, 2017).

These applications lead to the concept of data-driven landscapes. The data-driven landscape is a type of landscape that uses the characteristics of sensors and intelligent machines to collect data and feedback about the environment. These environments combine sensor networks and actuators to provide interest, beauty, comfort, and engagement for visitors, occupants, and users (Peiyi,2019). Data-driven design concept differs from the traditional landscape design. While traditional landscapes are generally designed according to the people's will and interests and are strongly tied to the requirements and needs of the government, developers, and customers, data-driven landscape design is no longer a human product but a collaborative work of nature and humans. This design concept is managed by algorithmic and logical controls that create the space's outputs and perceived sensations (Ervin, 2018). In other words, it is based on connected input and output sub-systems.

This concept brings new forms of media, resulting in landscape installations that can be located in public spaces. Landscape installations are closely linked to the physical characteristics of a site, offering a direct response to and interpretation of a location (Kwon, 2004). Several installations have been developed in city centers, train stations, urban parks, and nightlife zones in responsive, adaptive, or interactive forms. These installations can be interactive, spatial, social, or environmental tools added to the existing design solutions in the landscape (Suurenbroek et al., 2017). Considering the crisis of the unattractive and unhealthy urban space today that does not encourage the activity of the inhabitants (Gołębiewski, 2019), having these installations in landscapes is becoming increasingly significant. In the first place, by having these installations, our designs become more responsive and gain the ability to share information within an urban environment to create the opportunity for designers and planners to create places better attuned to the people who use them. Thus, rather than the commodification of user data for profit-driven operations, landscape architects and planners can design for social interaction, human comfort, and health (Van Ameijde, 2018). The data-driven installations in landscapes provide or enhance essential human-needs-oriented services for shelter, comfort, community, and engagement, involving aesthetic, intellectual, curiosity-based, and information-motivated pleasures. They use networked sensors to enhance the primary human senses of sight, sound, and touch, and actuators that can control a wide range of devices and actions, from solenoids, valves, and motors to digital audio-visual contents that enable dynamic aspects of landscape experience, and extend the performative and expressive variety of designed landscapes (Ervin, 2018). Correspondingly, this setting enables us to perceive invisible, intangible, and multilayered environmental data.

Besides, such installations have both ecological connotations and social function that gives character, meaning, and order to the environments that lack identity or give expression to shared meanings and forms of use; they make places more recognizable and appealing. Due to varied users ' differing rhythms, they can function as a linking component in places that take on a different character at different times. Various responsive installations encourage people to participate and engage with the installation and other visitors, or just view them from afar as spectators. These responsive installations encourage certain 'dramaturgies' and significantly impact the nature of all or a portion of the public area (Suurenbroek et al., 2017). They can also encourage interaction among visitors to a place, help people with personalizing their experience of a place, and finally help reinforce the public domain qualities of public spaces. These installations simply draw people out of their bubbles.

However, the study of how responsive technology could be employed in spatial designs to assist in activating public places is still in its early stages (Cantrell & Holzman, 2015; Ratti & Claudel, 2016). Similarly, landscape architecture needs a better track record of accepting new technology paradigms and needs to catch up to related disciplines in adopting innovative techniques and tools (Cantrell & Mekies, 2018). Indeed, the main problem for the industry is to gain from developments in computer science and other related fields in order to correctly identify and evaluate reliable data before integrating the results into a dynamic and adaptive system for landscape architecture (Schwab, 2016) that responds to human needs and emotions deduced from data. Hence, landscape Architecture must evolve from being a passive vessel for humans and their actions to an organism that interacts independently with our minds and needs and ensures the best possible response to the environmental conditions.

4. Method

This paper aims to give landscape architects a clear image and guidance on how data can be used or adjusted in physical urban projects rather than conceptual design phase. After extracting essential knowledge about data-driven design, a systematic literature review approach was carried out in order to provide an overview of the state-of-the-art of existing data-driven landscape architecture projects. A combination of academic databases, including Elsevier (Science Direct), Google Scholar, ResearchGate, and Scopus, have been used. The string of keywords and combinations employed to identify pertinent studies are: computational design, responsive, adaptive, interactive, performative design, landscape architecture, architecture, data-driven design, and smart cities. These keywords were extracted based on the initial screening of the data-driven design concept. Additionally, not only further searches were performed by combining the keywords, but also a reference list of included studies was examined for potential sources. While publications from any timeframe were considered, the focus was on recent studies to capture the latest developments in the field. Besides, to complement the academic search, an online exploration of projects was undertaken. Key websites such as Archdaily, Dezeen, and Designboom were searched using relevant keywords to identify contemporary examples of data-driven landscape architecture. Criteria for case selection were to find projects that relied on computational processes to translate the input data as an abstraction to various configurations within urban ecologies.

5. Case studies

Landscape architecture projects that use a data-driven design process have a data input that initiates the activation leading to system changes or output. According to our findings, input data can be obtained from environmental or human sources or a combination of both. We also found three categories of focus for the data output: adaptive, performative, and interactive (Figure 1). These terms were defined previously in Table 1. These projects mainly engage performance, adaptation, and interaction through a range of protocols and scales based on smart systems and provide a computational framework for data to be manipulated and triggered as a form of exchange.

5.1. Environment-sourced inputs

Projects employing information conveyed through the environment include data from ambient sound, weather data, ambient temperature, soil moisture, and air quality.

First and foremost, various projects employed ambient sound as the input; one of these examples is the interactive installation of Sonic Runway. In this installation, live sound signal input is analyzed and converted into light patterns based on the sound speed (Sonic Runway, 2017). The project uses LED-lined arches to visualize the speed of sound. Lightweave (FUTUREFORMS, 2018) is another interactive installation that translates ambient sounds into dynamic light patterns and auroras. Sound events in the surrounding vicinity of the installation often range from 50dB+ to 100dB+. Future Forms employs this project, previously known as Future City Lab. It is located under a pedestrian tunnel in Washington, DC, and aims to investigate if urban environments can become sentient participants, which can turn neglected voids into immersive spaces. Likewise, Sonomorph (Hildonen, 2011) is an adaptive installation made of nickel-titanium alloys (Nitinol) with shape memory properties that absorb sound and emit light by opening and closing cells. It is a research collaboration with Cornell University that functions as an augmented physical environment and engages people in a playful, dynamic context. Sonomorph cells are made of aluminum outer panels and glass-reinforced plastic inner panels with multiple sensory devices, servo motors, and LED lights. Infinity Field (SOFTlab, 2024) is another interactive installation that receives sound input. It encompasses fifty vertical mirrored chambers with a random distribution that provides a forest-like arrangement of shifting reflections for visitors while passing through the mirrors. Mirror Mirror (SOFTlab, 2024), another similar installation by the same lab, is programmed to respond to sound by producing light, allowing visitors to engage with the artwork and influence its appearance through their voices and bodies. Finally, Lightswarm (FUTUREFORMS, 2014), an interactive light installation applied to the façade of a building, investigates how buildings can become informative and dynamic urban interfaces that respond to data. Real-time data is collected from the building lobby and the surrounding city by sound-sensing spiders attached directly to individual glass panels in the lobby. These sensors provide data into a swarming algorithm, which coordinates the flowing light patterns to create an artificially intelligent installation that can sense, compute, respond, and interact with its surroundings.

On the other hand, the Infiltration Garden (Ervin, 2018) is a performative installation that represents the ambient temperature and the soil moisture with a weather sensor, algorithmic control, and colored LEDs in custom sculptural stainless-steel holders. The light flickers when rainfall penetrates the gardens. Moreover, the colder the temperature, the more intense the glow from the LED lights.

Air quality is another important environmental factor used as input data in Datascape and Living Light (Cantrell & Holzman, 2015). Datascape is a multi-component framework that brings forward hidden information to fight for environmental justice and address air quality issues. The framework contains five major components: a sensing system, data platform, communication platform, data visualizations, and infrastructural implementation. This system stores environmental data collected by the Bay Area Air Quality Management District (BAAQMD) and air sensors across West Oakland. Pollution con-

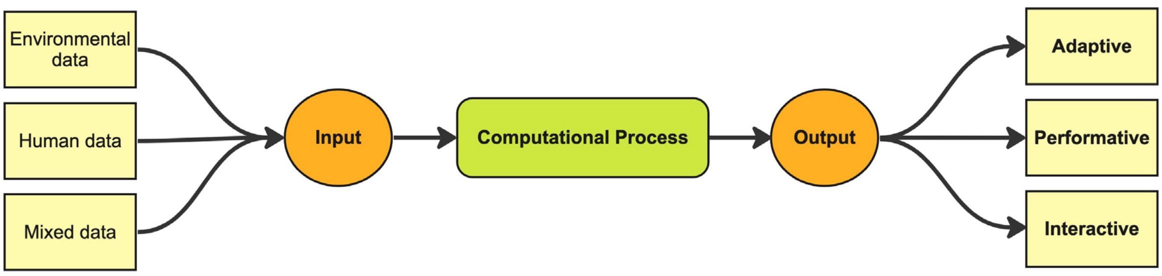

Figure 1. *The data-driven design process in landscape projects.*

centrations (PM2.5, PM10, DPM, and Ozone) can be measured in real-time using sensors and geo-tagged locations. An Air Quality Index (AQI) color range, as well as a monochromatic color palette, is developed, and a link between real-time data and time interval coordinates based on data given by one central monitoring tower in West Oakland is developed by using Grasshopper parametric modeling. The final interface highlights emission sources, while other essential components like a compass and weather information help users absorb their surroundings even more. Users will learn to read their surroundings based on these color and visual clues to air quality over time. Living Light, on the other hand, is a pavilion in Seoul, Korea, that uses a real-time light map to show air quality. Using community air quality monitoring data, Living Light establishes a link between individual communities and the invisible pollution phenomenon. The pavilion produces an actual and occupiable area that projects from the local to the city scale; this connection displaces territorial environmental data and makes it understandable as an abstract depiction. Living Light, as a prototype, offers a mode of communication between architectural objects, humans, and environmental events.

Dissimilarly, Urban Alphabets (Connecting Cities, 2014) is an interactive public screen installation based on the city's topographic details. Interested people can photograph letters used in graffiti, store signs, advertising columns, and other text located across the city using their cell phones. All of these letters combine to form an alphabet, which is displayed on a public screen. The exhibit invites passersby to notice typographic elements in urban design that contribute to forming a local character. In terms of space, the installation converts a nearly blank wall into a dynamic focal point. Urban Alphabets is also a fantastic illustration of how 'urban screens' may be employed as a stylistic technique in spatial design and how actual space can be activated as an interactive background. The goal of the Urban Alphabets project is to demonstrate to residents and visitors to a specific city how remarkable and unique that city is and to urge participants to look at their city in a new light: using letters as graphic markers for a city's visual identity. Participants create their version of their city's alphabet using the Urban Alphabets smartphone app. All letters are geo-tagged and submitted to the project website simultaneously. The city's letters are used to construct the city's alphabet, displayed on the website. This application proves that smartphone applications do not have to be intended to isolate their users from their surroundings. However, it may instead create a new user engagement experience with space.

Last but not least, drone-based data-driven projects exist in the landscape. Swarm compass (Ars Electronica Futurelab, 2024) is a drone-based routing system that leads pedestrians through crowded streets. They show available or blocked routes temporarily closed due to overcrowding by changing color. Using colored lights and the dynamics of the drones' motions can also enhance a location's ambience. Indeed, Swarm Compass's fundamental concept is to navigate people using swarm intelligence and to deliver an entirely new medium in the entertainment and communication service industry. Franchise Freedom (Studio Drift, 2024) is another performative drone-based installation that examined the natural flying patterns of starlings and converted them into software mainly designed and incorporated in Intel® Shooting StarTM drones. A self-flying flock of hundreds of drones questions the human sense of freedom and social construct. It allows visitors to look at the poetic side of technological advancement and reconnect with nature. An algorithm that reacts similarly to starling murmuration was used to construct their flying patterns. Besides, the intensity and color of each drone are affected by its distance from other drones, emphasizing the group's density.

The details of each project, including input and output types, designer, location, year, and the employed technology, are listed in Table 2, and the projects are displayed in Figure 2.

Table 2. *Data-driven landscape projects with environmental inputs.*

Data-driven landscape projects with environmental inputs							
Project	**Reference**	**Designer**	**Year**	**Location**	**Input**	**Technology**	**Output**
Sonic runway	(Sonic Runway, 2017)	Rob Jensen Warren Trezevant	2017	Chengdu, China	ambient sound	addressable LEDs	interactive
Lightweave	(FUTUREFORMS, 2018)	Jason Kelly Johnson Nataly Gattegno	2018	Washington DC, USA	ambient sound	suspended stainless steel, LED latticesles	interactive
Sonomorph	(Hildonen, 2011)	Blaine Brownell	2009	LosAngeles, USA	ambient sound	aluminum outer panel, glass-reinforced plastic inner panels, servo motors, and LED lights	adaptive
Infinity field	(SOFTlab, 2024)	Softlab	2020	Bangkok, Thailand	ambient sound	mirrored chambers, LEDs	interactive
Mirror mirror	(SOFTlab, 2024)	Softlab	2019	Alexandria, USA	ambient sound	vertical mirrored surface, LED fixtures	interactive
Lightswarm	(FUTUREFORMS, 2014)	Jason Kelly Johnson Nataly Gattegno	2014	San Fransisco, USA	ambient sound	sound sensing spiders, 3D-printed light modules, addressable LED strips, laser-cut skins of recyclable PET plastic and synthetic paper	interactive
Infiltration garden	(Ervin, 2018)	Chris Reed	2018	a university campus	ambient temperature, soil moisture	sensors for light, temperature, soil moisture, colored LEDs, stainless steel holder	performative
Datascape	(Cantrell & Holzman, 2015)	Yitian Wang, Yi Liu, and Matty A. Williams	2013	West Oakland, USA	air quality	Arduino, Firefly, Grasshopper	performative
Living light	(Cantrell & Holzman, 2015)	David Benjamin, Soo-In Yang	2009	Seoul, Korea	air quality	LED lighting, pavilion panels	interactive
Urban alphabets	(Connecting Cities, 2014)	Suse Miessner	2014	Helsinki, Finland	city's topographic details	public screen, smartphone app	interactive
Swarm compass	(Ars Electronica Futurelab, 2024)	NTT & Ars Electronica Futurelab	2017	Tokyo, Japan	routing information	drones, colored lighting, swarm intelligence	performative
Franchise freedom	(Studio Drift, 2024)	Drift Studio	2018	Amsterdam, Netherlands	Starlings' flight behavior	drones, software algorithm that reacts similar to murmuration, light source	performative

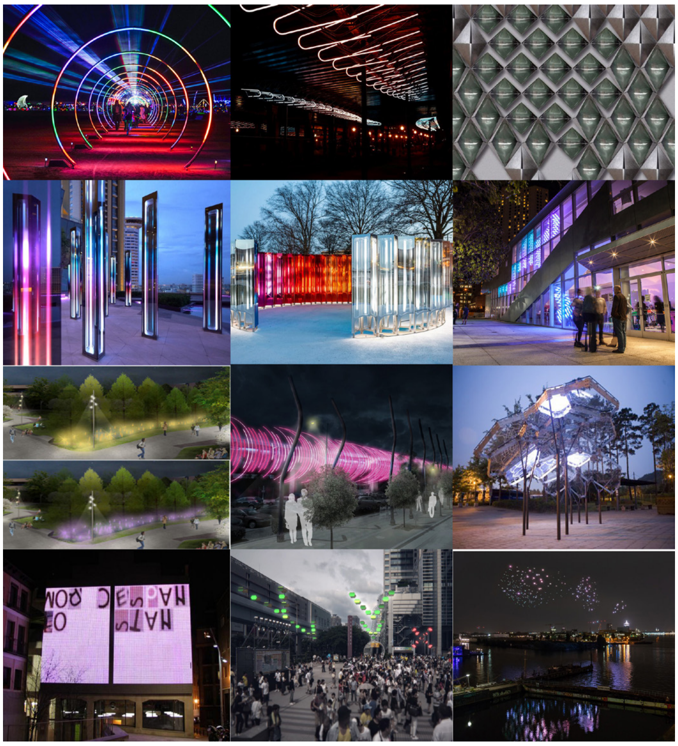

Figure 2. *Data-driven landscape projects with environmental inputs.*

5.2. Human-sourced inputs

Projects employing information conveyed through human-sourced data could vary from users' movements, touch, shadows, facial expressions, and heart rates to their plastic waste donations or their Twitter feeds.

For instance, Swingscape (Grønbæk et al. 2012) is an interactive swing installation that aims to revitalize urban environments by encouraging people to engage in outdoor activities even during the winter, join a collective activity, and let go of their usual behavioral patterns. While using the swing, the users' movement changes the project's light and sound. The installation consists of ten swings, each of which activates a different part of a more significant light and music cosmos. 2 different light zones are illuminated by different colors; variable beats are activated in the blue zone, whereas melodies are activated in the green zone. Depending on which swing and light zone is selected, the aural experience is distinct. Whereas, using a touch-and-video interface, Karen Lancel and Hermen Maat's Saving Face (Verhoeff & Cooley, 2014) project allows visitors to connect with the public in a place. When visitors stroke their faces in front of a tiny column equipped with a camera, the areas of their faces stroked are displayed on a giant screen. The picture of their face gradually fades until it is merged into a composite image of all the other faces shot up to that point. Public Face (von Bismarck, 2008) is another installation benefiting from the facial expressions of passersby. This interactive project comprises an eight-meter-tall neon smiling sculpture installed on an ancient gasometer in Berlin, a lighthouse in Lindau, and a block of flats in Vienna. Cameras across the city record people's facial expressions, subsequently utilized to calculate mood. The happier the passersby's facial expressions, the happier the city's smiling faces. The opposite also occurs: unhappy faces in the city cause the smiley's lips to close. Because of its magnitude, this artwork becomes a landmark that draws people's attention to an existing structure in the city.

Additionally, passersby's shadows are applied as valuable input for a data-driven project. Body Movies (Lozano-Hemmer, 2001) is an interactive installation that has been exhibited in cities all over the world. A seventeenth-century illustration of famous shadow plays of the period inspired it.

Passersby are urged to 'project' their shadows onto a blank wall in public by moving in the beams of a vital light source. Dune, Aviary, and ArenA Boulevard are other interactive projects with human-sourced input. The 60-meter-long permanent Dune (Studio Roosegaarde, 2011), located along the Maas River in Rotterdam, Netherlands, is a light landscape interacting with human behavior. The nature-technology hybrid comprises hundreds of strands that light up in response to the noises and actions of passing guests. Aviary (AREA C Projects, 2013) is a small-scale public installation of light poles that interacts with people's touch with light and music responses meant to be played like a musical instrument. The engagement and connection to the reaction are immediate, producing a feedback loop between the installation and the person. Next, Arena Boulevard (Suurenbroek et al.,2017), an interactive installation of LED strips based on pedestrian flows, aims to strengthen the place as a space in order to make the entire boulevard more efficient and reduce the perceived length of the route by improving the spatial quality and making the place livelier with lighting and sound, as well as improving the quality of this strip as a pedestrian passageway.

Then, Heart of the City (Anaisa Franco Studio, 2015) is a piece of urban furniture that invites passersby to sit for a while and create their own space to reflect on their surroundings. Visitors can put their finger on a sensor in the center of the couch; the installation then monitors the user's heart rate, and the LED strips in the sofa pulse in time with the heart rate. Even though individuals approach it individually, this distinctive item and pulsing light contribute to a personal experience of the place.

Contrarily, more performative projects such as Tetrabin and Northside beacons exist. Indeed, Tetrabin (TetraBIN, 2018) is a garbage bin covered with a LED screen that encourages visitors to public places to throw their trash in the trash cans. When litter is thrown into a garbage can, tetris-shaped pixels emerge, the form and direction of which are controlled by the time and shape of the binned object. TetraBIN is the first interactive receptacle with AI and IoT capabilities. It reimagines trash cans and standard information kiosks as interactive receptacles that foster suitable behavioral modifications and add joy to the mundane waste disposal task.

Similarly, Northside Beacons (Kollision, 2018) is a project for collecting and reusing the plastic waste disposed of during the Northside Festival 2018. When users threw a plate into the recycling station, they were rewarded with light pulses from sixteen enormous beacons that extended the whole 160-meter length of the festival grounds. The goal was to get more people to sort and recycle their trash. The beacons were made from a wooden base with a seat and transparent tops with individually controlled LEDs. Kollision's MAP software controls all of them linked to IR sensors within the collecting station. When not engaged by users, the installation functioned as discreetly lit navigational beacons for festival attendees to find one another.

Whereas adaptive projects such as Hylozoic Ground (Philip Beesley Studio, 2010) work like a vast lung, breathing in and out around its inhabitants. Tens of thousands of lightweight digitally manufactured components were equipped with microprocessors and proximity sensors that detected human presence. This sensitive habitat works like a giant lung, breathing in and out of its residents.

Moreover, some projects receive input from indirect human sources like Twitter feeds and wireless networks. Datagrove, Mimmi, and Immaterials are instances of such installations. Datagrove (FUTUREFORMS, 2012), designed as a "whispering wall," is made up of LEDs, speakers, and LCD monitors that are meant to depict hidden data streams from many sources as they flow through the urban environment, whispering Twitter and other social media information within a protected and quiet atmosphere. It questions the personal and immaterial experience of social media across individual devices. It starts by asking how giving physical and spatial connections to this data could shape architecture in new ways to influence social, political, and environmental behavior. Mimmi (Architizer, 2015), or the Minneapolis Interactive Macro-Mood Installation, is an iconic inflatable cloud hovering above the Minneapolis Convention Center Plaza plaza. It receives emotive data from Twitter feeds connected to Minneapolis residents and visitors to the plaza. It then uses real-time data analysis to respond to the city's input with abstracted light displays and misting.

Table 3. *Data-driven landscape projects with human-sourced inputs.*

Data-driven landscape projects with human-sourced inputs							
Project	**Reference**	**Designer**	**Year**	**Location**	**Input**	**Technology**	**Output**
Swingscape	Grønbæk et al. 2012)	Interactive Spaces Lab	2011	Roskilde, Denmark	user movements	swings, LED lights	interactive
Saving face	(Verhoeff & Cooley, 2014)	Karen Lancel Hermen Maat	2014	56th Venice Biennale	users' touch and gestures	algorithms, social media	interactive
Public face	(von Bismarck, 2008)	Julius von Bismarck Benjamin Maus Richard Wilhelmer	2008	Hamburg, Germany	facial expressions of passers-by	CCTV camera, apparatus mechanism, software	interactive
Body movies	(Lozano-Hemmer , 2001)	Rafalel Lozano-Hemmer	2001	Rotterdam, Netherlands	passer-by's shadow	projectors, transparencies, computerized tracking system, plasma screen, mirrors	interactive
Heart of the city	(Anaisa Franco Studio, 2015)	Anaisa Franco	2015	Sydney, Australia	users' heart rate	blocks of styrofoam, electric chain saw, fiberglass and resin, LED neon flex	interactive
Tetrabin	(TetraBIN, 2018)	Steven Bai	2018	Sydney, Australia	users' waste	AI, IoT, LED screens	performative
Northside beacons	(Kollision, 2018)	Northside, Martin by HARMAN	2018	Northside Festival, Denmark	users' plastic rubbish donation	wooden base, translucent tops,LEDs, Kollision's map software, IR sensors	performative
Hylozoic ground	(Philip Beesley Studio, 2010)	Philip Beesley	2010	Venice, Italy	human presence	microprocessors, touch sensors, shape memory alloy actuator	adaptive
Dune	(Studio Roosegaarde, 2011)	Studio Roosegarde	2011	Rotterdam, Netherlands	sounds and motions of passers-by	fibers, LEDs, sensors, speakers interactive software and electronics	interactive
Datagrove	(FUTUREFORMS, 2012)	Futureforms	2012	San Jose, California	Twitter feeds	text to speech module, Arduino, WiFly shield, Verizon Mifi, LCD panels, LEDs, IR sesnors	interactive
Mimmi	(Architizer, 2015)	Urbain DRC, INVIVIA	2013	Minneapolis, USA	Twitter feeds	web apps, language parsing of social media streams	interactive
Aviary	(AREA C Projects, 2013)	Höweler+Yoon Parallel development	2013	Dubai, UAE	people's touch	capacitive sensing	interactive
Immaterials	(Voyoslo, 2011)	Yourban	2011	Oslo, Norway	wireless networks	rods, LEDs, timelapse photography	interactive
Arena boulevard	(Suurenbroek etal., 2017)	Frank Suurenbroek	2017	Amsterdam, Netherlands	pedestrian flows	timelapse camera, LED strip, gobo projectors, LED screen	interactive

Similarly, Immaterials (Voyoslo, 2011) visualizes wifi networks in cities. It is based on the concept of a surveyor generating maps, offering an abstracted cross-section of the invisible networks and landscapes that are a vital part of how today's cities function. The 4m long rod contains 80 LEDs that pulse and rise in response to the power of a specified wifi network. Using time-lapse photography, the pulsating lights provide a tangible depiction of how different networks respond in their specific environments.

The details of these projects, including their input and output types, designer, location, year, and the employed technology, are listed in Table 3, and the projects are displayed in Figure 3.

5.3. Mixed-sourced inputs

Projects employing information conveyed through environmental and human-sourced data are rare; however, successful projects exist. For instance, Data Garden (Grow Your Own Cloud, 2020) combines nature and technology to interpret data better. It addresses a "new sort of data infrastructure" that creates an environment that encourages interaction and fusion between people, technology, and ecosystems. The Data Garden enables visitors to experience new materiality around data and explore a world in which data storage is green and exists as an accessible public resource that is shared among communities. It is a performative project that includes data-encoded plants. Encoding is done by transferring digital data such as text, JPEGs, and MP3s into a biological format, DNA, utilizing ACGT rather than binary. The DNA of the plants is decoded in real-time within the installation using the most advanced genetic sequencing technology and displayed in space, revealing hidden meanings. This research installation creates new options for understanding data and tackles challenges such as climate change.

Furthermore, ambient sounds plus users can provide inputs for the projects. An example of such installations is BruumRuum (Foges, 2017). Color and sound are combined in this interactive project using 522 in-ground linear luminaires implanted in a 3,300-square-meter area. Using sensors set around the plaza, the LEDs respond to the intensity of people's voices and ambient sound generated by the city. In a like manner, the "Public Sphere" (Wit & Bussiere, 2015) receives input data from ambient sound and users' touch. "Public Sphere" is an adaptive robotic kiosk that redefines a specific public space through information and interaction and re-centers the city around a publicly accessible and globally interconnected network. This project deconstructs the usual typology of an urban kiosk into playful and adaptive urban furniture.

On the other hand, Confluence (SCAPE, 2024) is a performative project depicting four critical phenomena in a park region below a bridge: water quality, fish flow, human flow, and river flow. Each phenomenon is separated and shown separately, resulting in distinct visualizations that clarify a complicated series of overlapping events.

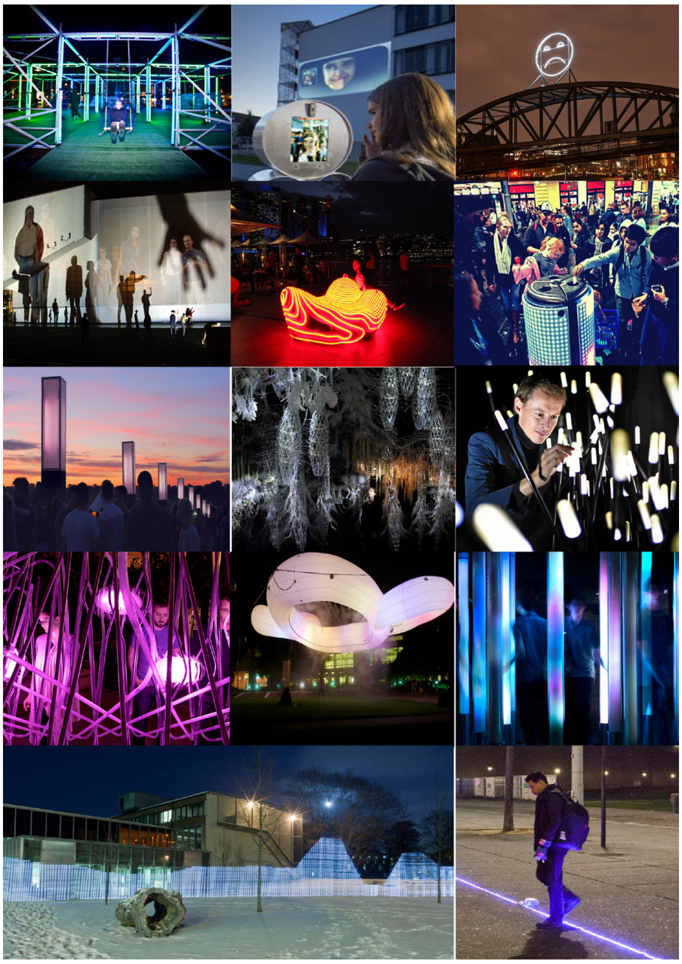

Figure 3. Data-driven landscape projects with human-sourced inputs.

Through a light field at ground level and the projection of light onto the bridge structure, the region under the bridge becomes the canvas for these visualizations. Finally, another distinctive example is the interactive space called Weather Report, which is a site-specific installation that represents both the quantitative data of weather information within sixty years of recorded history, including temperature, rain, snow, wind, and cloud cover, and the qualitative and subjective weather data from the memories of users on specific dates in the past (Swackhamer et al., 2017). In this installation, data is presented by more than 800 miniature balloons that are suspended to form two walls and can be touched in an attempt to make scientific data on. The depicted projects affirm that when input data is retained from a combination of both human and environmental sources, many creative processes can be applied and therefore lead to a more successful project that can be achieved in landscape architecture. The details of these projects are listed in Table 4, and the projects are displayed in Figure 4. Understandable to non-scientists.

6. Discussion

This paper presented data-driven design and its applications in landscape architecture. The study and the different examples that had been reviewed introduced a classification of these systems according to their input

Table 4. *Data-driven landscape projects with mixed-sourced inputs.*

Data-driven landscape projects with mixed-sourced inputs							
Project	**Reference**	**Designer**	**Year**	**Location**	**Input**	**Technology**	**Output**
Data garden	(Grow Your Own Cloud, 2020)	Cyrus Clarke Monika Seyfried	2020	Elsinore, Denmark	plants' real time DNA, visitors' digital data	genetic sequencing technology, nanopore sequencer	performative
BruumRuum	(Foges, 2017)	David Torrents Artec3 Studio	2014	Barcelona, Spain	passing visitors' sound, noise of the city	linked sensors, Madrix software, in-ground linear LED fixtures	interactive
Confluence	(SCAPE, 2024)	Scape/Landscape Architecture The Living	2011	NewYork, USA	water quality, fish flow, people flow, river flow	water flow sensors, LED lighting installation	performative
Public Sphere	(Wit & Bussiere, 2015)	Andrew John Wit Simon Bussiere	2015	Chicago,USA	ambient sound, users' touch	Arduino, Raspberry Pi, KUKA, grasshopper plugins like: Ladybug, Honeybee, Firefly	adaptive
Weather report	Swackhamer et al., 2017)	Daniel F. Keefe et al.	2016	Minneapolis, USA	weather data, user interaction	touch display, off-the-shelf steel tube frame, air-filled skin (gridded array of white balloons)	interactive

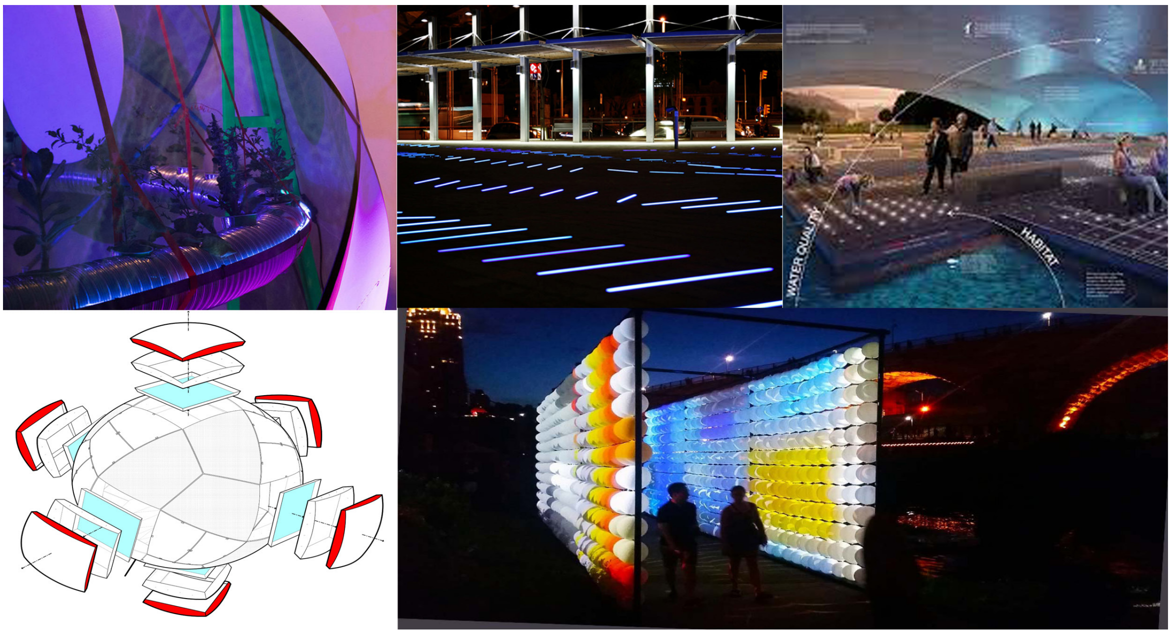

Figure 4. *Data-driven landscape projects with mixed-sourced inputs.*

and output types. As shown in Table 5, it is observed that the majority of data-driven projects in landscape receive their input data from human sources (45.2% of the existing installations) and then from environmental sources. However, only a few benefit from a combination of environmental and human-sourced data (16.11% of the existing installations) that creates the most beneficial projects to meet human needs and changes in landscape architecture. On the other hand, although adaptive and performative structures are the most efficient structures in terms of getting the best performance and the ultimate benefit from data-driven systems, it is observed that the interactive outputs receive the maximum priority while designing by data in landscape (64.52 % here). This finding, although it proved the efficiency of data-driven design in landscape architecture, highlights the area with limited focus but great potential. Thus, future research and projects need to focus on improving the performance and functionality of landscapes, while simultaneously keeping aesthetic possibilities.

Table 5. *Input and output type percentages.*

		Percentage
Input type	environmental- sourced	38.7
	human-sourced	45.2
	mixed-sourced	16.1
Output type	interactive	64.52
	adaptive	9.68
	performative	25.8

7. Conclusion

This research aimed to explore the potentials of data-driven design for various purposes of landscape architecture. After reviewing the state-of-the-art projects, cases demonstrated a variety of social and environmental contexts in which they provide or enhance landscape services. We have classified the cases based on input and output types, revealing a predominant reliance on human-sourced data and a focus on interactive outputs. Landscape architecture is a discipline that is characterized by its expansive, diverse, and fluid nature, and encompasses various elements, including art, engineering, urban design, and architecture. While most of the examined instances were solely artistic and expressive, projects existed that were focusing on functionality and landscape performance as well. Although artistic projects focused on the visual aesthetics mainly, projects with functionality had a broad spectrum of thermal comfort, acoustics, wind, shelter, climate change, etc. This finding helps us better understand Ervin, (2018) who stated that data-driven landscapes are more like "landscape art" than "landscape architecture." Yet, this article illustrated the potentials of data-driven design to boost landscape performance in many ways. Here, landscape performance refers to systems that can reconfigure themselves or mediate the surrounding environment for user comfort (Turrin et al., 2012). The novelty of this study emerges from its comprehensive synthesis and classification of the projects, which, to date, have been dispersed and not categorized. This research is regarded as a fundamental study that unifies data-driven projects under a single, input- and output-based framework. This classification provides an original viewpoint for researchers and designers to observe upcoming projects through, enabling better decision-making and encouraging creativity in the use of data-driven techniques in landscape design. To conclude, for these technologies to improve people's lives in the landscape, additional work must go into creating a system that can constantly adapt itself to suit human needs and changes in the landscapes, much like a living thing does. The landscape architecture can be improved for coming generations by bridging the gap between data, design, and functioning.

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