Adaptive Artifacts: Kinetic weather sensor, sculpture-like structure modulating sub-optimal wind conditions

P.J. Wozniczka
Entuitive Corporation

M.M. Assaqqaf
Turner Fleischer Architects

R. McKaye
The Bentway

M. Cichy
HOK

ABSTRACT: This paper introduces the ongoing research on Adaptive Artifacts, a kinetic weather sensor, sculpture-like structure that transforms with changing environmental conditions without motors by the means of passive actuation and manual rearrangement of parts by users. Movements of parts are then monitored and recorded, and predictive models improve the shape of the artifact over time. This demonstrates that adaptive, nature inspired, data-driven, digitally fabricated architecture can improve the quality of urban spaces through mitigating sub-optimal environmental conditions with focus on **thermal comfort, and wind.** The adaptive artifacts act as weather stations investigating local microclimates and understanding their impact on the thermal comfort of urban spaces. A smartphone app and a website interface let users interact with the artifact and review anonymized collected data to better understand environmental phenomena and how data is being collected. Users also submit feedback about their experience through the virtual interface and answer simple questions about their thermal comfort in the immediate surrounding of the artifact. This is a crucial step in building a viable model of thermally comfortable and engaging urban open spaces. Collected data of information exchange patterns, relationships and adaptive processes is being used in real-time to predict the most optimal spatial configuration of artifacts. It is also stored in an open-source database and will be used to support the development of future iterations of the project. Because of its open character, other designers can contribute by extending the database or using it in their own projects. This paper presents the current state of the proposed design, construction, and operation framework as applied in the development of one adaptive artifact. Ultimately this research aims to create a network of artifacts and to extend the local ecosystem of partnerships to further address the complexity of our research agenda and further contribute to building environments that are welcoming, inspiring, highly adaptive, responsive, and resilient.

1 INTRODUCTION

Adaptive Artifact (AA) is herein defined as any human made object (e.g., public infrastructure, building, sculpture, façade, etc.) that can transform over time improving its shape to mitigate sub-optimal environmental conditions. For the object to be able to operate within that paradigm it must have systems in place that are capable of: (1) Sensing the environment, (2) Interfacing with humans and other artifacts, (3) Kinetic actuation, (4) Modulating the surrounding conditions.

There is much ongoing exploration into kinetic systems and their application in structures and architecture. In "Pneumatic Textile System", Wang and Ahlquist demonstrate a seamless transformable system achieved through inflation (2016). Kim et al. (2015) demonstrate another similar precedent of soft robotics applied in architecture (Kim et al. 2015). In that example a layer of intelligence is developed through inflatable soft actuated surfaces (Wang, Ahlquist 2016). They take advantage of the levels of precision achievable through digital fabrication paired with new sensing and processing technologies (IoT). Possibly the most successful example is Ada - "the first architectural pavilion project to incorporate AI" (Sabin et al. 2020), a collaboration between Jenny Sabin Studio and Microsoft Research. Ada is a "socially and environmentally responsive structure that is interactive and transformative" (Sabin et al. 2020). Examples of architectural pavilions that are inspired by natural systems and leverage new discoveries in material sciences include works by Tibbits, Menges, Krieg, Correa, Knippers amongst others. This research investigates how to implement such structures full-scale in the context of urban open spaces to improve the quality of outdoor public spaces.

Urban open spaces often suffer from poor wind design, which creates conditions for formation of patterns of reinforced wind speed. Eddies and areas of increased winds create suboptimal conditions for residents of the city. "Thermally comfortable urban open spaces offer high-quality locations", however outdoor thermal comfort studies often reach conflicting conclusions (Lai et al. 2020). Moreover, Lai et al. summarize that "microclimate parameters such as radiation and wind have dynamic and directional features, but their dynamic and directional impact on thermal comfort has not been well investigated" (2020). *Adaptive Artifacts Project* has the potential to address problems of suboptimal environmental conditions in urban open spaces, contribute to the understanding of outdoor thermal comfort, and accelerate the full-scale deployment of AAs in public spaces.

Self-governed (Hunhevicz et al. 2021), human-centered, data-controlled entities that dynamically mitigate environmental conditions are a viable option for future architectural systems. Therefore, a rigorous prototypical investigation into how AAs can improve the understanding of outdoor thermal comfort and positively impact the user experience in public spaces is proposed.

2 Motivation and Contribution

The application of kinetic structures in the built environment remains confined to academic pavilions, expensive towers, and artistic sculptures with little long-term data about their impact on user experience. There is currently no existing application that rigorously tests a kinetic research hypothesis through an onsite deployment and a full-year cycle tracking of impact on user experience.

As described above it seems that the application of AAs to the built environment is likely to shape how physical space will be built, owned, and operated in the future. There is a need to investigate the feasibility, opportunities, and challenges for the application of AAs to the built environment.

First, a preliminary conceptualization of AAs is introduced. The conceptualization serves as an overview of areas of integration between physical and virtual, static and kinetic, human and machine, energy and matter, geometry and topology.

Second, to showcase the feasibility of adaptive artifacts, an ongoing research project, Adaptive Artifacts Wind Shelter (AAWS) is demonstrated. This is a full-scale infrastructure prototype that implements AAs regarding chosen environmental/functional situation.

3 ADAPTIVE ARTIFACTS CONCEPTUAL FRAMEWORK

To structure our thinking around potential functionalities of AAs, a preliminary conceptual framework is proposed (Figure 1). Five main elements of the adaptive artifacts conceptual framework are proposed that need to be present for the AA to integrate with the built environment fully: (1) "sensing environment", (2) parts that are capable of "kinetic actuation", (3) ability to change existing environmental conditions – "modulating surrounding", (4) "interfacing with humans", and (5) "interfacing with other artifacts".

3.1 *Sensing the Surrounding Environment*

AAs can sense the conditions of the surrounding environment. This means that they are equipped with sensors that are connected to form a network. Information collected from sensors is sent over a local internet to a central server. This information is then used to create models representing the environment, simulations, and predictions as well as to improve shape of the artifact. This information is also displayed in real-time over a user-interface (on personal mobile devices and on the internet) to inform the user about the conditions and engage them in a learning process. This data is also stored in a database representing the local microclimate as well as linked to information about the current configuration of the artifact (modulating effect). Through this setup the artifact can learn about its impact on the environment. The users can submit answers to surveys posted on the app by the artifact.

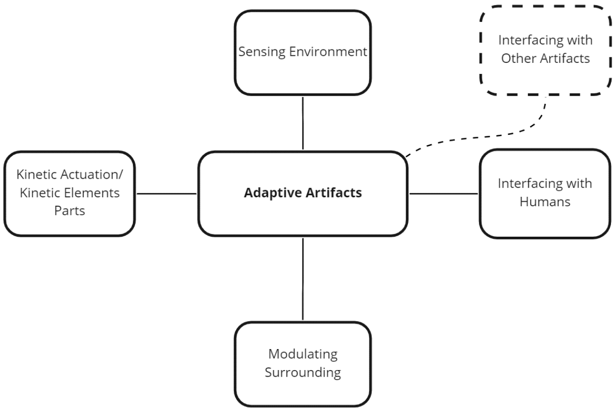


Figure 1. Conceptual Framework.

3.2 *Kinetic Actuation*

AAs are built from a set of discrete elements that are highly integrated to form a whole. Elements, as well as assemblies of those elements, can be kinetically actuated either passively or actively to change the modulating effect on the environment if modulating targets are not met. Kinetic elements are introduced as robotic end-effectors nested into the grid shell. These end-effectors can be manually or automatically displaced within the grid or swapped for another type of end-effector. This enables continuous and iterative self-improvement of the artifact (Figure 2).

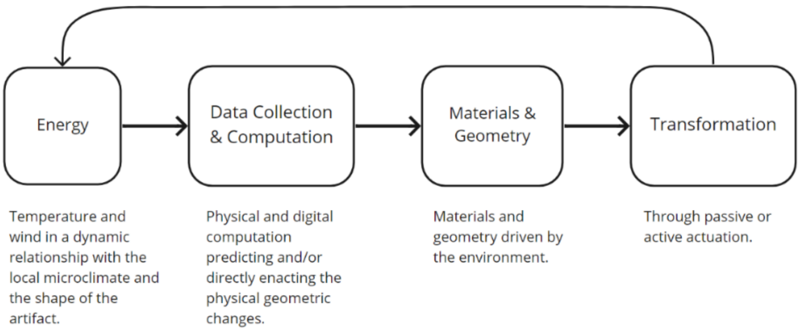


Figure 2 Iterative self-improvement.

3.3 *Modulating Surrounding*

The geometric shape of the elements and the whole that they form can impact the local conditions around the AA. Two main categories of modulation are identified: (1) functional and (2) environmental. In this paper we focus on the latter, narrowing it further to wind and noise. By modulating onsite wind conditions through our prototype, we aim to achieve improvement of outdoor thermal comfort (OTC) indicators (through models built from collected data, surveys, calibrated simulation results).

3.4 *Interfacing with Humans and other Artifacts*

AAs can interact with humans through physical and virtual interfaces (web or mobile app). AAs can interface with other AAs to create a network effect. They can strategize together and modulate their surrounding on a larger scale (local to global impact).

4 Adaptive Artifacts: first demonstrator

The first AAs demonstrator, AAWS, is an ongoing research project to build the first full-scale prototype of AAs. The focus is on creating a framework for a large-scale deployment of AAs in public spaces and deploying the first demonstrator in two phases. It can be understood as a minimum viable prototype (MVP) that will be extended and improved over time. In this paper we focus on using the artifact to modulate the environmental conditions of the surrounding area, specifically as it relates to wind and noise.

The primary research purposes are: (1) demonstration of the concept of AAs and its technical feasibility, (2) creating a framework for continuous deployment and experimentation in the realm of public space, and (3) identifying technical challenges of AAs in public space for future research.

The project is being developed through a partnership between an urban space operator (The Bentway Conservancy, Toronto), industry partners (Entuitive Engineering, HOK, Turner Fleischer Architects) and academia (University of Waterloo). The full-scale prototype is being deployed at the Bentway, an active 4-season programming and recreation space below the active Gardiner Expressway in Toronto, Canada. As both a site of active urban renewal and a catalyst for public participation in city-building dialogues, The Bentway's unique microclimate and amenities present an opportunity to investigate the project at a manageable scale, speculating on larger scale deployment in under-utilized and sub-optimal urban spaces throughout the city at large. The AA responds to site-specific environmental conditions present at the Bentway.

Adaptive Artifacts Project is aiming at a long-term investigation of existing microclimates onsite and is deployed in two phases. Phase 1: collect on-site environmental data, establish baseline, and define targets. Phase 2: deploy a full-scale artifact to the site and measure the performance of the artifact against the baseline and defined targets. Study the impact of the AA on its surrounding.

Both phases 1 and 2 collect and share data on user experience within the vicinity of the AAs correlated with changing configurations and shapes.

4.1 *Functionality*

AAWS is designed as a grid shell (an "urban skin") with a nested modular end-effectors and an array of sensors hosted onto it. It acts as a sculpture-like kinetic weather sensor that transforms with changing environmental conditions without motors by the means of passive actuation and manual rearrangement of parts by users. Movements of parts are then monitored and recorded, and predictive models improve the shape of the AAWS over time. Its shape modulates the existing wind conditions to improve user comfort in the vicinity. The patterns of modulation linked to a specific spatial configuration are then being recorded in a database.

The functionality of the artifact was chosen for several reasons. (1) The wind shelter can be built as a small grid shell-like structure that can be moved to various locations (if required). (2) The wind shelter is relatively simple to use with only one environmental metric to track and reduces the effort to think about complicated user interaction and user interface. (3) The wind shelter requires enough technical equipment to act as a convincing proof of concept. (4) The wind shelter can be replicated to create a larger field of influence.

4.2 *Technical Setup*

To connect the physical AAWS with the digital world, the proposed technical setup of AAWS is presented in Figure 1. Five primary interacting components are suggested for any AA: (1) structural grid shell, (2) network of sensors, (3) kinetic end-effectors, (4) interface with humans, and (5) interface with other artifacts. These components are needed to integrate the physical and the digital and enable the flow of information between users and machines to support a self-improving kinetic loop. The components enable playful digital exploration of potential configurations and their impact on local environmental conditions.

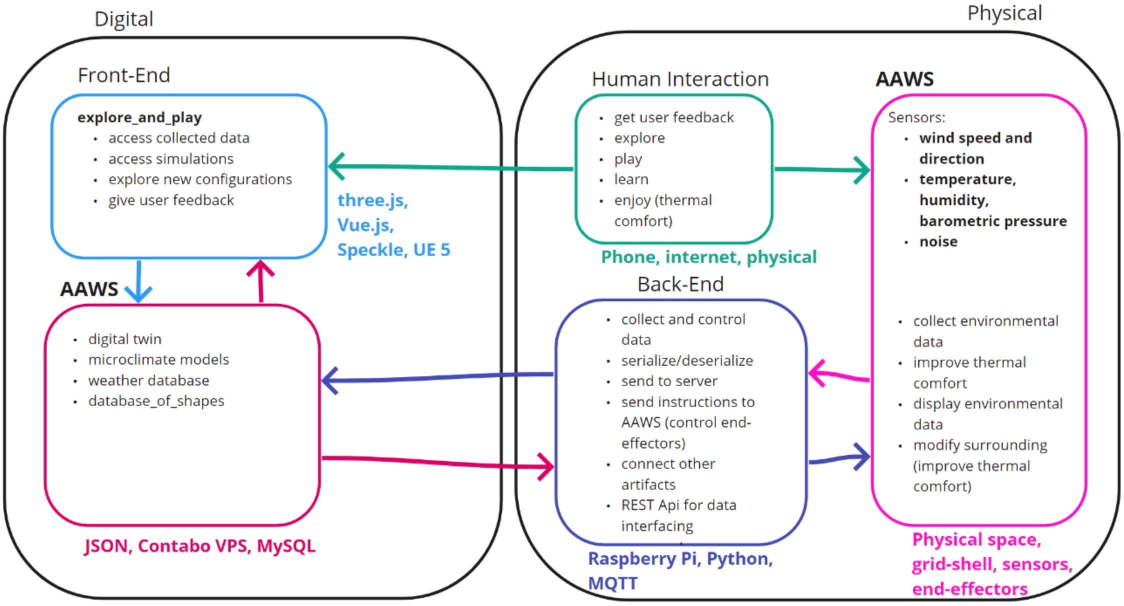


Figure 3 Technical Setup Diagram

4.3 *Environment (Local Microclimate)*

AAWS focuses on wind and noise. Phase 1 of AAWS is to create an environmental baseline of the site. Seven custom weather stations designed and digitally fabricated following the principles of AAs are deployed (Figure 1). Each weather station is built of a structural grid shell, network of sensor nodes, prototypical self-actuating end-effectors, and both human-artifact and artifact-artifact interfaces. All stations are collecting onsite weather data and AAWS is building a model of the local microclimate. At this point users can interact with the AAWS by rating their thermal comfort in the vicinity of the weather station.

Computational Fluid Dynamics (CFD) simulations have indicated patterns of reinforced wind speeds throughout the site (Figure 4). The deployed network of seven weather stations is currently building a local microclimate model to calibrate and validate the CFD results against onsite measurements. It was hypothesized that the AAWS urban skin porous membrane will act as a windbreak and will improve experienced outdoor thermal comfort (Figure 5) and extend the duration of shoulder season in a winter-dominated climate with freeze-thaw conditions.

4.4 *User Experience (Outdoor Thermal Comfort)*

“Microclimate parameters such as radiation and wind have dynamic and directional features, but their dynamic and directional impact on thermal comfort has not been well investigated” (Lai et al. 2020).

To build an accurate OTC of the Bentway the following model integrating three elements is proposed: (1) user-submitted score (OTC survey), (2) environmental computation and simulation, and (3) collected sensor data.

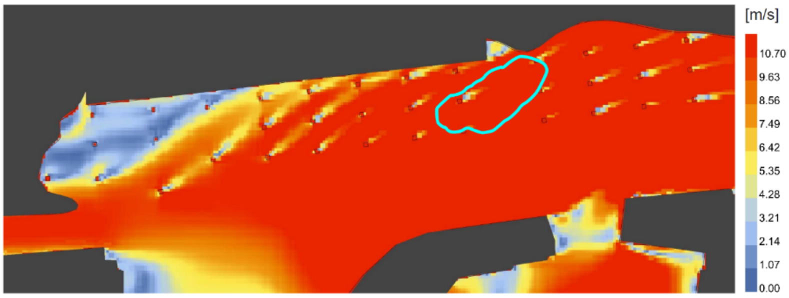


Figure 4 Baseline wind conditions with reinforced wind speed patterns.

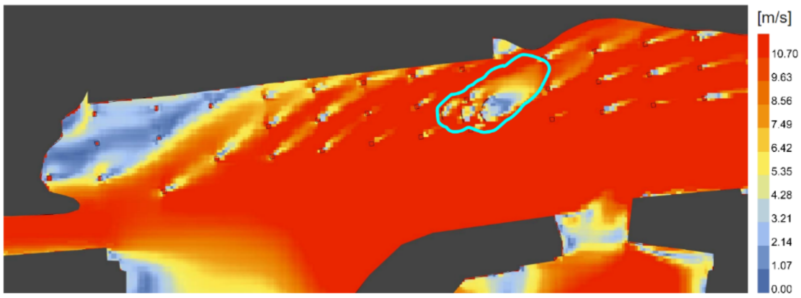
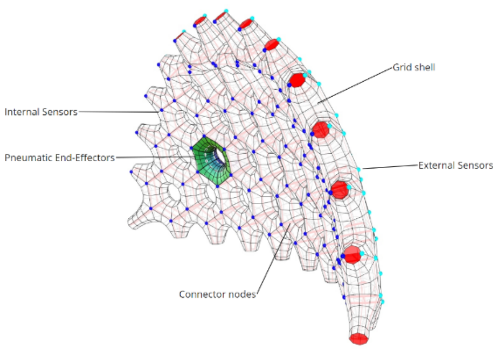


Figure 5 Hypothesis. AAWS modulating the local wind conditions.

4.5 *Structural exoskeleton/ grid shell*

The grid shell of the AAWS is its structural support system that hosts a network of sensors and kinetic end-effectors (Figure 1). Both sensors and end-effectors are attached to the shell through connector nodes. The grid shell is designed as a tessellated, modular shell that can be easily assembled. It can also be disassembled to be re-purposed and/or re-assembled to change the way the AAWS modulates its surrounding.

To support the form-finding process and to relate the form of the artifact to the form of the site (incorporate the form of the environment as part of the reward function) a series of geometry rationalizing (understanding and interpreting) routines were run on the accurate 3D model of the existing site. Kangaroo 3D© engine is used to support the form-finding process and Karamba 3D© to evaluate the structural fitness of generated design options. A detailed shell model of connector nodes is used for connection design and structural simulations are performed with Karamba 3D©. SAP2000© is used for validation. The same approach is proposed to be implemented in the design and construction of the full-scale AA modulating the environment.



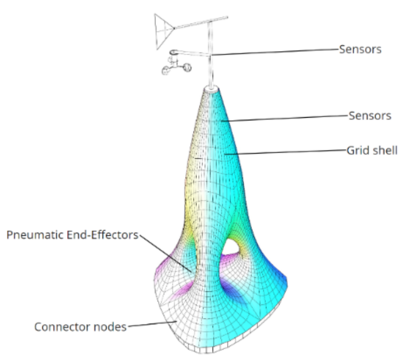


Figure 6 Rendering of the digital AAWS

Figure 7 Weather Station.

prototype with sensors, end-effectors
(highlighted green), and connector nodes.

4.6 *Network of Sensors*

For the AAWS to sense its environment and appropriately embed itself in its surrounding it requires a network of sensors that read the information about the environment.

A network of nodes utilizing AdaFruit sensors and microprocessors is developed to communicate data over an MQTT protocol. AA can measure and influence various metrics (Figure 1) but AAWS focuses on wind and noise. Recorded data is then being transferred over the local internet to a central Raspberry Pi minicomputer.

4.7 *Kinetic End-Effectors*

The main purpose of the kinetic end-effectors is to modulate local wind conditions to improve thermal comfort in the vicinity of the artifact. They are adaptive because the dynamic nature of wind calls for dynamic spatial response. Testing of various kinetic actuation mechanisms and appropriate materials is currently underway. Pneumatic actuation has the most potential for application in wind modulation. The wind is characterized by swift speed and direction changes, and high variation in the kinetic potential.

End-effectors act as extensions of the AAWS that kinetically adapt their shape to decelerate or accelerate the wind speed in the vicinity of the artifacts depending on the difference between target thermal conditions and the impact of current wind pattern on the temperature distribution around the artifact.

AAWS end-effectors are designed so that the changing kinetic energy of the wind will cause pneumatic pockets to expand or contract – closing and opening pores in the skin of the artifact.

4.8 *Interfacing with Humans*

AAWS interacts with humans through physical and digital interfaces. The physical interface includes (1) Impacting OTC of the user by modulating local wind conditions, (2) Users can manually rearrange the distribution of end-effectors to change the mitigating effect of the AAWS. Digital interface is organized into these elements: (1) user experience feedback (e.g.: impact of AAWS on OTC) (2) *"explore_and_play"* web app - digital twin solution hosted on the web, using Unreal Engine 4/5 and Speckle facilitating user interactions with the AAWS, (3) *"database_of_shapes"* - an open-source database of collected hourly weather data and associated spatial changes of the physical AAWS powered by integrative digital system leveraging open source simulation engines (energy, wind) and machine learning (ML) pipelines to help improve the physical shape of the AAWS over time and use for predictive digital models and visualization of future states.

4.9 *Interfacing with other Artifacts*

AAWS collects data from all artifacts connected to the same network and combines it to create models of local microclimates, run predictive analysis, and control individual artifacts to maximize the user experience benefit in localized nodes.

4.10 *Data collection*

The data is collected from the ESP32 by reading what is sent by the various sensors connected to the ESP32 microcontroller. The ESP32 microcontroller then packages the data in

JSON format and sends it over MQTT protocol to a specific topic that is used for sensor information collection. This data is being sent every five minutes to the Raspberry Pi, which is also connected via MQTT protocol, and it is running a small app that is listening to the topic that has the sensor information. This app then deserializes the JSON data, converts the data into SQL statements, then executes the SQL statements so that the data is stored in the database. The database is hosted on a server that holds a MySQL database. A REST API is implemented to give users an easy-to-use interface so that they can access the data in a clean, robust, and understandable manner.

5 Discussion

The presented ideas are in an early stage of development with research on the final prototype still ongoing. Phase 1 weather stations are deployed onsite. They constitute the physical prototypes, are an integral element of the conceptual framework, and are built of all systems necessary for a full-scale AA (Figure 7). The CFD analysis show the positive impact of the AA on the microclimate of the outdoor space, but these results need to be validated onsite. In the next twelve months data will be collected onsite to build a model of the local microclimate and the associated levels of OTC. In parallel to that, the development of the AAWS will continue to deploy it onsite. Phase 2 will investigate the impact of AAWS on the local microclimate, test the hypothesis and will result in more prototypes of end-effectors deployed and tested onsite. An open-source database will be created with thousands of spatial configurations and their performance metrics. This will constitute a labeled dataset and can be used by other designers and data analysts in their ML pipelines. The selected approach for evaluating the thermal comfort of users of the outdoor space is a mix of traverse field surveys and longitudinal tests (Lai et al. 2020). It could help to bridge the gap between simulations and onsite performance.

6 Conclusion

AAs could help change the way we think about comfort in public spaces. It could also help bring the full-scale scale deployment of kinetic architecture in the urban context into the mainstream.
Early research and experimentation show promising results and point toward a future where the built environment is shaped by AAs. The introduced ongoing research on AAs demonstrates that adaptive, nature inspired, data-driven, digitally fabricated architecture can improve the quality of urban spaces by mitigating sub-optimal environmental conditions. This paper summarized the early thinking to help frame the research on AAs and intends to draw attention to the possibilities and many unknowns on the topic of AAs. Future research will be guided by (1) investigating spatial configurations that can result in the highest level of OTC improvement and optimized material use, (2) optimal morphological-material systems for harnessing kinetic wind energy, (3) improving integration of physical and digital systems, and (4) investigating the distributed autonomous space models for the deployment of future AAs.

References

Decker M. 2015. Soft Robotics and Emergent Materials in Architecture. In eCAADe 2015 Real Time: Extending the Reach of Computation. Proceedings of the 33rd Annual Conference of the Association for Education and Research in Computer Aided Design in Europe. Vienna, Austria. eCAADe. 409-416.
Groenewolt A., Schwimm T., Nguyen L., Menges A. 2017. An interactive agent-based framework for materialization-informed architectural design. Springer. https://doi.org/10.1007/s11721-017-0151-8

Hunhevicz J.J., Wang H., Hess L., Hall D. 2021. no1s1 – a blockchain-based DAO prototype for autonomous space. In Proceedings of the European Conference on Computing in Construction. http://doi.org/10.35490/ec3.2021.185

Kim S., Yim M., Alcedo K., et al. 2015. Soft robotics applied to architecture. In Acadia 2015 Computational Ecologies: Design in the Anthropocene. Proceedings of the 35th Annual Conference of the Association for Computer Aided Design in Architecture edited by Lonn Combs and Chris Perry. Cincinnati, OH: ACADIA. 232–242.

Lai D., Lian. Z, Liu W., Guo Ch., et al. 2020. A comprehensive review of thermal comfort studies in urban open spaces. In Science of Total Environment 742 (2020). Elsevier. https://doi.org/10.1016/j.scitotenv.2020.140092

Latifi M., Prohasky D., Burry J., et al. 2016. Breathing Skins for Wind Modulation Through Morphology. In CAADRIA 2016 Living Systems and Micro-Utopias: Towards Continuous Designing. Proceedings of the 21st International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2016). Melbourne, Australia

Sabin J. E., Hilla J., Pranger D., et al. 2020. Embedded Architecture: ADA, Driven by Humans, Powered by AI. In Fabricate 2020 Making Resilient Architecture edited by Burry J., Sabin J., Sheil R., Skavara M. London, UK. FABRICATE 246-255.

Tibbits S. 2021. Things Fall Together: A Guide to the New Materials Revolution. Princeton and Oxford: Princeton University Press.

Wang A., Ahlquist S. 2016. Pneumatic Textile Systems. In Acadia 2016 Posthuman Frontiers: Data, Designers, and Cognitive Machines: Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture edited by Kathy Velikov, Sean Ahlquist, Matias Del Campo. Ann Arbor, MI. ACADIA 290-297.