cartOut

Cardboard architecture *4* climate challange

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This study was carried out as Eureka Research Doctorate in collaboration with the Di Battista box factory. Founded in the Marche Region of Italy in 1977, the company designs and manufactures corrugated cardboard packaging and other items. This family-run company focuses on the production of packaging and has an enlightened vision of research in which it invests time and resources. The company is very environmentally conscious, boasting eco-sustainable production and sharing the same values as the "Eduardo Vittoria" School of Architecture and Design at the University of Camerino.

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Abstract

Our cities suffer from the urban heat island phenomenon, in which climate change is reflected and amplified. Becoming aware of this and understanding how it is happening is necessary for developing a strategy to curb the problem.

Cardboard is an ancient material that has only recently been used in architecture. Today it is being rediscovered as a versatile material that can be worked quickly via digital technologies. The algorithmic study of geometries and automated processing present many avenues of research. Today's computational power allows us to insert and verify different geometries in realistic contexts in which the microclimate and its effects can be investigated.

In architecture, the use of cardboard has always implied a technological challenge in improving construction techniques to allow for temporary and permanent constructions. Architects have been interested in using this semi-finished material given its unique characteristics. It is a light, versatile material that can yield various construction solutions through the use of different techniques. Its durability has been improved over time while maintaining a low impact on the environment due to its renewable life cycle.

Today, using cardboard outdoors means solving various technological problems in an innovative way while respecting the environment and architecture has thus responded to climate change through sustainable production and realization. The aim of this research is to use cardboard to create outdoor elements capable of controlling the microclimate in built areas.

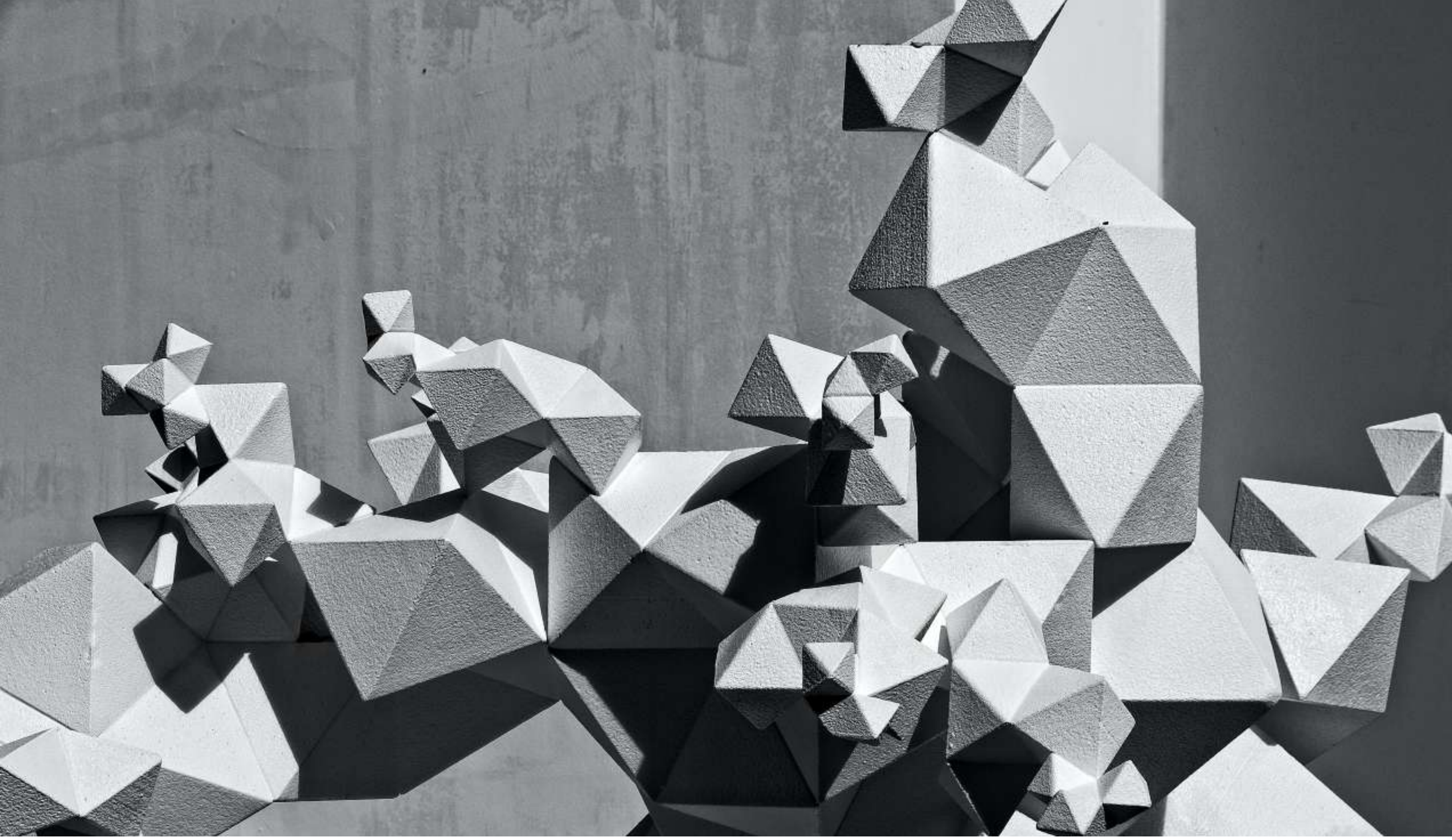
The studies made have shown how effective geometry can be in controlling the microclimate. Regenerating outdoor spaces through the use of geometrically designed cardboard elements regenerates and enriches the heritage and acting on the factors that affect comfort means improving the quality of the outdoor environment. Improving the usability of outdoor spaces is even more important in light of the ongoing pandemic, due to which outdoor spaces have gained new importance in conducting social activities.

Introduction

In recent years, climate change has changed the way architecture approaches the design or redevelopment of urban spaces.

Urban areas are growing more and more, especially in developing countries, which can lead to climate and air quality problems. In order to try to fix these issues, architects and scientists are researching ways to improve the urban environment. The increase in temperature is most pronounced in urban areas due to the urban heat island effect. This phenomenon increases air temperature by several degrees in areas with a higher density of buildings and infrastructure than in surrounding agricultural territory. This phenomenon becomes a critical factor during the hottest months of the year. The urban heat island has several adverse effects on both outdoor and indoor spaces: one consequence of the heat island is that buildings require more energy for cooling, related to climate change. The need to find new sustainable architectural solutions that provide tangible benefits for the environment is driving technological research in the application of innovative systems. The traditional view of cities is gradually changing, as environmental concerns are becoming more critical. Architects and urban planners must have much control of urban transformations, as they must now consider environmental problems. In developing countries, where there is greater inequality and anomalies in city growth, it is now recognized that urban design must be undertaken with a more multidisciplinary view. There is a need for a cultural renewal that ensures the qualities of cities in the past are not lost. At the same time, architecture as a discipline should modify and update its investigation methods, reviewing and reinterpreting the terms and parameters that have constituted reliable disciplinary support for many years.

Climate change has caused changes in society, cities, and landscapes throughout history adapted and reshaped based on new scenarios. Today, it is necessary to consider urban comfort when designing anything new, as it is an unavoidable objective. The methodology developed in the research will allow designers to manage the complexity of relationships among meteorological variables and geometric ratios that characterize the urban microclimate and technological interventions that may be necessary to modify relationships between surface permeability/impermeability albedo values and thermal fluxes. The study also addresses the empathic aspect of architecture, creating an emotional connection between people and their living spaces.



Cardboard is a lightweight, highly versatile, low-cost material with a sustainable lifecycle. It is widely used in the packaging sector, and restricting its use to this purpose is highly limiting for a material whose particular features have still not been fully expressed. Examples of Japanese and Dutch architecture have amply demonstrated how this apparently poor material can enrich many aspects of architectural elements. The experiments conducted over the years have shown the achievements and limits that this material can have when used as structural elements. There is much debate surrounding the environmental impacts of cardboard, as it is seen as a more environmentally friendly material than some others. However, it is essential to look at this on a case-by-case basis, as different types of cardboard can have different impacts. Additionally, the term "green" has been overused in marketing, so it is important to consider all the factors involved in cardboard production when assessing its sustainability. In order to create a truly sustainable building, all aspects of its life cycle need to be considered, including the materials used and the energy required to produce and maintain it.

In general, the paper industry consumes large amounts of natural resources in the production process, using energy and freshwater to impact the environment significantly. The regeneration of paper through the recycling process is strongly encouraged. Paper and cardboard are highly recyclable materials, and the process to regenerate and recycle the paper falls within the paper-production process described in 'The industrialized papermaking process'. For the recycled paper to be fed back into the manufacturing process, it must be sorted and decontaminated of non-fibrous elements such as glue, metal, and plastic residues. Depending on the production aim, a virgin component can be added to the recycled pulp to increase its mechanical resistance. The recycling limit recommended by the Confederation of European Paper Industries is a maximum of six times. The circular economy is a sustainable economic model that refers to the sustainable production of items that use as little new raw materials and energy as possible. The objective of this model is to restore the health of the system from which resources are drawn and discourage the chain of events that damage the environment on different scales, even in places seemingly far from the production site. The circular economy approach has recently featured prominently on the European political agenda, asking how economic growth can be decoupled from new resources by investing in sustainability, favouring lower CO2 emissions, and improving general environmental conditions. Effectiveness evaluation for circular economy strategies should not optimize only one part of the chain (e. g. production) at the expense of other parts (e. g. end-of-life) or unintentionally favour one category of actors (e. g. consumers) at the expense of others (e. g. waste management operators and regulators). It is necessary to go beyond a study of the impacts of the production.

The ease of production and processing thanks to automated digital techniques can now give this material ambitious but concrete objectives, such as the possibility of creating outdoor devices for controlling the urban microclimate. The scientific literature confirms the relationship between the geometry of the built environment and the microclimate and tries to respond by keeping the research at the urban scale without detailing the micro-geometry (Bonamente et al., 2013; Lee and Mayer, 2018; Mohamed

Ishak et al., 2019) or exploiting new technologically advanced materials (Lim, 2019; Yuan et al., 2015b, 2015a).

To obtain an architectural product capable of functioning well in outdoor environments, it is necessary to minimize the characteristics that are ill-suited to such uses, for example, its natural ability to absorb water, and develop the geometrical structure to build resistant structures.

The use of cardboard in architecture has been influenced by ancient techniques such as Japanese paper art (e.g. origami and kirigami) whose digital evolution opens the way to new opportunities for the cardboard industry. The purpose of this study is to improve outdoor comfort within urban canyons through an innovative use of cardboard. The temporary nature of cardboard objects can allow the shapes to change over time to adapt to new environmental conditions. In this respect, there is a clear need for devices that can adapt to cope with change in the present and future.

Digitizing the surfaces enables the creation of algorithms capable of rationalizing the shapes so they can be tested with energy simulation tools such as EnergyPlus and ENVI-met. Through the parametric study of geometries suitably reduced and simplified to permit simulation, the behaviour of different shapes can be evaluated, concentrating on those that yield the best performance. Computational processes allow an array of variables to be evaluated simultaneously, yielding a wide range of solutions that meet the initial requirements. These processes are implemented using 'parametric thinking' at the heart of the design process, which allows data to be interpreted and scenarios to be simulated in order to test the design. Every aspect related to the design and production of the architectural element must be traced back to a parameter which can then undergo a process of genetic optimization in order to find the best combination in the shortest possible time. These systems are based on algorithms that simulate the steps of genetic evolution that select the best characteristics leading to adaptation (Rutten, 2010).

This study aims to investigate methods and methodologies for designing cardboard devices for the microclimatic control of our cities. The objectives are to study the relationship between climate and the city's geometry, construct algorithms for environmental analysis, and study innovative solutions to make cardboard geometries.

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We have to base architecture on
the environment.

Toyo Ito

Background

For over a decade, more than 50% of the world's population has lived in cities, an estimate that tends to increase continuously. This trend is very accentuated in emerging countries and less so in countries with a more developed economy. Italian cities are not excluded from this phenomenon, growing by 8. 7% from 2001 to 2011 (ISTAT, 2017). Urbanized spaces suffer more in relation to the microclimate conditions, clean air, and environmental comfort in general. The study of microclimate characteristics on the urban scale and the strategies and technologies to modify it is therefore a fundamental task for contrasting the negative effects directly impacting the liveability and health of urban environments, as well as the quality of outdoor and indoor spaces. Many factors are involved in assessing the quality of urban spaces, including sources of noise and atmospheric pollution, health, and environmental hygiene. There are now expanding applications and spreading analyses and studies on the urban environment aimed at researching the microclimate and identifying the most effective scenarios and strategies to achieve qualitative transformations. In fact, improvement is obtained by controlling a specific microclimate phenomenon that impacts health and also energy consumption and global climate change: urban 'heat islands'.

Locally, the increase in global temperature is mostly seen in the urban space because it is subject to the urban heat island phenomenon, leading to an increase in air temperature of several degrees where the urban fabric has a higher density than the surrounding agricultural territory. The urban heat island is not problematic during the winter, when it may even protect (at least minimally) from the harshness of the winter in certain circumstances (Ottone et al., 2019). The increase in temperature undoubtedly becomes a critical factor in the warmest months of the year, however, when the temperature gradient within the city varies only minimally between day and night, even persisting for several days. These so-called 'heat waves' are monitored in Italy by the Civil Protection Service by means of the HI (heat index), i.e. a synthetic index that relates temperature and relative humidity to estimate the level of risk that these imply for the health of the population (Steadman, 1979).

In summer 2003, there were prolonged and extreme weather conditions in Italy and Western Europe. The temperature and relative humidity remained nearly constant for a certain period, creating discomfort and leading to several deaths.

Figure 1
A representation of the urban heat island phenomenon

This has repeated with increasing frequency and intensity over the years (Conti et al., 2005). Beyond affecting the quality, liveability, and usability of open spaces, the urban heat island also has specific effects on the conditions of indoor spaces, leading to a higher use of energy for mechanical cooling. This latter aspect is closely tied to the question of climate change, because it is related to the increase in energy consumption.

CLIMATE IN CITIES

The increase in temperature in the urban area of London was first observed by the meteorologist Luke Howard in 1818, but the definition of urban heat island only appeared in the literature in 1958 in an article by Gordon Manley in the Quarterly Journal of the Royal Meteorology Society. Manley used the term 'island' to highlight the image of air temperature (mapped using isotherms) in the city compared to the 'sea' of surrounding rural areas at lower temperatures ***Fig. 1***. Understandably, not all parts of the city are subject equally to this phenomenon. The indicator used to quantify this deviation is the urban heat island intensity, which is defined as the difference between the urban and rural temperature (Oke, 1982). Massive buildings, their morphology, materials, differing surface permeability, the presence of vegetation, heat emissions, and pollution from anthropic activity characterize the urban environment and interactions with atmospheric forcing such as sunlight and wind. These dynamics modify the microclimate, altering the temperature-humidity balance of the area in ways that are not easy to predict. One of the results of this imbalance is the urban heat island, which is generated in urban areas, but it is also a considerable effect of a broader climate situation. In urban areas where this phenomenon is present, temperatures higher by 5 or even 6°C compared to the surrounding rural areas can be detected (Dimoudi et al., 2013; Oke, 1995). The intensification of this phenomenon is tied to a range of factors, including materials and the dimensional relationships of the urban layout that generate radiative exchange between the surfaces and between the surfaces and the sky. The factor with the highest incidence is anthropogenic heat, that is, heat generated by emissions tied to energy-production processes, leading to the emission of atmospheric pollution. The factors combining to create the urban heat island may be traced to various changes in the urban energy balance:

- *Greater absorption of solar radiation by buildings and impermeable surfaces in general compared to the land;*
- *Less heat dissipation due to the complexity of the geometry, which promotes reflections that trap thermal radiation;*
- *Increase in thermal energy accumulation in the environment affected by the urban layout due to the elevated heat capacity of construction materials constituting the built area;*
- *Decrease in evapotranspiration from the land due to the lower presence of vegetation that would otherwise contribute positively to mitigating the microclimate;*
- *Little dissipation of infrared radiation caused by the enhanced greenhouse effect;*
- *Little dissipation in general due to masses of air that move with more difficulty through the web of the urban fabric;*
- *Heat emission due to vehicular traffic. The latter does not particularly affect the balance, but it does contributes to generating the urban heat island.*

The observation of these factors shows which contribute in different ways to the urban heat island. The first three play a particularly important role. The increase in absorption of solar ration by the built environment, the decrease in dissipated thermal radiation, the increase in stored thermal energy as a result of the elevated heat capacity of construction materials are the factors most commonly studied when designing interventions to identify and reduce the phenomenon (Ratti et al., 2003; Ottone et al., 2019). The most common strategies for 'cooling the city' entail the use of reflecting surfaces (higher albedo) and nature-based solutions (NBS). The cooling activity of NBS is based on albedo, but especially on evapotranspiration and, for trees, shading (Angelucci, 2018).

Comfort Assessing

To verify how the environmental variables positively or negatively influence the state of comfort, it is useful to assess a synthetic datum that relates these variables to a person's physical state. Over time, various indices have been developed to meet this need ***Fig. 2***. One of the most common indices is the PMV[1] (Fanger, 1970), which is based on the

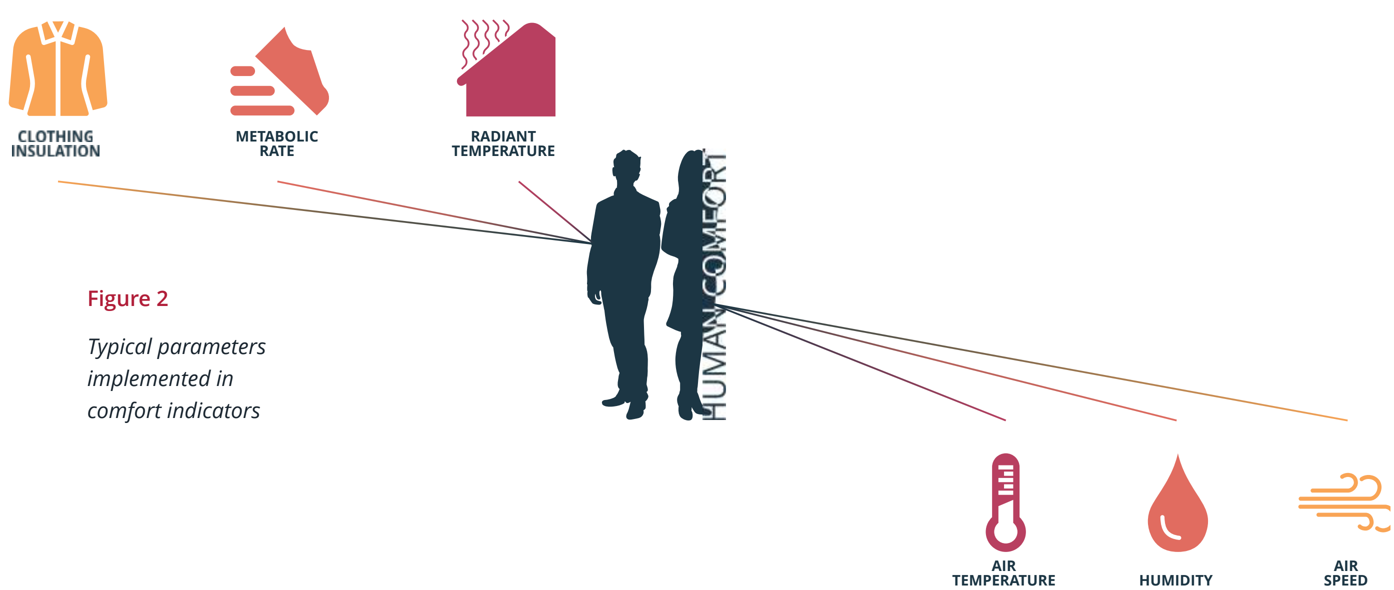
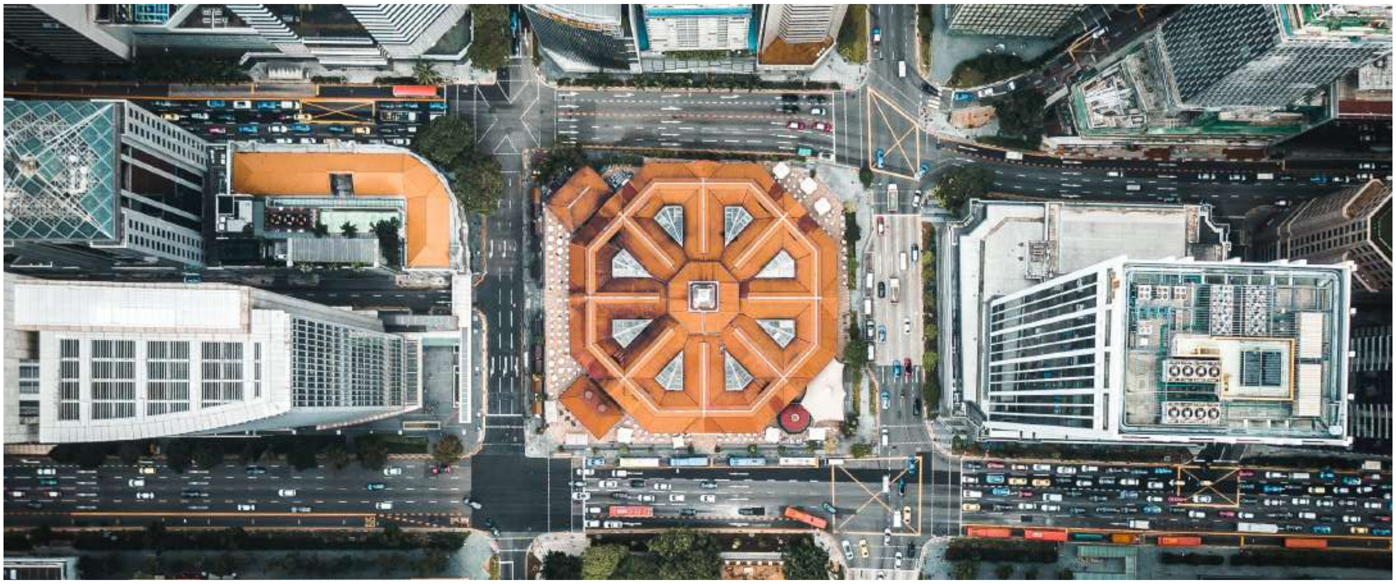


Figure 2

Typical parameters implemented in comfort indicators



energy balance of the human body and empirical assessments of temperature-humidity well-being tested on a wide range of people. The PMV is widespread in the literature and has also been adopted in German engineering guidelines (VDI 3787). This index considers air temperature, radiation temperature, wind speed, and relative humidity, comparing them with two parameters tied to individuals, such as clothing insulation and metabolic rate.

The PET[2] is an index based on a model that extends the comfort calculation to the outdoor space, making it one of the most common indices used today (Höppe, 1984, 1999). It is based on the 'Munich Energy-balance Model for Individuals' (MEMI) a model that characterizes the thermal conditions of the human body. PET is calculated in two different steps. The first regards an assessment of the thermal conditions of the human body for a given simplified combination of microclimate variables (no wind or solar radiation). The second introduces values calculated for 'mean skin temperature' and 'core temperature' in the MEMI to solve the thermal balance equation.

The UTCI comfort index[3] is the most recent index proposed. It derives from the concept of equivalent temperature described by the UTCI-Fiala thermal-physiological model (Fiala et al. 2012) combined with a complex mathematical model that describes the insulating and evapotranspiration characteristics of the clothing (Havenith et al., 2012). To calculate this index, air temperature, mean radiation temperature, wind speed, and humidity (expressed as water vapour pressure or relative humidity) are required.

The evolution of models to assess comfort has improved noticeably, refining the results and simplifying the interpretation of the data (Zare et al., 2018). The use of increasingly refined tool is even more useful for representing the impact of climate change on health (Di Napoli et al., 2018).

Appendix B

THE URBAN HERITAGE AND NEW STRATEGIES

The theme of environmental sustainability in urban transformation processes has substantially modified the traditional view of cities. Architects/urban planners are progressively losing their role as directors of urban transformations, since environmental problems have introduced new aspects to address and resolve. In developing countries, where there is greater inequality and anomalies in city growth, there is now an awareness that urban design must be undertaken with a more explicit multidisciplinary view (Balbo, 2005). 'The process of urbanization, capital accumulation, deregulation, globalization, environmental protection, and so on, are much more significant for the shaping of urban relationship than are the spatial forms of urbanism in and of themself' (Waldheim, 2006). There is thus a need for an overall cultural renewal that ensures, on the one hand, that a precious heritage of specific contributions that have defined the qualitative characteristics of cities (form, function, etc.) in the past are not lost. On the other hand, architecture as a discipline should modify and update its own investigation methods, reviewing and reinterpreting the terms and parameters that have constituted reliable disciplinary support for many years, the exclusive prerogative of urban-planning disciplines. Starting in the 1800s with the texts by Camillo Sitte (Sitte, 1981), and continuing today with the work by Rem Koolhaas (Koolhaas, 2002)and Bernardo Secchi (Secchi and Viganò, 2009), urban theories have increasingly described urban phenomena as a more or less definite and flexible 'design' in which the urban architect is the main advocate (or victim, as in the case of Koolhaas) of the transformations. Albeit with different meanings and balances, such theories are mainly based on interpretational parameters referring to the form and function:

- *form and dimensions of open spaces*
- *form and arrangement of buildings*
- *communication and infrastructure routes*

the permitted use of areas (zoning), defined based on balances among different functions

(residential, industrial, service, etc.). In the 1970s, theories by architects such as Aldo Rossi (Rossi, 2018), Robert Venturi & Denise Scott Brown (Venturi and Brown, 1977), and other important architect/intellectual figures influenced entire generations of scholars, researchers, and designers who realized projects according to a one-eyed approach. Today, this approach is no longer sufficient for making efficient interventions on cities. The increasing incidence of topics tied to environmental sustainability in processes of growth and urban transformation requires an effort to be open to cultural influence and disciplinary renewal. This study highlights how new early-investigation tools based on parametric programmes and optimization models can be moulded to build platforms of shared work that make the investigation of complex urban fabrics extremely quick, effective, and focused, with the primary goal of improving the quality of life in cities. In fact, it is believed that the investigations that are implemented and enriched are those that tend to highlight synchronization between low energy impact and quality of life, demonstrating that where passive measures are adopted to reduce the energy impact, people live better in terms of urban comfort.

The climate and climate change have always represented primary factors of change, not only with respect to society, but also in the appearance of the city itself (Behringer, 2013).

Climate change has occurred many times throughout history, leading to changes in society, cities, and landscapes, which have been readapted and reshaped based on new scenarios that were being projected (Rahm, 2014).

Today, nothing new can be designed or existing aspects intervened on without being aware that achieving urban comfort is an unavoidable objective, just like the form, functional organization, and dimension/proportion of the built area. From this point of view, an urban and/or architectural design can control the complexity deriving from simultaneously implementing the necessary parameters and considering all the possible variables. This research aims to delineate a matrix of case studies — cities —whose analysis is performed in consideration of three factors deemed decisive in the evaluation of urban quality: climate, empathy,

Figure 3
Green roof in Ørestad, Copenhagen, Denmark

and technology. The methodology developed will allow designers to manage the complexity of non-linear relationships among the meteorological variables and geometric ratios that characterize the urban microcli-mate (defining the impact of urbanization on local climate conditions and mitigation factors). It will also for the management of possible technological interventions designed to modify the relationships between surface permeability/impermeability, albedo values, and thermal fluxes. Finally, it will address questions tied to the empathic aspect of architecture intended as an 'emotional catalyst and an ideal transmission vehicle for content that can be shared socially (Garramone, 2013) and measured through comfort indices. In addition to deeming necessary recourse to the inclusion of new tools and data within contemporary design parameters (Rahm, 2014), it an initial study was made within a range of indicators that refer specifically to the theme of climate change and land consumption, interweaving them with factors related to the form and dimension of the built environment. The initial concept is that individuals inevitably establish an empathic relationship with the surrounding environment. One no longer speaks of urban space with a Modernist reminiscence, that is, a city designed mainly as a space destined for the movement of transport, which has characterized the last 150 years of planning. Rather, what prevails today is the concept of 'cities for people' (Gehl, 2017) that see '... how important it is to pay attention to people in cities in order to have vibrant, safe, sustainable, and healthy cities, all important objectives for the twenty-first century'. A concrete example of this change in trend can be seen in the different operations that the City of Copenhagen is implementing ***Fig. 3***. Through urban planning and design strategies, the focus of the built space has moved from vehicle traffic to people, to slow spaces, to spaces for interaction, to the development of green infrastructure, not only on the horizontal plane on the ground floor, but also on top of the buildings, i.e., 'green roofs'[4]. One example that combines the various parameters described above is the by Philippe Rahm, Public Air, where the City of Copenhagen requested that the entire biking and pedestrian network be redesigned in order to separate it from the flow of vehicles. Emphasis was placed on parameters such as the materials used on the ground and façades and their relationship with people. '... for example, the façades could absorb sound or the materials could be warmed in winter or at least lead to human comfort'(Rahm, 2014). The idea of controlling the urban heat island by placing more attention on the parameters of liveability, prioritizing people, can generate interesting interventions from alternative, innovative points of view. However, weighty architectural interventions are not always needed to improve urban comfort. With a careful reading and correct analysis tools, one can understand in detail where and how to act. One example of light intervention on the level of city impact is found in New York with its NYC CoolRoofs programme, carried out in collaboration with NYC Service and the NYC Department of Buildings[5]. The initiative involves a group of volunteers and building owners who decided to improve urban comfort by painting the roofs of some buildings with a white reflective material, reducing the absorption of heat from the Sun and consequently decreasing the internal temperature of the building by up to 30%. Thanks to the high reflectance of the colour chosen, the temperature of the surrounding area is also reduced, helping to counteract the urban heat island. But how can the initial parameters be determined in order to render the most objective vision possible of the comfort of a specific area? Immaterial technology in this case is a decisive factor.

An urban design should be able to make use of certain data deriving from a set of technological tools to monitor environmental and human phenomena.

The data can then be processed in complex preliminary analysis that encompasses the varied information deriving from different areas. Immaterial technology is the fruit of this new millennium, permeating the city in each of its areas and delineating a new infrastructure that is important both for design analysis and for the good liveability and functionality of the space. This system of invisible control is — and will be even more in the future — present in every dimension of urban and private space as a necessary tool to foresee and design the city. There is a shift, therefore, from a smart city to the 'senseable city' defined by Carlo Ratti: 'Optimization plus humanization do not give access to a metropolitan- seized computer nor to a network-based far west. It is the convergence of bits and atoms; systems and citizens interact' (Ratti et al., 2016)". If technology is integrated within the urban fabric, it becomes the means to transmit real, usable data regarding flows of vehicles, people, and the climate. Environmental data implemented with current information-transmission technologies could be strengthened and used easily, taking the place of the sparse surveying stations spread over the territory. In the future, a person living in the city could be a vector and transmitter of data in specific places, mapping the entire urban space with high precision. ***Appendix C***

CARDBOARD PRODUCTION AND ITS ENVIRONMENTAL IMPACT

Cardboard is generally considered an environmentally friendly material, although this should be studied on different scales as a generic material and then as a building material to understand the impacts of its production and disposal.

The value of the adjective 'green', which is often attributed to the image of paper, has become enormously inflated by marketing. Cardboard products (other than packaging) are described as sustainable, but the very complex production process behind them could undermine the possibility of recycling or reusing the raw material. 'Green' approaches to the built environment therefore involve a holistic approach to building design. All resources that go into a building, whether materials, fuel, or user contributions, need to be considered if a sustainable building is to be produced (Woolley et al., 1997).

In the life cycle of an object, two sources of energy are necessary: energy to produce the object and energy to maintain (or move) it (Dixit et al., 2010). Life-cycle assessment is a method used to measure and assess the environmental impact of production systems or activities by describing and evaluating the energy and materials used and released into the environment over the life cycle of an object, from its production to disposal. Several studies have shown the need to make a life cycle assessment of materials, and cardboard in particular, to understand the actual impact on the environment and how production processes can improve the unfavourable conditions imposed by the production of new material (Brummett and Hicks, 1998; Haggith, 2008; Suresh, 2018). These studies have been adopted by governments and transformed into regulations to safeguard resources.

THE CIRCULAR ECONOMY OF CARDBOARD

The circular economy is an economic principle that refers to sustainable production, i.e. a set of processes to produce items that use as little new raw materials and energy as possible. It is referred to as a circular, non-linear trend because it is based on tracking the life cycle of products, waste material, water, and energy needed for transformation. The primary objective of this model is to restore the health of the system from which resources are drawn and discourage the chain of events that damage the environment on different scales, even in places seemingly far from the production site. The circular economy approach has recently featured prominently on the European political agenda, asking how economic growth can be decoupled from new resources by investing in sustainability, favouring lower CO_2 emissions, and improving general environmental conditions (EU Commission, 2015).

Effectiveness evaluation for circular economy strategies should not optimize only one part of the chain (e. g. production) at the expense of other parts (e. g. end-of-life) or unintentionally favour one category of actors (e. g. consumers) at the expense of others (e. g. waste management operators and regulators) (Niero and Hauschild, 2017). It is necessary to go beyond a study of the impacts that the production of new resources has on nature and optimize all manufacturing processes cyclically. Applying these processes at every step of production or the product lifecycle is very effective. They combine practices for saving resources, preventing waste generation, increasing product lifespans, using as much recycled material as possible, increasing the service life of objects by extending their use, recovering/reusing materials and products, and increasing recycling rates.

Over 3. 5 million tonnes of paper and cardboard packaging are put back into the production chain in Italy. According to estimates illustrated in the COMIECO report, Italy has reached a key position in the European ranking, recycling up to 81% of paper and cardboard, with an average of 57. 5 kilograms of paper collected per inhabitant (COMIECO, 2019).

In 2019, the Italian paper industry had a total material consumption of 10. 08 million tonnes for 8.9 million tonnes of products. Of the total consumption, 50. 2% consisted of secondary matter, 35. 4% of virgin fibre, and 14. 4% of non-fibrous materials such as calcium carbonate, starches (another renewable material, estimated at 3. 5%), minerals, bleaching agents, and other production.

Overall, even considering the share of starches, it can be estimated that about 89. 1% of the materials used are composed of secondary materials (waste) or renewable materials (cellulose fibre and starches). In 2019, 3, 575, 400 tonnes of virgin fibre was used in Italy. As a proportion of paper production, the consumption of virgin fibre has gradually contracted over the past decade (by about 3. 5%), reaching its lowest in 2018. Italy does not have independent pulp production — except for a minor amount, 324, 500 tonnes — instead importing 94. 1% (i.e. pulp from virgin fibres), mainly from Europe and the Americas, with no imports from Africa or Asia. In Italy and European countries, the pulp comes from cultivated forests and increasingly from certified forests. In Europe and other areas, forests grown for pulpwood are increasingly being managed sustainably, with 89. 8% owned or managed by the European paper industry and certified under the FSC or PEFC schemes. Ninety percent of the pulp purchased by the European paper industry is certified. Even in Italy, where pulp production from primary

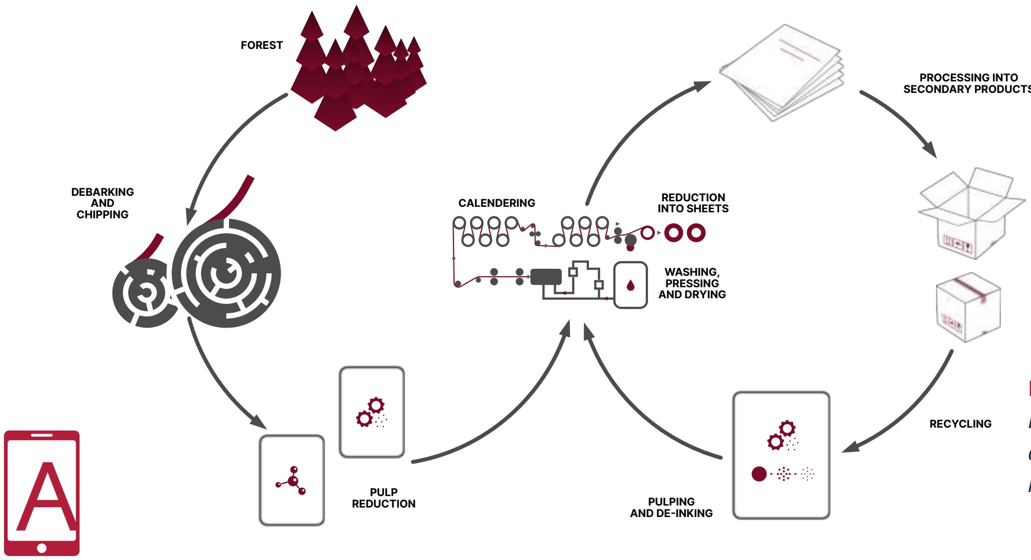


Figure 4
Paper making and recycling representation

fibres is almost non-existent, 72% of wood and 85% of purchased pulp are provided with forest certification. Although a minor user of wood, the paper sector is proportionally the primary user of certified wood and it is precisely the fact that wood supplies now come from cultivated forests that generates another significant benefit of recycling, along with the main benefit of reducing energy consumption and water/atmospheric pollution associated with primary production. As a result of recycling and the lower demand for raw material, resources are freed either to plant new natural forests or for other productive uses of biomass, both as timber and biomass/biofuel to replace fossil fuels. Italy benefits from a double gain in recycling: reducing emissions by avoiding primary production, and the 'creation' of biofuels with neutral CO_2 emissions to replace methane and oil (Assocarta, 2020).

RECYCLING OR REUSING PAPER AND CARDBOARD

In general, the paper industry consumes large amounts of natural resources in the production process, using energy and fresh water with a significant impact on the environment. The regeneration of paper through the recycling process is therefore strongly encouraged. Paper and cardboard are highly recyclable materials, and the process to regenerate and recycle the paper falls within the paper-production process described in 'The industrialized papermaking process' *Fig. 4*. For the recycled paper to be fed back into the manufacturing process, it must be sorted and decontaminated of non-fibrous elements such as glue, metal, and plastic residues. If the final purpose is to produce paper for printing or hygienic use, the pulp undergoes further treatment to lighten the final product by eliminating ink residues. Depending on the production aim, a virgin component can be added to the recycled pulp to increase its mechanical resistance. The recycling limit recommended by the Confederation of European Paper Industries is a maximum of six times.

The elements that make cardboard recycling difficult are various constituents, coatings, or additives used to improve its mechanical strength. In some cases, it is necessary to mechanically remove the element with which the paperboard has been hybridized to allow for disposal or recycling. It is always necessary to find a balance that defines an improvement of the material while maintaining the sustainability of production and recycling (Schonwalder and Rots, 2007).

ENVIRONMENTAL IMPACTS

During the life cycle of paper products, several greenhouse gases are emitted into the environment related to production, transport, and disposal, the primary one of which is carbon dioxide (CO_2), mainly deriving from anthropogenic activities involving the use of fossil fuels. Greenhouse gases contribute to climate change by reflecting energy from the Sun back to the Earth's surface. The energy cannot escape the atmosphere and remains trapped, causing a global increase in temperature. The quantity of carbon dioxide that cannot be sequestered by forests due to logging required for paper and board production should also be included in the environmental impact for paper and board production. The production of new paper requires the collection of wood in large areas of forests called fibre baskets. These actions have repercussions that give rise to forests with characteristics very different from pristine ones. The presence of logging activities for several years has ruined the balance of the forest ecosystem (Suresh, 2018). According to the IPCC, about 33% of the CO_2 load in the atmosphere is due to anthropogenic activities related to deforestation (Stocker and Intergovernmental Panel on Climate Change, 2013). According to the study, much of the green land currently in use would be sufficient to reabsorb much of the CO_2 produced if it were not continuously used for production.

The IPCC provides estimates that between 40 and 70 billion tonnes of carbon could be reabsorbed, indicating a general improvement of ecosystems disturbed by human action for paper production.

Footnotes

1. *Predicted Mean Vote: a comfort index tied to the PPD (Predicted Percentage of Dissatisfied) that generally ranges between +3 and -3, where 0 represents a state of comfort.*
2. *Physiological Equivalent Temperature is an index expressed in degrees Celsius whose comfort range varies based on the surrounding conditions.*
3. *Universal Thermal Climate Index is an index expressed in degrees Celsius whose comfort range lies between 9 and 26°C.*
4. *An account of these changes can be found in the numerous initiatives promoted by the Copenhagen City*
Administration and the report 'Green Roofs Copenhagen' promoted by Copenhagen Together. This report illustrates the tendency for change in the city, starting from the requirement for green roofs in most new local plans as of 2010 and including a list of different current or completed interventions whose main theme is urban renewal on a human and sensory scale. http://en.klimatilpasning.dk/media/704006/1017_sJ43Q6DDyY.pdf
5. *The programme supports the City's objective of reducing carbon emissions by 80% by 2050 (80 x 50), as indicated in 'One New York: The Plan for a Strong and Just City' by Mayor de Blasio. The initiative is a partnership between the NYC Department of Small Business Services, the Mayor's Office of Sustainability, the Mayor's Office of Recovery and Resiliency, and Sustainable South Bronx, a division of The HOPE Program. http://www.nyc.gov/html/onenyc/downloads/pdf/publications/OneNYC.pdf*

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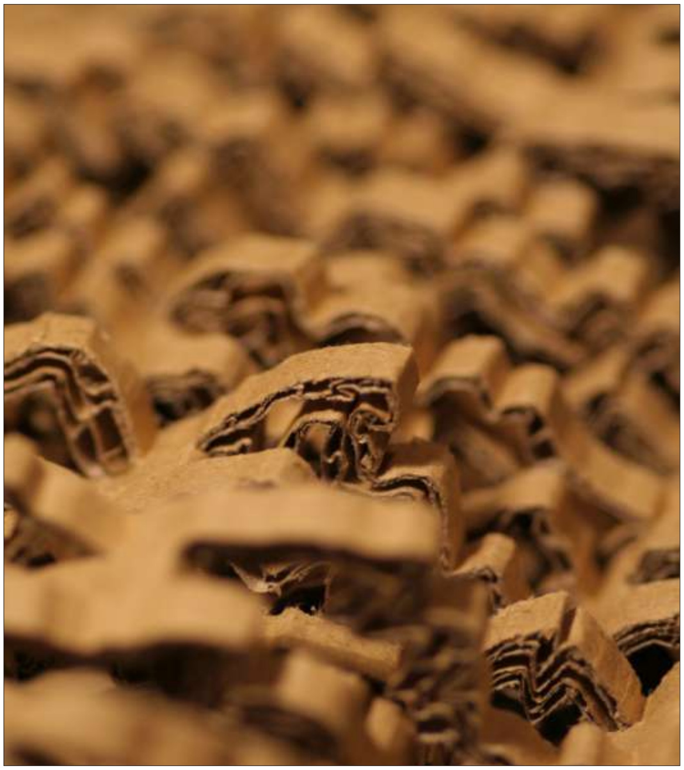

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“” One day I saw a pile of corrugated cardboard outside of my office – the material which I prefer for building architecture models – and I began to play with it, to glue it together and to cut it into shapes with a hand saw and a pocket knife.

Frank Gehry

Cardboard in Architecture

The image of cardboard remains fixed as packaging material, but several projects have been built using cardboard in recent years, both in Italy and abroad. In the modern era, one of the first experimenters in the 1940s was Buckminster Fuller, who experimented with his architectural concept using corrugated cardboard instead of traditional materials. He was inspired by cardboard because of its qualities related to environmental sustainability, recycling, and low cost. His experiments with cardboard geodesic domes began the path of research on the use of this material (Fuller, 1953). Fuller designed a prototype for a corrugated cardboard house, but decided not to use cardboard as the primary material to avoid structural weakening due to moisture and its vulnerability to fire. The limits of experimentation are primarily related to the level of technology that matured in the 1940s, which did not allow for further progress. Subsequent experiments by Buckminster Fuller, Keith Critchlow, and Michael Ben-Eli inspired many other designers who began to use cardboard as a material for primary or secondary structures. The greater spread of the use of cardboard in architecture was also due to a paradigm shift in the 1980s regarding environmental compatibility and sustainable materials that made cardboard quite famous in architectural applications.

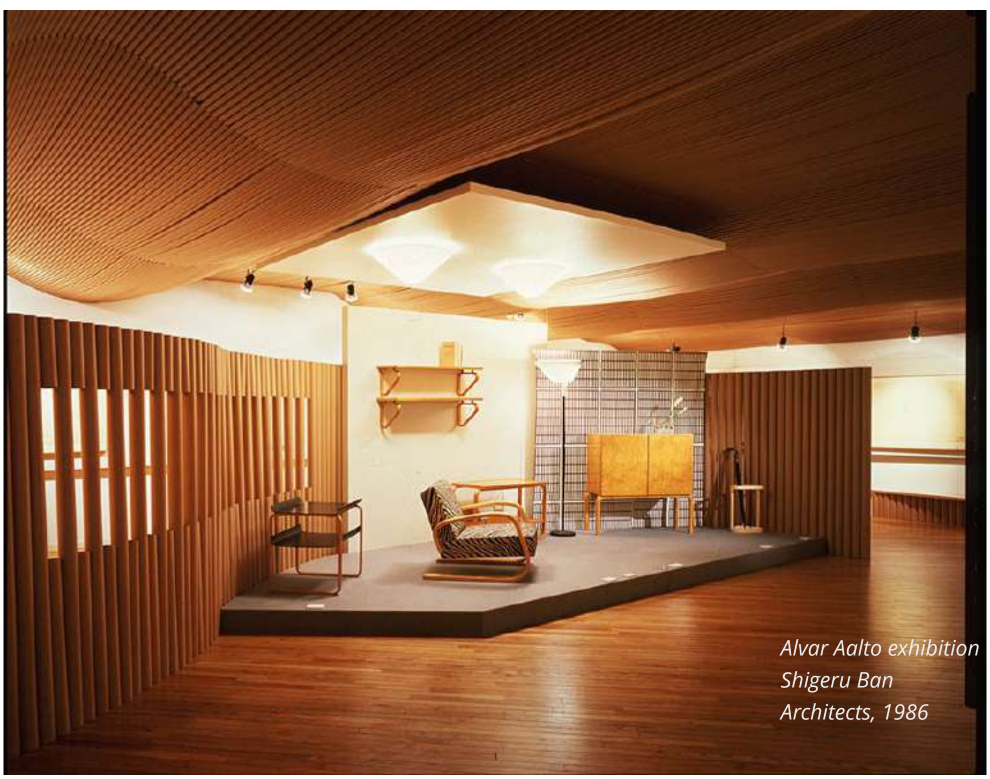
It was in these years that a new era for cardboard architecture began with the arrival of projects from Japan by a young Shigeru Ban, who is credited with having promoted cardboard as a construction material since his first studies in 1985 and a project for the installation of a pavilion for the architect and artist Emilio Ambasz

Ban organized the exhibition space using tubular cardboard structures with a square cross-section and honeycomb panels. This was followed by his project for an exhibition in honour of the Finnish architect Alvar Aalto, where he once again used this material due to both economic reasons and the aesthetic reference that cardboard has with wood, which was a symbolic material in Aalto's work. On this occasion the project saw the use of cardboard as a 'space generator'. Shigeru Ban later conducted a series of studies on the use of cardboard as a structural element in architecture, investigating the behaviour of cardboard subjected to axial stress, bending, and tearing, as well as the structural response of perforated and bolted cardboard nodes. The results of these studies later allowed him to obtain permits for the construction of permanent cardboard structures.

Alvar Aalto exhibition
Shigeru Ban
Architects, 1986

PRIVATE CARDBOARD ARCHITECTURE

Paper-based products (corrugated cardboard, paper tubes, honeycomb boards) have always been used to produce home furnishings, furniture, elements of separation, and small objects. In addition to interior design, cardboard has also been used since the 1990s as a low-cost, environmentally friendly material for generating architectural forms. New architectural solutions must involve materials that are sustainable, easy to produce, cost-effective, long-life and which can be reused, refurbished, or recycled. Cardboard has many of these characteristics, but its life cycle is potentially limited. A survey of a sample of young Swiss people conducted by Ozlem Ayan illustrates the propensity to choose to live in a building that does not have a long-life span as long as it is economically convenient and environmentally friendly (Ayah, 2009). Ayan described the high energy consumption of the Swiss building sector and the growing awareness of ecology in Swiss society, which prompted her to introduce a 'new', sustainable material on the market that is useful for reducing the energy impact of buildings.



*Alvar Aalto exhibition
Shigeru Ban
Architects, 1986*

Figure 1
Interior view of Paper House designed by Shigeru Ban Architects

Figure 2
Exterior view of Paper House designed by Shigeru Ban Architects regetis

Paper House - Shigeru Ban Architects - 1995

The first permanent project to receive certification for the structural use of cardboard was the Paper House built in the Yamanashi Prefecture in Japan in 1995. The project involved the use of cardboard both for structural use and as a tool to organize the spaces. Ban arranged 110 cardboard tubes with a diameter of 275 mm and a height of 2.7 m in an 'S' shape in a space of 100 m^2 *Fig. 1 and 2*. Of these tubes, 10 were specifically tasked with resisting the vertical load of the roof, while 80 were dedicated to supporting lateral thrusts. The structure was anchored to the wooden plinth by means of connection joints. The design emphasized cardboard tubes as a support for the roof by exposing them to the outside through transparent walls.

Paper Dome - Shigeru Ban Architects and VAN - 1998

In 1998, Shigeru Ban and VAN designed an outdoor extension to the work area of a wooden construction company. The client requested the creation of a covered structure for woodworking that could be assembled quickly by unskilled labour *Fig. 3*. A 27 m x 23 m open space with a shell covering and a maximum height of 8 m was designed. The structure, composed of rigid elements, was segmented into modules to create the curved arch. Between the modules, the cardboard segments were held together using wooden joints. The weight of the ribs was unloaded onto concrete foundations and additional cardboard tubes were installed in the lower part of the arch to strengthen the structure by absorbing part of the bending load. Metal ties were also added for the same purpose. Finally, a further safety measure was implemented by inserting metal bracing to prevent accidental overloads on the structure, for example, due to snow or wind. The lateral stability of the arch was achieved through the use of structural plywood panels binding the ribs on the extrados *Fig. 4*. The panels were then perforated in the centre to allow natural light to filter through and covered and closed with translucent plastic sheet.

Although cardboard structures had already been accepted by Japanese regulations, further investigations were required for approval of this project. Tests conducted to evaluate the flexural strength of the material showed that performance declined with increasing humidity. It was also shown that the compressive strength did not change up to a moisture level of 7%, but it gradually decreased between 7% and 13%, the threshold above which the strength was severely compromised. Tests were also conducted with the mixed wood and cardboard structure to verify that the assembled system would function correctly. Given the uncontrolled environment and high humidity levels, the cardboard was pre-treated for waterproofing (Jodidio, 2010; McQuaid, 2006; Miyake et al., 2009). The technologies developed in the Paper Dome project were subsequently used in several other projects by the same architect.

Wikkel House - Fiction Factory - 2012

The Wikkel House project is the brainchild of Dutch inventor René Snel, who developed idea for a cardboard house in the late 1990s. He was inspired by the production process for fruit crate wrapping, which consisted of a layer of shaped cardboard. The name Wikkel means 'wrapping' in Dutch.

The initial aim of the project was to provide temporary emergency housing to be built on site. Snel therefore developed a machine that could be transported on a trailer and which could produce the components the house like the components used for packaging. However, none of the NGOs involved in the emergency relief efforts were interested in starting the project and production was therefore halted in 2008.

In the following years, the Dutch company Fiction Factory bought the intellectual property rights and the machinery needed

Figure 3
Paper Dome designed by Shigeru Ban Architects and VAN, 1998

Figure 4
Dome bottom view where the perforated panels are visible

Figure 5
The Wikkel House and a section of the cardboard wall

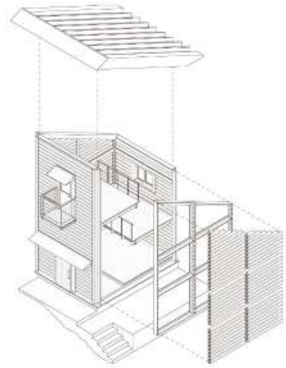


Figure 6
Yakushima Takatsuka Lodge in Yakushima Island

Figure 7
Axonometric exploded view of Yakushima Takatsuka Lodge

Figure 8
Yakushima Takatsuka Lodge side view

for production. After the acquisition, the Wikkel House was developed and made into a private house. The first prototype was exhibited at Amsterdam Airport in 2012.

The Wikkel House consists of prefabricated sections 4.6 m long and 3.5 m high. Corrugated cardboard with a standard width of 1.2 m is used to produce each section, with a surface area of 5 m^2. The construction involves 24 layers of cardboard laminated ***Fig. 5*** on site and held in place by a wooden frame. The cardboard is not only used as an envelope, but also serves a structural purpose. The wooden frames are used to hold the cardboard in place during the production process; they act as a connecting element and safety system in case the cardboard is damaged. The machine used to assemble the layers of cardboard is calibrated to adjust the tension of the paper according to the desired shape.

In order to make the cardboard resistant to the weather, it is covered with a waterproof and breathable fabric on the top surface, which is further covered with a horizontal wooden board. The soffit, on the other hand, is covered with a sheet of plywood. The total weight of one section is approximately 500 kg and up to two sections can be transported without the need for special equipment.

The sections are clamped together using steel rods running horizontally from frame to frame. The perforations necessary to insert the tie rods are also used to drain off excess moisture that accumulates when the layers are bonded. This is very important to avoid compromising the structural integrity of the cardboard. During assembly, a sheath is applied between the sections to prevent infiltration. The foundation is made of wooden or steel beams subsequently welded to a concrete base. The front and back walls may be transparent. The construction of a section requires one day's work at the factory.

Wikkel House is sold as a prefabricated, environmentally friendly, and comfortable solution perfect for warm climates. It can be fully furnished and equipped with every comfort. The basic solution (consisting of three modules) is priced at €25, 000 and is ready in just a few hours. The manufacturer estimates a life cycle of 50 years while applying a legal product warranty of 15 years.

Yakushima Takatsuka Lodge - Shigeru Ban Architects - 2013

In 2013, architect Shigeru Ban designed and built a shelter off the southern coast of Japan on Yakushima Island. The building is located inside the forest in the Kirishima-Yaku National Park on the southern edge of the island *Fig. 19*. The subtropical landscape is a destination for hikers, featuring 2000-m-high mountains covered with Japanese cedar forests (sugi). The Yakushima Takatsuka Lodge is intended to be a place to rest during trekking activities and can accommodate several people at once.

The project follows the reconstruction of an older cabin (now demolished), using those foundations to avoid new land consumption. The structure of the building consists of a wooden frame braced with metal tie rods on three levels. The roof is built with a sloping pitch for rainwater runoff. Recycled cardboard tubes were arranged horizontally and inserted within the frames *Fig. 7 and 8*. The cardboard infill provides shelter but allows sunlight to filter through. The use of cardboard makes for easy maintenance, in which damaged parts can be removed and quickly replaced over time.

PUBLIC CARDBOARD ARCHITECTURE

Cardboard is not a material designed for long-term use. However, studies and finished public buildings using cardboard have demonstrated the possibility of prolonging the life of these buildings even beyond twenty years. The desire to overcome structural and architectural limitations and employ a material that is promising in terms of environmental compatibility have driven

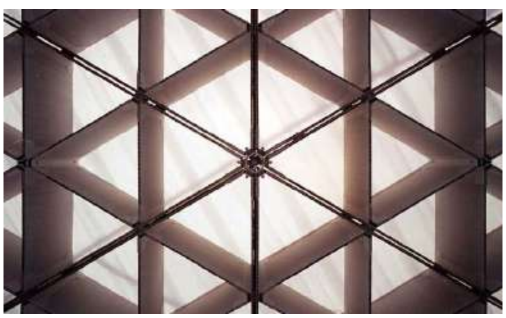


Figure 9
The roof of the museum seen from below shows the interlocking panels

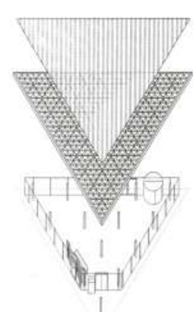


Figure 10
Axonometric exploded view of the museum

Figure 11
Nemunoki Children's Art Museum designed by Shigeru Ban Architects, 1999

Figure 12
Westborough Primary School external view

architects and engineers to create public buildings in cardboard. Although cardboard production is generally not expensive, it has been shown that the study and application of innovative solutions for public architecture based on this material have higher construction costs than solutions that rely on classic techniques and materials.

Figure 13
Construction detail of the column-beam node

Nemunoki Children's Art Museum - Shigeru Ban Architects – 1999

Shigeru Ban used a grid of honeycomb panels as light reinforcement for the roof structure in his 1999 project for the Nemunoki Children's Art Museum in Kakegawa, Japan *Fig. 11*. Each honeycomb panel was covered with a translucent plastic to provide solar shading.

The panel used in the museum was not, however, a typical honeycomb panel *Fig. 9 and 10*. It consisted of two moulded half-panels coupled to create a more resistant material. The grid of the roof consisted of equilateral triangles 60 cm high and 3 m wide. The nodes between panels were solved by inserting a joint composed of a metal plate and a wooden rib that held the cardboard panels in place at 60° angles.

The entire roof structure consisted of 64 units with a triangular base. This triangular structure made it possible to create a light and strong planar structure using just a few connections. The entire structure was protected from the weather with the application of plastic and vertical glass walls.

Prior to construction, specific structural studies were carried out on the panels. Tension, compression, bending moment, and adhesion strength between the parts were all tested. The tests were performed at different humidity levels, showing that the panels maintained a moisture content of 9.5% at a relative humidity level of 60% and a moisture content of 15.8% at 90% relative humidity. This increase in moisture content within the panel caused its performance to drop to 61% in high humidity. For this reason, the museum was air-conditioned to maintain a constant temperature of 20°C with a relative humidity of 60%. These studies carried out on the roof were necessary for authorization in Japan and also led to approval of the use of this technology in Germany.

Westborough Primary School - Cottrell & Vermeulen Architecture and Buro Happold Engineering - 2001

Westborough Primary School was the first permanent building in Europe to consist of a cardboard structure *Fig. 12*. The school was made from 90% recyclable materials and designed to be recycled again at the end of its life cycle (20 years). The building was the result of a collaborative experiment between Cottrell & Vermeulen Architecture and Buro Happold Engineering in 2001. As well as an architectural experience, it was an opportunity to teach the importance of reusing materials to children, who were asked to recover material to be used in the construction of the studio prototype.

Cardboard tubes and sandwich panels were used for the main hall and the space dedicated to services. The cardboard tubes have a structural function and support the double-pitch roof *Fig. 13*. The sandwich panels consist of a 4-mm solid cardboard layer, 50 mm of honeycomb layers, and two 16-mm fibre cement layers embedded in a wooden frame with maximum dimensions 2.7 m by 1.5 m. To protect the cardboard from humidity, a vapour barrier was inserted into the package and a waterproof but breathable film covers the outside. The panels were used for both the roof and walls on the front of the building (Cripps, 2004). The panels were screwed to prefabricated wooden joints or simple frames used to connect the tubes together. The exposed surfaces were treated with a fireproof material to reduce risks. This project demonstrated that cardboard can be used as a construction material, thereby increasing the recyclability of architecture and construction.

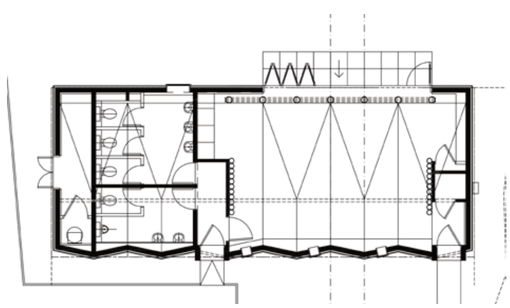


Figure 14
The plan view of the school

Figure 15
The cardboard columns beyond which are the openings

Figure 16
Internal views of the school

Figure 17
Picture taken during the positioning of the roofing structure

Figure 18
Detail of Tuball joint connecting cardboard tubes

Figure 19
Exterior view of the Ring Pass Field Hockey Club

For study purposes, a medium-scale prototype was built to test the feasibility of the construction process, which allowed several construction details to be improved before installation. Tests of mechanical strength, water resistance, and fire resistance showed that an untreated 5 mm thick solid board subjected to an open flame does not burn, but rather chars, creating a natural fire barrier that protects the subsequent layers. However, tests showed that the cardboard alone was not sufficient to meet the regulatory requirements and a fire retardant layer was integrated.

In the first months after construction, deformations were noticed in the structure due to the absorption of moisture contained in the cardboard and partitions were inserted to stiffen the walls *Fig. 16*.

The construction costs were very high, but this was justified by the fact that it was a unique construction, an experiment, which even received several awards in the years following its construction.

Ring Pass Field Hockey Club – Nils-Jan Eekhout and Octatube - 2010

In 2010 Nils-Jan Eekhout and Octatube designed and built the clubhouse extension to the Ring Pass Field Hockey and Tennis Club in Delft. Octatube already had experience with cardboard in architecture having previously worked with Shigeru Ban on the Nomadic Paper Dome (2003), Vasarely Pavilion (2006), and Paper Bridge (2007) projects. Unlike the clubhouse expansion, the previous projects were characterized by the temporary nature of the structures. In this case, cardboard tubes were used to build the lattice supporting the roof *Fig. 17 snd 19*. The structure was assembled on the ground and divided into two parts with an 8 m x 8 m area. Tuball metal joints were used to hold the cardboard tubes together *Fig. 18*. As already learned from the Nomadic Paper Dome, the tubes were inserted directly without the aid of screws to allow for small deformations, thereby preventing damage to the cardboard. In order to hold the metal and cardboard elements together, a metal tie rod was used to connect the joints, which was pre-stressed as it was passed through the tube to improve the structural response. The flanges of the nodes were sealed to avoid condensation inside the tubes, which would have compromised the solidity. In addition, the tubes were made hydrophobic by applying paint or polyethylene film.

The Dutch authorities granted permission for the construction of the frame, making this the first example of a permanent cardboard construction in the Netherlands. The structure was fully compliant with local fire and safety requirements due to the structural resistance of the cardboard when exposed to flame.

Shigeru Ban Studio at Kyoto University of Art and Design – Shigeru Ban Architects and KUAD students – 2013

Following Shigeru Ban's appointment as professor at Kyoto University of Art and Design, he involved his students in the design of a structure similar to the Paper Dome *Fig. 20*. The students took part in the construction of the studio and the project therefore did not involve the use of large mechanics. This new arch covered a square-shaped area 12 m on a side. Unlike the Paper Dome, this space had to be enclosed, which was done with wooden frames supporting translucent PVC panels.

Another major difference with the Paper Dome structure was the use of metal joints to connect the cardboard tubes so the structure could be disassembled waste-free. Each rib of the arch consisted of six 1860-mm-long tubes with an internal diameter of 170 mm and a thickness of 3.5 mm *Fig. 21*. Twelve arches were built to cover the entire area, connected horizontally by tubes similar to

Figure 20
Studio at Kyoto University of Art and Design designed by Shigeru Ban and KUAD students, 2013

Figure 21
The structure of the cardboard box is covered with laminated wood panels

Figure 22
The tralsucent plastic cover on the roof

Figure 23
Apeldoorn Cardboard Theatre during the application of plastic cover

Figure 24
The joint connecting six panels

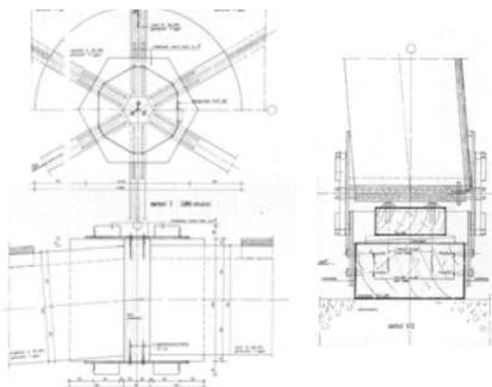


Figure 25
Details of joints and ground connection

the previous ones but 850 mm long. The tubes were not connected to the joint with screws, but rather, as on other occasions, held firmly to the joint by steel cables passing through the inside of the tube, compressing it. The transverse tubes, used only for connection, were screwed to the joints. Additional metal bracing alternately connected the joints to compensate for any loads due to snow. The roof was made of structural plywood panels with holes in the middle covered with a plastic material ***Fig. 21 and 22***. Wooden elements were inserted under the arch to reinforce the structure and to serve as shelves for the studio. The entire structure was erected on the concrete roof slab of a hall at the university and anchored to it via two HE 250 steel beams.

TEMPORARY CARDBOARD ARCHITECTURE AND EXHIBITIONS

Fairs, exhibitions, sporting events and other short-lived events have high costs and in many cases leave an ecological burden in the form of construction waste. Construction and demolition waste is the largest waste stream in the EU; its volume is relatively stable over time and the recovery rate is high. Although this may indicate a highly circular construction sector, waste management analyses show that the use of recovered materials relies mainly on low-quality operations such as recycled aggregates in road construction (European Environment agency, 2020). In this context, the use of cardboard has been proven suitable for counteracting this trend, since it is a naturally recyclable material.

Apeldoorn Cardboard Theatre - Hans Ruijssenaars and ABT Building Technology Consultants - 1992

The Apeldoorn Cardboard Theatre was a temporary theatre designed by architect Hans Ruijssenaars in 1992 as commissioned for the 1200th anniversary of the founding of the city of Apeldoorn in the Netherlands ***Fig. 23***. The use of cardboard was due to the

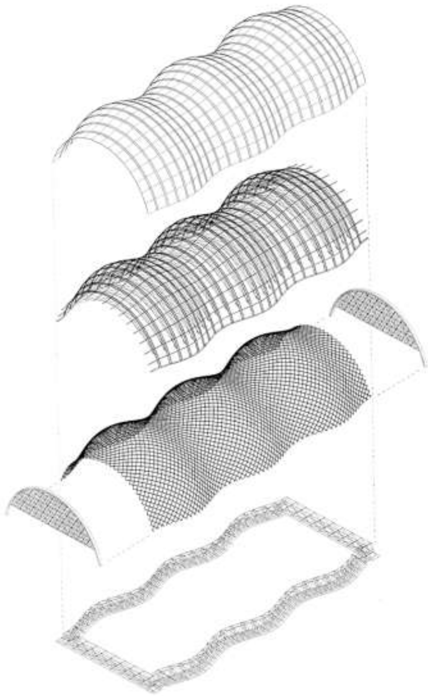


Figure 27
Axonometric view of the pavilion showing the double structure and the coverregetis

proximity of the city of Apeldoorn to the Veluwe region, which is known for its paper production.

The theatre consisted of a barrel vault roof with an opening of 12 m and a length of about 20 m. The structure consisted of cardboard ribbing organized in a triangular pattern connected by knots. The rib elements were made of 7 layers of cardboard coupled to form a panel measuring 1200 mm by 350 mm and 35 mm thick. Six panels converged at each node *Fig. 24*. Triangular panels of plasticized corrugated cardboard were added to the extrados and held together with adhesive tape and the entire structure was covered with a waterproof sheet for water resistance *Fig. 23*. The sheet further stabilized the structure because it was directly anchored to the ground. The theatre was placed on precast concrete slabs to which the lower nodes were tied via a system of metal plates. The entire theatre had a maximum capacity of 200 people and remained in operation for six weeks, which is less time than the cardboard needed to show signs of weakening due to humidity (Eekhout et al., 2008; van Kranenburg et al., 2008).

Because the Apeldoorn Cardboard Theatre was a temporary structure made mainly of cardboard, it produced limited waste when dismantled. Given the short life expectancy of the work, the cardboard elements were not treated for weather resistance, though possible treatment could certainly have extended its lifespan.

Japan Pavilion at World Expo – Shigeru Ban Architects and Frei Otto consultant – 2000

The Japan Pavilion at the World Exhibition in Hanover in 2000 was designed by Shigeru Ban in collaboration with Frey Otto *Fig. 26*. This project marked a step forward in the construction of exhibition pavilions made of cardboard, although construction work was delayed several times due to technical problems. The title of the 2000 exhibition was 'Man, Nature, Technology' and, in accordance with the

Figure 26
The Japan Pavilion at the World Exhibition in Hanover, 2000

Figure 28
The cardboard structure during forming operations

Figure 29
Interior view of the pavilion

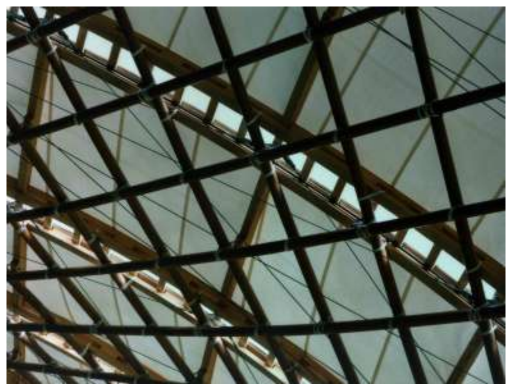


Figure 30
Detail of the "soft connection" *linking the cardboard structure*

theme of environmental sustainability, Japan wanted to build a pavilion whose disposal would produce as little industrial waste as possible.

The first idea was to build an arch similar to the Paper Dome, but this would have required the use of very expensive wooden joints, so the choice fell to a 'soft' shell composed of a grid of 440 long cardboard tubes, not connected but tied together. The entire pavilion measured 73.8 m, was 25 m wide, and 15.9 m high. The major concern in such structures is lateral deformation and the tubes were therefore intertwined to form a grid 'warped' in two directions. The tubes were tied together at the intersections using narrow straps to force them into the correct position ***Fig. 28***. Given the three-dimensional nature of the structure, the application of a 'soft connection' between the tubes also allowed them to deform naturally by twisting without causing structural damage ***Fig. 30***. The tube diameter was 120 mm, that is, the maximum diameter such that they could be flexed into a 10 m radius of curvature.

A wooden exoskeleton with steel bracing was placed atop the cardboard structure to improve its structural strength and prevent the tubes from slipping ***Fig. 27***. A translucent membrane was then placed over the wooden structure. It was not finished with ordinary PVC, whose use would have clashed with the theme of the exhibition; rather, a very similar, environmentally friendly material was used that would not produce dioxins if burned. The tubes were impregnated with an acrylic paint to make them hydrophobic ***Fig. 29***.

The walls of the two semicircular gables were edged with wooden arches at the ends of the shell. The side walls were composed of triangular plywood panels, honeycomb cardboard panels, and a treated paper membrane. The tubes were manufactured by Sonoco and tested by the University of Dortmund for their long-term structural capabilities. In addition, the axial compression strength was also tested following an assembly simulation in order to verify the strength when subjected to curving. The tests showed no structural failure of the tubes. Some samples treated with acrylic paint were aged under alternating cycles of high temperature and high humidity in order to test their compressive and flexural strength. These tests showed the high strength of the material even under extreme conditions over time. Fire tests were also carried out on the roofing membrane and paper membranes with positive results.

Contrary to the original plans, the Japanese pavilion was demolished and not reused (McQuaid, 2006; Miyake et al., 2009). The work is still considered a milestone in cardboard architecture that met the strict requirements of the German building code even for the limited time it was used (Ban et al., 2014).

Nomadic Paper Dome - Shigeru Ban Architects, STUT Architecten and Octatube - 2003

This project consisted of a geodesic dome made of cardboard tubes meant to be disassembled and reassembled in different places *Fig. 31 and 33*. The first version was built in Amsterdam in 2003 and rebuilt in Utrecht the following year. Shigeru Ban initially designed a 16-frequency geodesic to give it a spherical appearance, but modified the idea to a 10-frequency division to reduce the number of cardboard elements and joints (individually designed) without compromising the appearance *Fig. 33*. The dome was 10 m high with a base diameter of 26 m and the interior was accessed through five openings anchored to steel uprights.

The lower edge consisted of five curved profiles with a 150 mm deflection, which ended in the same number of foundations. This height was not sufficient to allow access, so the site was excavated in the first case, and the dome was raised in the second.

Figure 31
Nomadic Paper Dome designed by Shigeru Ban, 2003

Figure 32
Detail of the joint and cover tensioning system

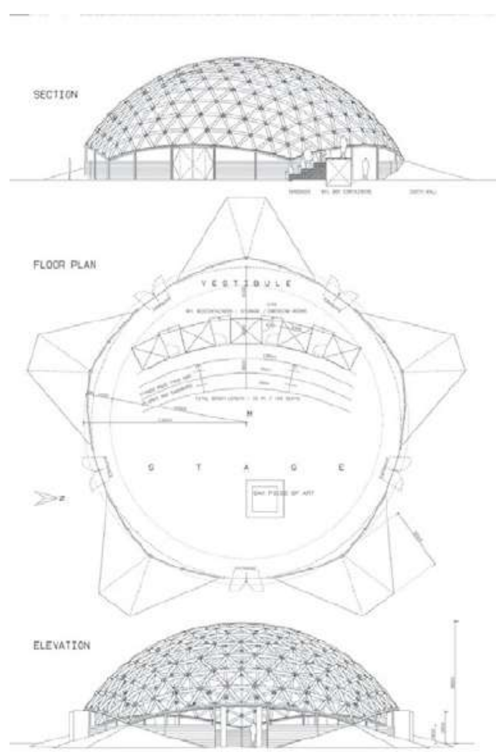


Figure 33
Front and plan views of the dome

Figure 34
Cardboard House designed by Stutchbury and Smith, 2004

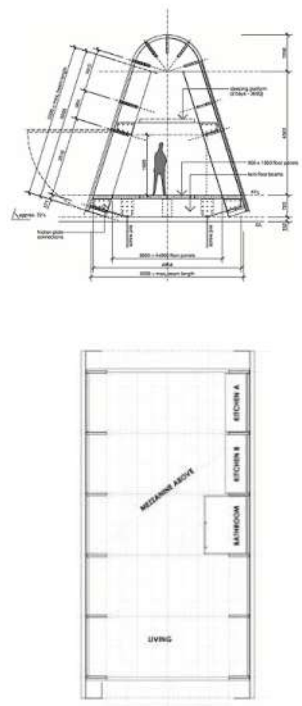
The work was covered with a PVC-coated polyester membrane. The membrane was supported at the nodes with small discs whose distance from the node could be adjusted. When the membrane was laid over the structure, the distance from the plates to the nodes was adjusted to stretch the membrane *Fig. 32*.

Four months of development by Octatube in cooperation with the School of Architecture at TU Delft were needed to build this temporary structure, with studies focusing on the resistance of the cardboard tubes in a humid environment. Preliminary tests did not yield good results because tubes were made of recycled material. Subsequent studies with virgin fibre tubes showed a 40% increase in performance compared to the recycled material. The tests also showed the poor strength of cardboard tubes at the joint when screwed together and a new type of splice was devised to avoid damaging the materials during disassembly. For the first time, a steel cable running through the cardboard tube was used to connect two tubes with a bonded joint and cardboard tube (Eekhout et al., 2008). This construction technique, devised by Luis Weber at Octatube, was used several times in the following years to build similar structures because it simplified assembly operations and lent solidity to the construction.

More than 700 tubes of varying lengths with an external diameter of 200 mm and a thickness of 20 mm were used for the construction. Each tube was impregnated with water-repellent paint on the outside, on the cut edges, and 100 mm from the ends on the inside. The set of pieces needed for construction could be transported in four or five containers to respect its nomadic features (Jodidio, 2010; Miyake et al., 2009).

The Nomadic Paper Dome was assembled and disassembled twice, with its parts currently stored in containers in Amsterdam awaiting relocation.

Figure 35
Cardboard House: Section and plan view of the small building



Cardboard House - Peter Stutchbury and Richard Smith – 2004

This project was part of the 'House of the Future' exhibition. Six teams of architects were called upon to design 'new living concepts' through ambitious experiments and the final building had to meet two requirements: it had to be built using only one material and it had to be transportable. The competition resulted in objects made of cement, cardboard, glass, clay, steel, and wood. Of them all, the Cardboard House proved to be a low-energy, lightweight, and recyclable solution that was easy to transport and assemble. With this idea, Stutchbury and Smith won the challenge to create a building made from 100% recycled material at a low cost *Fig. 34*. The design was made in collaboration with the Ian Buchan Fell Housing Research Unit at the University of Sydney. Houses built from cardboard require fewer resources, which may encourage people to change their perception of typical living. The targets for the Cardboard House are Australian citizens who are used to camping on holiday, thus quickly changing their lifestyle from urban comfort to the simplicity and freedom of camping.

The Cardboard House is very cheap and portable and can be used for both short-term and emergency accommodation. All materials in the house are recycled and can be recycled again at the end of its useful life.

The Cardboard House is conceived as a kit consisting of a flat pack of frames, and infill floor and wall panels. It uses minimal fixings: nylon wing nuts, hand-tightened polyester tape stays and Velcro fastenings are used to assemble the frames and protective skin system. The last element provided in the kit is a polyester sheet to cover and protect the structure *Fig. 34 and 35*.

The simplicity of the project means that it can be completely assembled by two unskilled people in six hours using just a ladder.

The structure consists of a series of spaced frames stabilized by a substructure made of

Figure 36
Nomadic Museum designed by Shigeru Ban, 2005

Figure 37
Nomadic Museum: An inside view of the exhibition pavilion

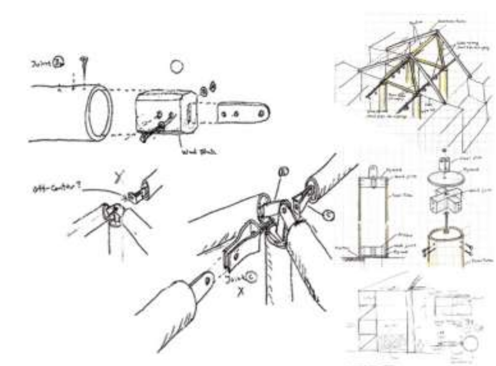


Figure 38
Nomadic Museum: Sketches

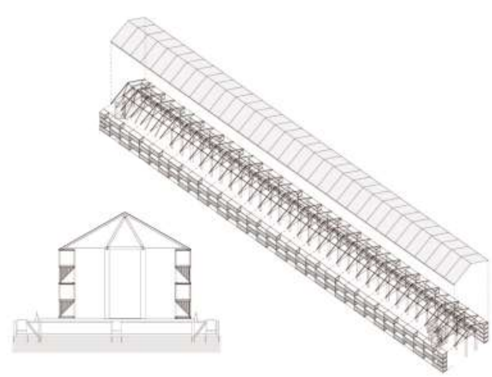


Figure 39
Nomadic Museum: Axonometric exploded view and frontal view

Figure 40
Packed Pavillion designed by Chen, Zausinger and Leidi, 2010

Figure 41
Temporary Concert Hall designed by Shigeru Ban Architects, 2011

cardboard sheets. The shape of the building is strongly characterized by the geometry of the structure. The layout of the structure also characterizes the position of the furniture, the flooring, the frames for the doors and windows, and the lighting. The roof is made of plastic in order to make it lightweight, transportable, and semi-transparent to make the most of sunlight.

To keep the building off the grid, the Cardboard House is equipped with several systems. Rainwater is collected in tanks beneath the floor, which also act as ballast. Wastewater is treated with a composting system that produced a liquid containing many dissolved nutrients useful for cultivation. Finally, power is supplied from a semi-transparent car battery housed in a compartment under the roof.

Nomadic Museum - Shigeru Ban Architects - 2005

Famous works by Shigeru Ban also include the Nomadic Museum in New York, an example of so-called 'architecture in motion'. The purpose of the museum was to host a travelling exhibition 'Ash and Snow', a photography exhibition by Gregory Colbert. This architecture in motion was designed to move with the exhibition itself, which travelled to Mexico City following Santa Monica, New York, and Tokyo. Since the images consisted of large format works, the building also had to be imposing: a total of 4180 m^2, a length of 205 m and a height of 16 m.

To minimize the impact of transport on the cost of the work, Ban decided to use containers as a standard universal element that was easily available at the exhibition sites; the containers were rented in each city ***Fig. 36***.

The structure supporting the roof of the Nomadic Museum was made of cardboard tubes, as were the vertical uprights supporting the entire building. The entire cardboard part of the structure was covered with a waterproof membrane *Fig. 39*. The cardboard tubes were maintained in each edition except for the Mexican version, where they were replaced with bamboo structures designed by Colombian Simòn Vélez in collaboration with Colbert.

Packed Pavillion - Min-Chieh Chen, Dominik Zausinger and Michele Leidi - 2010

This pavilion is the result of fully parametric development by a group in the Master of Advanced Study in Computer Aided Architectural Design (MAS CAAD) at ETH Zurich. The work was exhibited at the 3D paperArt exhibition at the Shanghai Museum of Arts and Crafts in 2010 and then at Fudan University in an event related to the Shanghai World EXPO 2010 *Fig. 40*.

The hemisphere of the pavilion is composed of 409 truncated cones of varying cross section connected to form a network. Each element consists of 28 layers of corrugated cardboard, cut, arranged, and glued together. Designed through a digital process, the elements were also produced using numerically controlled machines in Zurich and assembled directly in Shanghai. For shipment, the cones were nested inside each other, thereby reducing the volume (Acocella, 2015).

Parametric programming systems were used in the ideation process, which proved essential for optimizing the geometries. The students produced specific programs to control every aspect of production. The aim of this experiment was to demonstrate the potential of CAD and parametric modelling tools and the possibilities open to architects who make use of these technologies.

Temporary Concert Hall - Shigeru Ban Architects - 2011

Shigeru Ban has also left a tangible sign of his building in Italy, with the Paper Concert Hall built in L'Aquila (Abruzzo) after the 2009 earthquake *Fig. 41*. The work is also known as the L'Aquila Temporary Concert Hall to underline its ability to be dismantled and

Figure 42
Paper Partition System Camerino, 2016

Figure 43
Detail of the perforated pipe system

Figure 44
Students of the University of Architecture of Camerino involved in the project

Figure 45
Pre-processed pipes ready for assembly

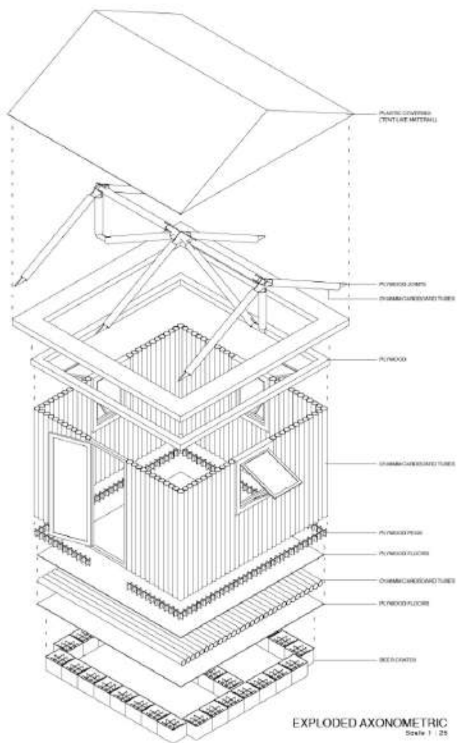


Figure 46
Paper Log House axonometric exploded view

Figure 47
Paper Log House an external view

Figure 48
Paper Log House during assembly

rebuilt in another place, a typical feature of cardboard constructions. The project was presented immediately after the earthquake on 6 April 2009, which caused hundreds of deaths and injuries and extensive damage to the building stock. The construction of the building was a contribution from the Japanese government to show its solidarity with Italy. Contrary to Ban's original idea, the Concert Hall was not built with a pressed cardboard tube structure due to Italian legislation that does not permit structures to be built in materials other than cement, wood, or steel. Nevertheless, cardboard was used for the non-structural parts, giving it a functional role in the acoustics of the concert hall and showing that if treated properly, this material can also solve acoustic problems.

EMERGENCY CARDBOARD ARCHITECTURE

One event shifting Shigeru Ban's attention to the issue of emergencies was the crisis in Rwanda in 1994 involving the massacre of Tutsis and moderate Hutus which resulted in more than two million refugees. Quick solutions had to be found. The architect declared his disbelief at learning of the UN's means of coping with the emergency and was soon appointed as a consultant by the UN High Commission for Refugees. At the time, the UN dealt with such emergencies by distributing plastic sheeting to refugees and procuring timber on site to build temporary shelters. Ban's main concerns with this approach to the crisis was deforestation, the release of large amounts of plastic into the environment, and the time needed to build wooden structures. He proposed the use of prefabricated cardboard tubes, which made construction quicker and more resistant to thieves. This initial experience led to the creation of the Voluntary Architects' Network (VAN) in 1995, a non-governmental organization whose aim is to build structures to help victims of natural disasters and wars. The activities of the VAN encompass research, design, and construction of emergency buildings. The volunteers involved in the organization are mostly Shigeru Ban's students, but they also include architectural students and professionals from different parts of the world who would like to participate in the projects (Ban, 2010).

Paper Partition System - Shigeru Ban Architects and VAN

The Paper Partition System is a system developed by Shigeru Ban in collaboration with VAN to immediately respond to the need for shelter for victims of natural disasters. The system provides a series of micro flats to be inserted within large public containers such as sports centres. The system delimits small reserved areas to guarantee privacy for the families housed there.

The Paper Partition System consists of cardboard tubes woven into a frame and textile dividers. The system was developed in response to the 1995 Kobe earthquake and was also used for the 2004 Indonesian tsunami and the 2008 Sichuan earthquake. The fourth step in the evolution of the project came after the 2011 Japan earthquake, where 1800 units were built in 50 different locations thanks to international funding. The system was also used in Italy in 2016 following the earthquake in the Marche region *Fig. 42-45*, where 50 modules were assembled in collaboration with the Eduardo Vittoria School of Architecture and Design.

With curtain partitions that can be opened or closed, their modular organization makes it possible to adapt the size of the accommodation to different families. The basic module is composed of 2-m-long cardboard tubes interlocked with perforated vertical supports and fixed with simple adhesive tape.

Paper Log House - Shigeru Ban Architects and VAN

The Paper Log House was a temporary housing project first proposed in 1995 by the VAN following the Hanshin-Awaji earthquake in Kobe, Japan *Fig. 46*. The project consisted of small 6-m x 6-m buildings supported by a 108-mm-diameter structure and 4-mm-thick cardboard tubes placed vertically side by side, held together by self-adhesive tape (for initial placement) and horizontal steel bars *Fig. 47*. The floor slab consisted of cardboard tubes covered with wooden planking and supported by foundations made of simple beverage crates weighted with earth or sand *Fig. 48*. The vertical walls were connected to the floor slab via a wooden joint. The light cover consisted of plastic sheets laid over the cardboard structure. The only finishing operation was the application of a polyurethane-based paint to the bare paper tubes to guarantee their weather resistance. The construction of each building was simple and could be carried out in a short time (about six hours) by unskilled labour at a cost per unit of less than $2000. Over the years, the project has been repeated in Turkey (2000), India (2001), and the Philippines (2014). As implemented in Turkey and India, the design was revised slightly due to the number of household members involved. In Turkey, the tubes used for the walls were also filled with recycled paper to increase thermal insulation. Since it was not possible to find plastic boxes in India, the rubble of destroyed buildings was used for the foundations, which were covered with a layer of soil, and the roof was made of matting. The project was most recently used in the Philippines, where cardboard was used only as a frame and

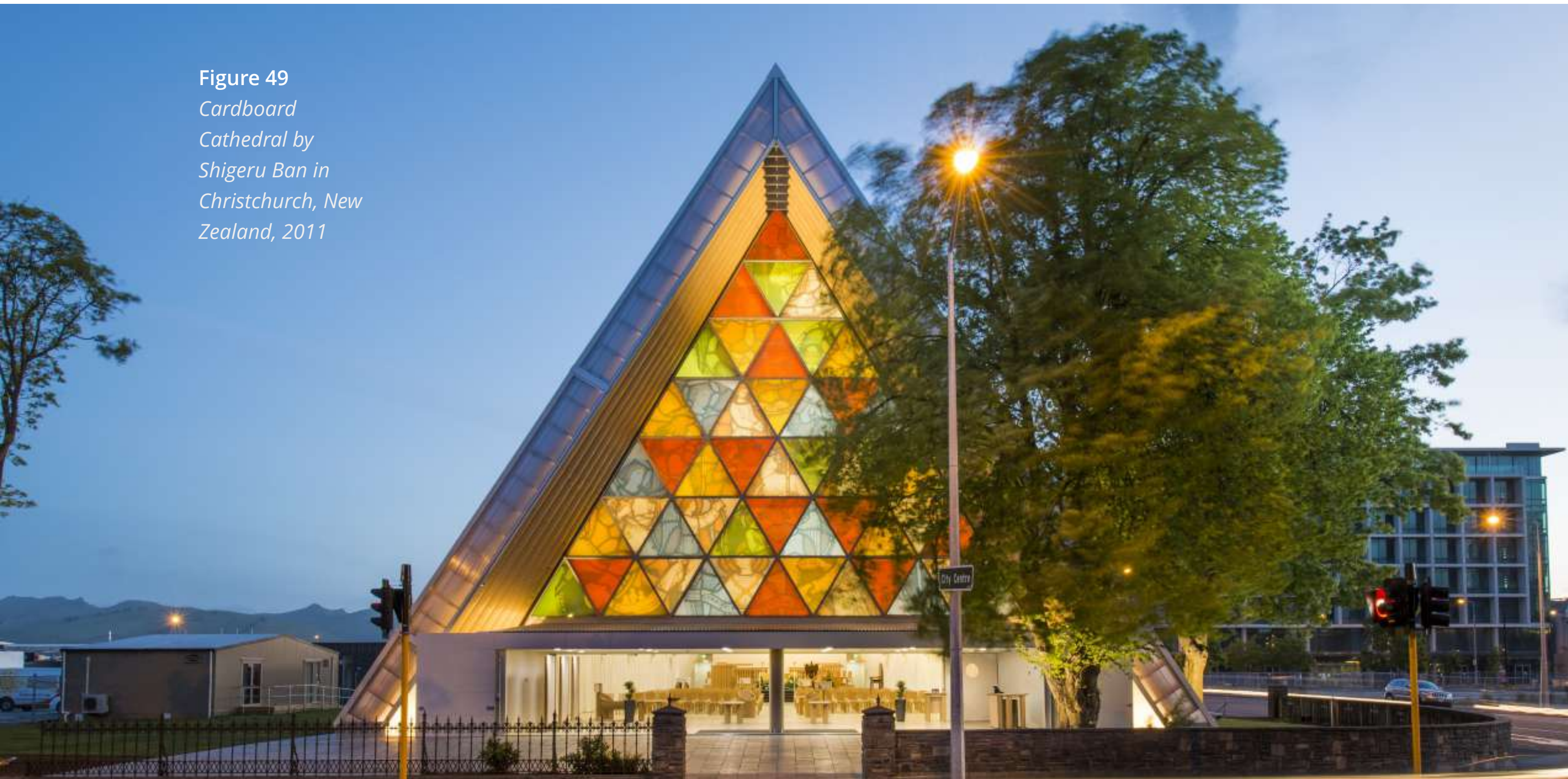


Figure 49
Cardboard Cathedral by Shigeru Ban in Christchurch, New Zealand, 2011

the structure was again covered with matting. Given the favourable climate conditions, a permeable outer surface was useful for letting air and light filter into the interior. The idea of using cardboard only for the frame structure came from Shigeru Ban's Partition System, a system of lightweight partitions for emergency.

POTENTIAL AND LIMITS OF THE USE OF CARDBOARD IN ARCHITECTURE

Cardboard is a common material in our daily lives. It is light, low cost, and, in specific contexts, environmentally friendly. The packaging industry makes wide use of it, while it has been and remains a material tied to experimentation in the building sector. In various processes it presents interesting mechanical properties, but it is also subject to several vulnerabilities. Its light weight, ease of transport, low cost, and ability to slide and be folded has already led to several projects for temporary housing in disaster and war-torn areas. Its mechanical compressive strength when shaped as a tube means that this material has also been chosen for structures intended to last over time. However, it is still a material with two significant weaknesses: poor resistance to atmospheric agents and poor fire resistance. Unless they are overcome, these specific disadvantages prevent cardboard from playing a decisive role or being widely used in construction. Current research on cardboard shows that the possibilities of this material have not been fully explored, and new hybridization can improve these characteristics, guaranteeing a robustness and durability that it does not currently possess.

Contemporary architecture has had many opportunities to employ cardboard. It has been used in architecture in a variety of forms and technologies, evolving into increasingly innovative solutions. As well as responding to technological challenges, the use of cardboard has been rewarded in contexts where it was necessary to contain costs or minimize building waste. With the tenacity of early adopters and studies conducted today in different regions around the world, the use of cardboard for structural purposes is also permitted by legislation.

COCNLUSION

Designers have been using cardboard as a building material for some time now, and it is becoming more popular. Buckminster Fuller was one of the first to experiment with it, and his work inspired others to continue exploring its potential. There are limitations to what can be done with cardboard due to the technology available, but current designers are finding new ways to use it. Cardboard is environmentally friendly and sustainable, making it a popular choice for green architecture. Shigeru Ban is credited with promoting cardboard as a construction material and has used it in various projects, including an exhibition pavilion and an exhibition in honour of Finnish architect Alvar Aalto. He has also conducted studies on the use of cardboard as a structural element in architecture.

The use of paper-based products for home furnishings and furniture has been around for a long time. However, in recent years, cardboard has also been used as a low-cost and environmentally friendly material for architectural forms. New architectural solutions must involve materials that are sustainable and easy to produce. Cardboard has many of these characteristics, even if its life cycle is potentially limited. The durability of cardboard has been tested in public buildings and has been tested to last for over 20 years. Despite this, cardboard is not generally considered a long-term building material. Architects and engineers have nevertheless continued to explore its potential in public architecture due to its environmental compatibility. While cardboard is not expensive to produce, innovative solutions for public architecture based on this material can be more costly than traditional techniques and materials. However, the high cost and ecological burden of short-lived events, such as fairs, exhibitions, and sporting events, has led to a trend of using cardboard as a naturally recyclable material to counteract this. Cardboard architecture for emergency use is an emerging field that uses cardboard and recyclable material to create temporary or emergency shelters. Shigeru Ban's attention to emergencies was sparked by the 1994 Rwandan genocide, during which he was appalled by the UN's response. He soon became a consultant for the UNHCR, and began developing prefabricated cardboard shelters as a more efficient and environmentally-friendly alternative to traditional emergency shelters. This work led to the creation of the Voluntary Architects' Network, which helps build emergency structures in disaster zones.

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How much does your building weigh?

A question often used to challenge architects to consider how efficiently materials were used for the space enclosed.

Richard Buckminster Fuller

Cardboard workings

Corrugated cardboard was invented and patented in the mid 1800s and has always been used primarily for packaging. It is a light, versatile, low-cost material with an eco-sustainable lifecycle. Even today, the cardboard industry produces this material purely for packaging; it is little used in the construction sector. According to Italian regulations, it cannot be used in architecture as a structural material, so any use must instead exploit its thermal/physical characteristics to the fullest. This material can play an important role in architecture as an insulator and cladding due to its mechanical, acoustic, and thermal properties, which can be improved by hybridizing it or modifying its geometry.

First invented in the East, paper arrived in Europe with the Muslim conquest of the Iberian Peninsula, where the first paper mill was founded in the city of Xàtiva in 1144. The Arabs established paper production sites in Italy in Amalfi and Fabriano, leading to innovations in the production process. Paper production also soon began in the rest of Europe. The expansion of paper production progressively touched countries in Central Europe, Northern Europe, and Eastern Europe, arriving in the New World in 1690 (Scott et al., 1997).

When paper appeared in Europe in the twelfth century, parchment was still the most widely used material for writing. Parchment was a valuable material for disseminating information, but it took several centuries for it to be replaced with paper, and in 1452, the Gutenberg Bible was printed simultaneously on parchment and paper (Helfrich and Peters, 2011).

In modern times, the Frenchman Louis-Nicolas Robert patented a machine for the continuous production of paper, touching off a series of subsequent inventions that optimized paper production until becoming the process we know today. Inventions in the eighteenth and nineteenth centuries concerning raw materials and the production of paper and cardboard led to a revolution in the paper industry, which in turn led to the inexpensive, mass production of paper products and further developments. Most importantly, paper became a widely available material (Biermann, 1996).

One important invention was the first single-wall corrugated cardboard produced in 1881 by the American company Thomson & Norris. Corrugated cardboard had been invented and patented by two Englishmen, Edward Healey and Edward Allen, in 1856 and this neat fluted paper was used to line men's hats. In 1871, Albert L. Jones had used corrugated cardboard to wrap fragile objects such as

The old Japanese technique for making paper.

bottles(Helfrich and Peters, 2011), and a few years later, corrugated cardboard with one or both sides glued to a liner was patented in the United States. As a material for boxes, corrugated cardboard has been used since the early 1900s.

Modern paper production reached a record high in 2010 with the creation of a paper machine producing 600 m of 11. 8 m wide rolls at a speed of 1700 m per minute. However, due to the advent of new digital technologies, printing paper production has steadily declined since then, according to statistics provided by the CEPI (Confederation of European Paper Industries) (CEPI, 2020). Paper manufacturers are currently looking for new ways to compete in the global market, and one such way may be the innovative use of cardboard in architecture.

CLASSIFICATION OF PAPER AND CARDBOARD IN MODERN INDUSTRY

Corrugated cardboard was invented and patented in the mid 1800s and since then has been used primarily for packaging purposes. It is produced by assembling several sheets of cardboard leading to a light material with a high compressive strength. The mechanical strength of the cardboard is guaranteed by the application of one (or more) corrugated components *Fig. 1*. According to the number of corrugated elements, the cartons may be classified as:

- *SINGLE FACE: one liners and one fluted;*
- *SINGLE WALL: two liners and one fluted centre;*
- *DOUBLE WALL: two liners, two fluting sections, and a sheet sandwiched between the sections;*
- *TRIPLE WALL: two liners, three fluting sections, and two sheets sandwiched between the sections.*

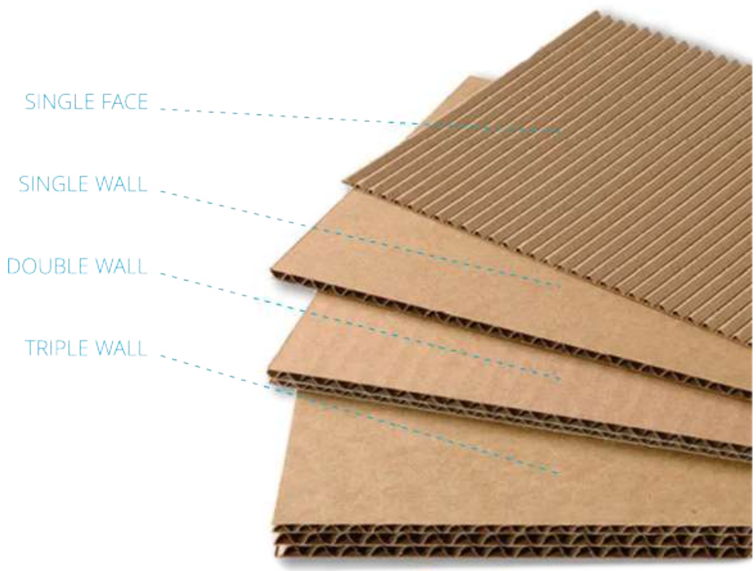
Modern production of this material is also classified according to fluting profile, paper quality, and weight. Depending on the thickness, cardboard is classified with a letter according to the following standard:

	CLASSIFICATION	THICKNESS
HIGH FLUTING	A	4. 5 mm
	K	5 mm
MEDIUM FLUTING	C	> 3. 5 mm
LOW FLUTING	B	> 2. 5 mm
MICRO FLUTING	E	> 1. 2 mm
	F	> 0. 8 mm

With specific reference to the mechanical characteristics of the paper, further differentiation and classification can be made between liner paper (e. g. Kraft and Test) and fluting paper (e. g. Fluting and Semi-Chem). This production is specified in the table below:

LINER PAPERS	CLASSIFICATION
CHIP	C
WHITE CHIP	K
TEST	WC
WHITE TEST	T
LINER	WT
WHITE LINER	L
KRAFT	K
WHITE KRAFT	WL
KRAFT	K
WHITE KRAFT	WK

Figure 1
Types of corrugated cardboard based on the number of sheets used



CHIP is a liner paper produced from recycled pulp; it usually has reduced mechanical characteristics. TEST is a paper produced from one or more layers with a more fibrous material inside to improve its mechanical characteristics. LINER paper is produced similar to the previous ones, but with a pulp mixed in to increase its mechanical performance. Finally, KRAFT paper contains a mix of pulp derived from conifers and at most 20% from broadleaf trees to ensure maximum mechanical performance. It is produced in both brown and white with the same characteristics *Fig. 2*.

CLASSIFICATION	WEIGHT
class 2	125 g/m²
class 3	150 g/m²
class 4	175 g/m²
class 5	200 g/m²
class 6	225 g/m²
class 8	275 g/m²
class 9	300 g/m²
class 02	337 g/m²
class 04	400 g/m²
class 06	440 g/m²

Liners are classified according to their weight as follows:

FLUTING PAPER	CLASSIFICATION
FLUTING	F
MEDIUM	M
SEMI-CHEM	S
SCANDINAVIAN SEMI-CHEM	SS

Light liner paper of 125 g/m² up to heavier paper of 440 g/m² are commonly available on the market.

FLUTING paper is a recycled paper with low mechanical performance (similar to CHIP paper). Paper in the MEDIUM class combines recycled pulp and SEMI-CHEM pulp with good mechanical characteristics. SEMI-CHEM paper contains 65% of broadleaf pulp for high mechanical performance. The production of SCANDINAVIAN SEMI-CHEM paper differs from the above due to the origin of the production; it has very high mechanical properties.

	CLASSIFICATION	WEIGHT
FLUTING	class 2	120 g/m²
	class 4	145 g/m²
	class 6	170 g/m²
	class 9	210 g/m²
MEDIUM SEMI-CHEM	class 2	112 g/m²
	class 4	127 g/m²
	class 6	150 g/m²
	class 9	180 g/m²

Fluting paper is classified based on weight, as follows:

The market commonly offers lightweight recycled corrugated paper weights of 120 g/m² to heavier paper weights of 210 g/m², while the most robust papers have weights from 112 g/m² to 180 g/m².

These distinctions are helpful when creating an accurate classification.

Manufacturers and buyers refer to the types produced by identifying the cardboard assembly. As an example, for simple single-wall cardboard, it is described from outside to inside using the following coding from left to right:

corrugated cardboard ***KSL 322 C***

- ***K*** *indicates an external liner made of KRAFT paper;*
- ***S*** *indicates fluting in SEMI-CHEM paper;*
- ***L*** *indicates the inner layer in LINER paper;*
- *the number* ***3*** *indicates the weight (according to the classification) of the liner;*
- *the number* ***2*** *indicates the weight of the fluting;*
- *the number* ***2*** *indicates the class of the inner layer;*
- ***C*** *indicates the type of fluting used (medium fluting)*

Figure 3
Wood chips ready for pulp reduction.

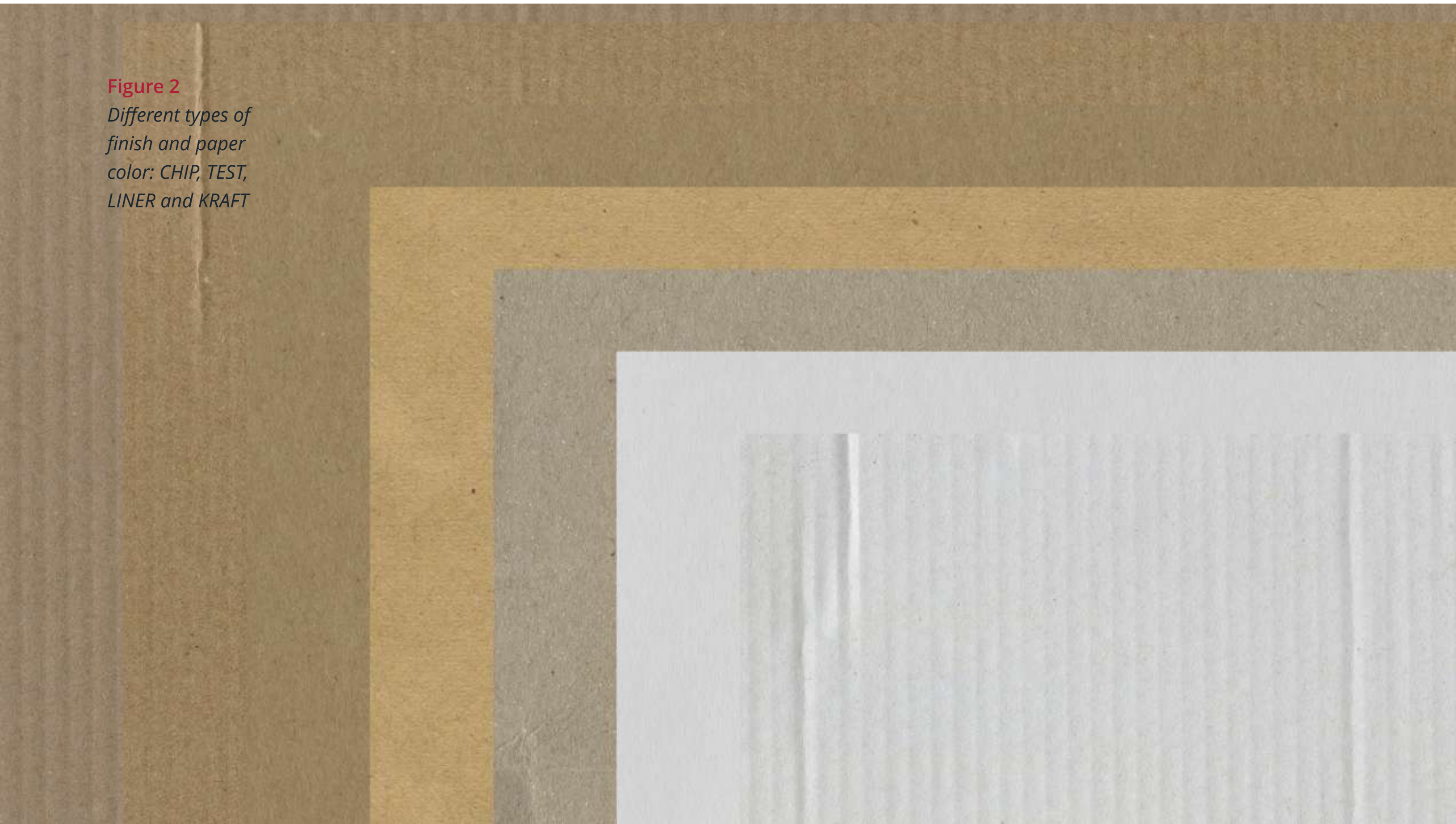


Figure 2
Different types of finish and paper color: CHIP, TEST, LINER and KRAFT

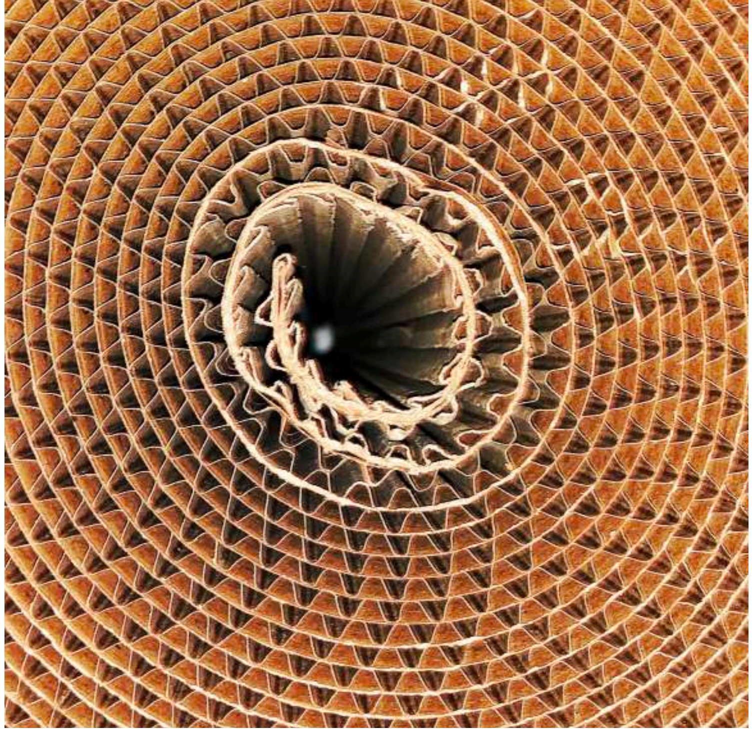


Figure 4

A single sheet carbord coil

THE INDUSTRIALIZED PAPERMAKING PROCESS

The heart of quality cardboard production is, of course, paper production. Nowadays, high-quality paper production requires a technologically advanced process that starts with wood and integrates a recycling phase that uses production waste and a large percentage of recycled material. The main phases in paper production are the following:

- *debarking and chipping;*
- *pulp reduction;*
- *washing;*
- *pressing;*
- *drying;*
- *calendering;*
- *reduction into sheets;*
- *processing into secondary products;*
- *recycling.*

The production process starts in the forest where wood, the renewable raw material used in the *Fig. 3* pulp industry is grown in sustainably managed forests. The bark is removed from the trunk and the rest of the wood is made into pulp through two possible processes, mechanical or chemical. In the first case, chips are ground to separate the fibre. This type of processing produces pulp used mainly for high-volume printing products such as newspapers or magazines. Chemical processing involves heating the material to remove the lignin, with the burning process self-powered by production waste. The washing (or cleaning) process is used to hydrate and soften the compound, which can be used directly or undergo a leaching process using sodium carbonate, caustic soda, or lime. The compound is spread on a metal band where it is further diluted (up to a hundred times its weight) so that the fibres can spread and consolidate to form a sheet. The material is fed into a press that reduces the water content by half and is dried between metal cylinders heated to 100°C. The paper then undergoes a coating process and pigment is applied. This process can be repeated several times to improve the printability characteristics. After coating, the paper may be calendered to give it a smooth, glossy appearance. The final production stage involves winding the paper onto a reel or reducing it into sheets for printing or further converting.

FROM PAPER TO CARDBOARD

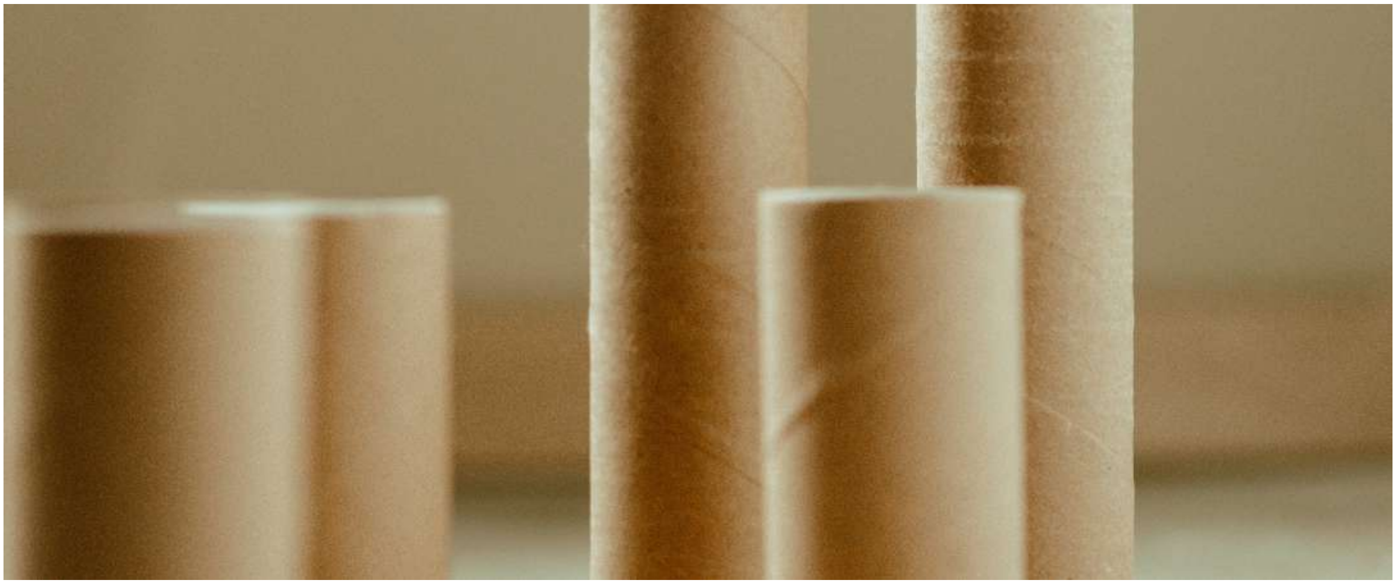
The transformation of paper into cardboard starts with a reel of paper that is fed into a machine that squeezes the paper between two rollers and sprays it with steam to imprint the corrugated shape. Glue, which mainly consists of water and starch to avoid possible contamination if the cardboard is used for food, is applied to one side of the corrugated cardboard for assembly. One liner is glued at a time until the finished product is complete. In this phase, recycled material is used for its workability. The finished cardboard is then cut and sold for further transformation into finished products.

CARDBOARD: BEYOND PACKAGING PRODUCTION

While the origin of this material is ancient, its use for purposes other than printing is relatively recent. Only in the last 150 years have paper and its derivatives been used as elements for producing everyday objects or structures, emphasizing the positive characteristics that this material gives to the finished product. In the history of architecture and design, there are many cases in which materials based on paper, cardboard, paper tubes, and honeycomb panels have been used in different ways for furniture production, internal partitions, entire construction pavilions, or larger architectural structures.

As a material, paper is associated with a use in geometric shapes that best characterize the use for which they are designed, sometimes with a preference for cylindrical shapes and sometimes for folds derived from the world of origami or joint frames.

The average lifespan of these objects can be defined according to the accumulated experience of cardboard creations, and their duration is tied to the quality of the design and the intensity with which the product is used. For example, for furniture objects in industrial design, arts and crafts, or everyday objects, we can estimate an average lifespan of five years. Moving up the scale to exhibition pavilions, stage sets, and objects designed for temporary use, a one-year lifespan can be estimated. Architecture and buildings may have a lifespan between twenty and fifty years. Momentary structures for emergency use made of cardboard are thought to last around five years, with the hope they will



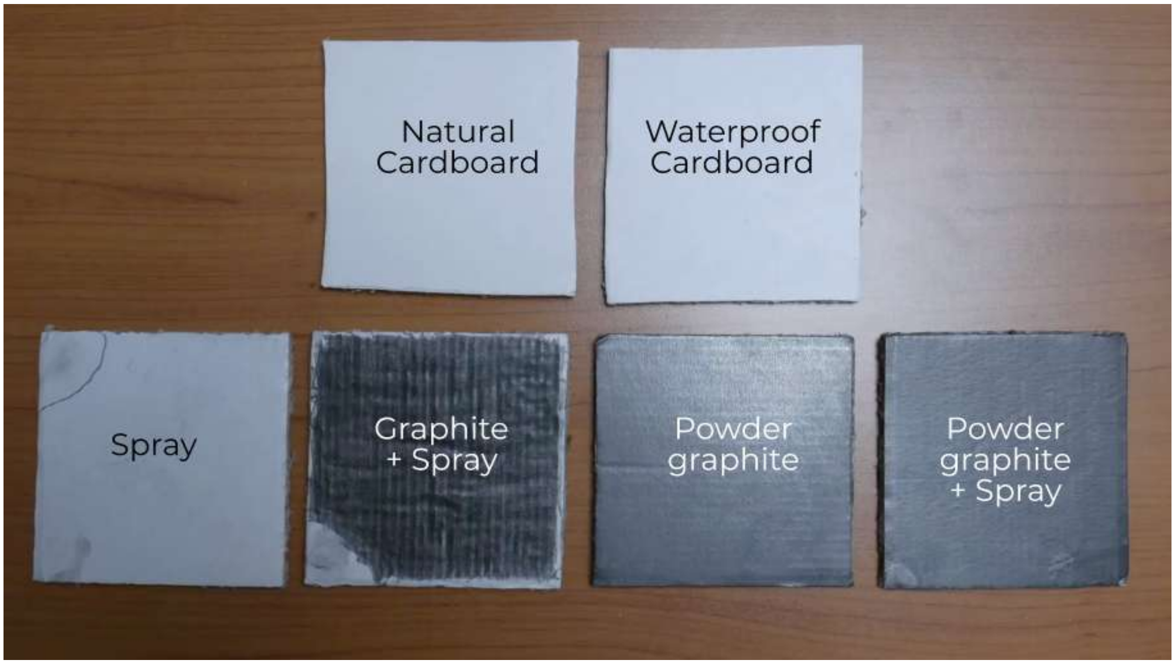


Figure 5
Waterproof cardboard test

be needed for much less time. More than a century and a half of architectural production in paper and cardboard show that this is a material that can strongly inspire new forms of building by encouraging parallel and transverse lines of research in different disciplines.

STRENGTH ASSESSMENTS ON CORRUGATED CARDBOARD

Cardboard is a material that can be used for many different processes. In addition, its thermophysical characteristics have been studied and regulated to guarantee high-quality standards depending on the use. For this reason, there is no one size fits all for every physical quantity measured. The tests conducted on the board to determine the best characteristics are:

- ***Cardboard grammage**: is the weight of the cardboard per square metre; it will be nothing more than the sum of the weights of the covers, plus the weight of the waves (the weight per square metre will have to be increased according to a waviness coefficient which will vary according to the thickness and pitch of the wave) and the weight of the adhesives.*
- ***Cardboard thickness:** measures the distance in mm between the two outer surfaces of a corrugated board.*
- ***Edge Crush Test (ECT):** it is a compression test that is carried out on a strip of cardboard, aimed at measuring the effort expressed in kN/m (in the S.I. system; the data expressed in kg*cm can also be commonly obtained) necessary to deform the strip itself. It compares the various corrugated cartons with their*

resistance to compression and is closely related to the stacking resistance of the packaging.

• ***Burst resistance:*** *Measures the drilling resistance of a corrugated carton. It is expressed in kPa in the S.I. system (or more commonly in kg/cm²) and is the measurement of the breaking resistance of a cardboard subjected to pressure in an orthogonal direction to its surface.*

• ***Box Compression Test (BCT):*** *measures the resistance of an empty corrugated box to vertical compression, i.e. how many kilograms a box can carry before it crushes. This figure correlates strongly with the ECT of the cardboard box.*

• ***Water absorption (COBB):*** *measured in g/m2 the amount of water absorbed by a given board subjected to a water column pressure of 1 cm in a given time interval. The data obtained can be helpful both for printing considerations (as flexo colours are water-based) and when using a board in humid environments (e.g. cold stores or cellars).*

• ***Air permeability (Gurley test):*** *is usually applied to individual papers and measures in seconds/centimetre (time×paper area/air volume) the time it takes for the amount of air contained in a volume of 100 ml to flow through a 6.45 cm² (1 square inch) paper surface. This is important when the board is handled using automatic suction cup machines.*

INSULATING MATERIAL FROM PAPER AND CARDBOARD

To optimize the insulating properties of paper and cardboard is possible to reduce it to cellulose fibre. This material was developed in the first half of the nineteenth century and immediately demonstrated excellent resistance to time, but the old cellulose fibre required maintenance and had a maximum life span of 70-80 years. Modern technology has further improved the resistance characteristics, particularly the introduction of mineral salts mixed with cellulose fibre. Cellulose Fiber is a naturally dry-applied insulation material made from recycled paper that is shredded. Mineral salts are also added to the fibre compound to make the product resistant to fire, water and insects, mould, microbes and rodents. Cellulose fibre is highly breathable and acts as a "hygrometric reservoir", i.e. it absorbs moisture, making the environment drier to be released when it becomes less humid, thus promoting healthy structures and the home well-being. Furthermore, cellulose fibre comes from wood and therefore has the best thermal characteristics of this noble material. In summer, cellulose fibre achieves the highest thermal inertia value among natural and synthetic insulating agents, thus bringing the most significant benefit to the most relaxed home, thanks to the massive elimination time of the heatwave.

The three main technical characteristics of the natural insulation in bulk in Cellulose Fiber are:

• ***Thermal Conductivity (λ)****: 0, 037 W/m2K. This value indicates the heat transmission capacity of cellulose fibre. For an insulation, the thermal conductivity must be as low as possible; that is, it must pass through little energy through its thickness.*

• ***specific heat****: 2100 J/Kg°K. This value represents the amount of energy (Watt) required to heat one kilogram of this material. Therefore, the higher the value, the more significant the phase shift of the heatwave, i.e. the delay in the time it takes for the sun in summer to transport heat.*

• ***Breathability coefficient (μ)****: the value varies from 1 to 2*

Cellulose fibre is found to be of very high quality and performance.

IMPROVE CARDBOARD WATERPROOFNESS

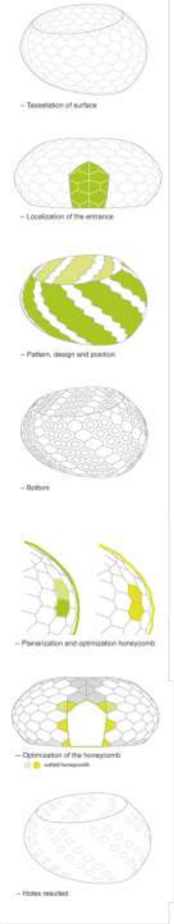
In order to improve the resistance of corrugated board to liquid absorption, experiments were carried out using graphite as a sealing material to be applied to the outer surface of the board. This surface waterproofing method was chosen in order not to alter the recyclability properties of the board.

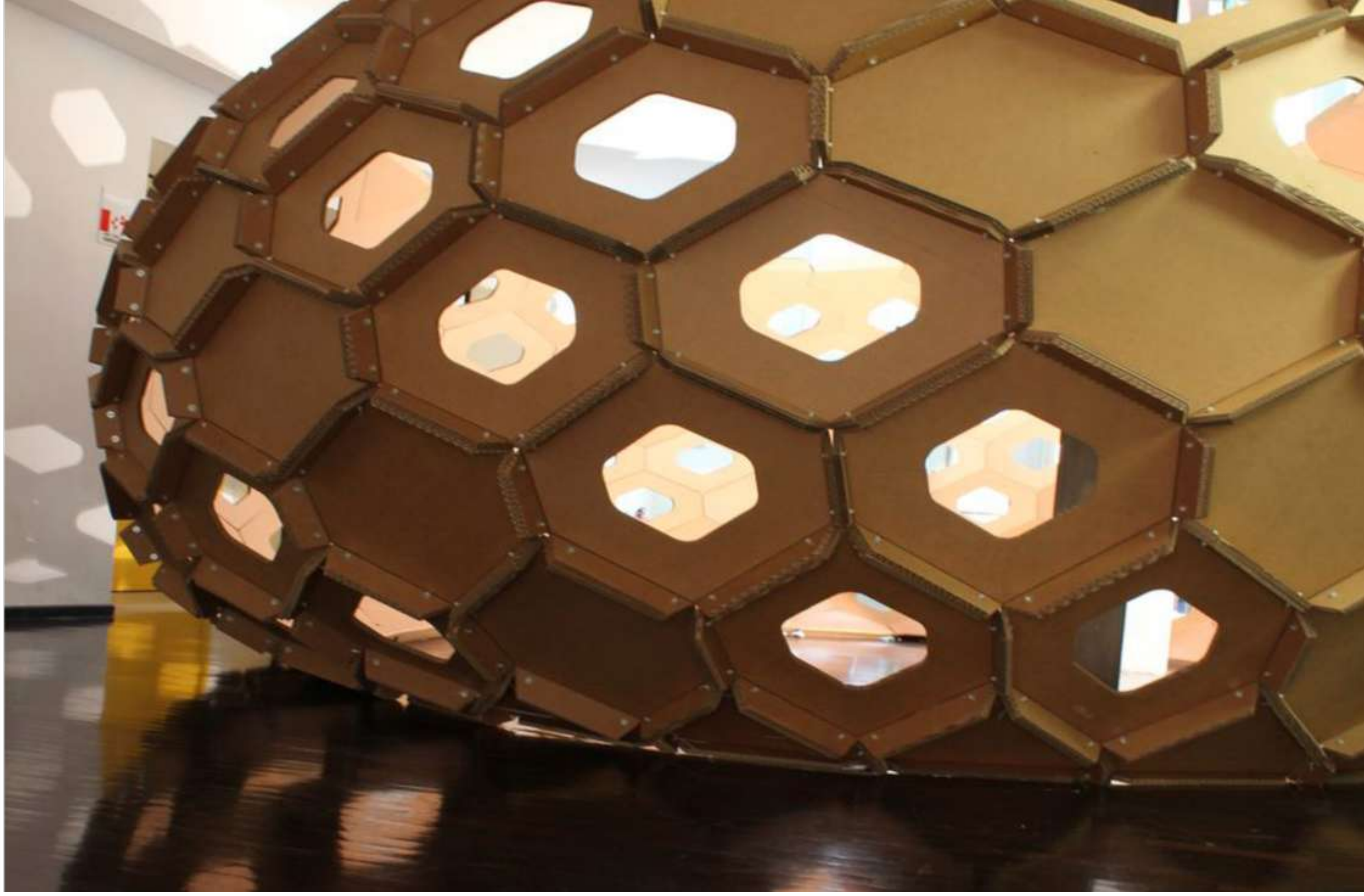
The tests were carried out on microwave corrugated cardboard surfaces. Each of the samples was subjected to a water jet to check the absorption of the material.

- *The first sample was not treated at all.*
- *The second (control sample) was covered with a layer of transparent waterproofing paint.*
- *Finally, the third sample was treated by applying a thin layer of graphite to the surface.*

The first sample showed the absorption of the liquid and lost a large part of its structural capacity. the second sample, treated with the varnish, did not suffer any damaged point. Finally, the third sample, treated with the graphite layer, performed similarly to the second sample ***Fig. 5***.

Currently, the use of paints makes the cardboard not reusable because it is a special waste. This test has shown that it is possible to develop an in-house cardboard processing technique to improve the impermeability of





TECHNOLOGIES AND TECHNIQUES FOR CARDBOARD CONSTRUCTIONS

Architecture and design continuously use and update the methods of representation and construction. As in the design phase, which is now entirely supported by the use of computers, the project realization phase has also relied on computers to enable the automation and robotization of production systems. Digital manufacturing has sparked a revolution in design with myriad inventions and architectural innovations that wouldP be difficult without the help of such automation. Digital practices have the potential to reduce the gap between representation and construction, offering a continuous hypothetical connection between design and realization of the building (Iwamoto, 2013). Computers are indispensable tools at every stage of the design-construction process. Digital manufacturing intervenes in the last part of the production process, where it is possible to make prototypes for study purposes or to realize an idea quickly and with extreme precision. Digital manufacturing refers to the set of techniques and technologies developed in industry and already widely used for decades, which are now also accessible to architecture and design.

In recent years, many architects have experimented with digital manufacturing technologies. Frank Ghery was one of the first to use these technologies to study large-scale works when he designed and built the Walt Disney Concert Hall in Los Angeles in 1989. The forms were studied using CATIA software (Computer Aided Three-Dimensional Interactive Application) which had been developed for the aerospace industry. The outer envelope of the building was initially designed in stone and glass. The studio produced mockups in cut stone using numerically controlled milling machines, illustrating the feasibility of the work and the low cost of manufacturing unique elements because they were made using innovative techniques. Gary Lee Partners has continued to use these technologies countless

Figure 6
Cocoon pavillion MEDAARCH and Co-de-iT

Figure 7
Cardboard Houses Exhibition University of Chongqing in China

times and in 2002, it contributed to the development of Digital Project, a version of CATIA *Fig. 8 and 9* adapted and specialized for complex architectural works.

The shift from design to construction involves translating the three-dimensional drawing into 'digital data' (two- or three-dimensional) which can be interpreted by numerically controlled machines. This means that architects have to learn a new language and change the way in which they approach the design phase. Some operations used to translate into machine language are automated, but requires new digital skills specific to each process. Professionals using digital technologies study such tools and test different combinations of processes and material processing. They have now identified which processes are preferable based on the material and resulting visual effect. The compositions may take shape through assembly, modelling, ornamentation, or organization between the constituent parts. Digital manufacturing offers different solutions for cutting, milling, punching, die-cutting, or shaping through the addition of material.

With digital production techniques, it is possible to lend new quality and a new artisan language to architecture.

Among the many materials tested using digital manufacturing techniques, cardboard has certainly stood out for its ability to be employed with different techniques. Possible actions include cutting and engraving, folding, layering, and interlocking.

CUTTING AND ENGRAVING

Underlying any possible work with cardboard are cutting and engraving operations, which are essential for the subsequent assembly. The elements can be cut using blades or lasers. Although it is widely used in the production of cardboard packaging, die-cutting does not fall within the family of techniques for digital manufacturing since such processing does not allow each job to be

Figure 8
Walt Disney Concert Hall by Frank Gehry

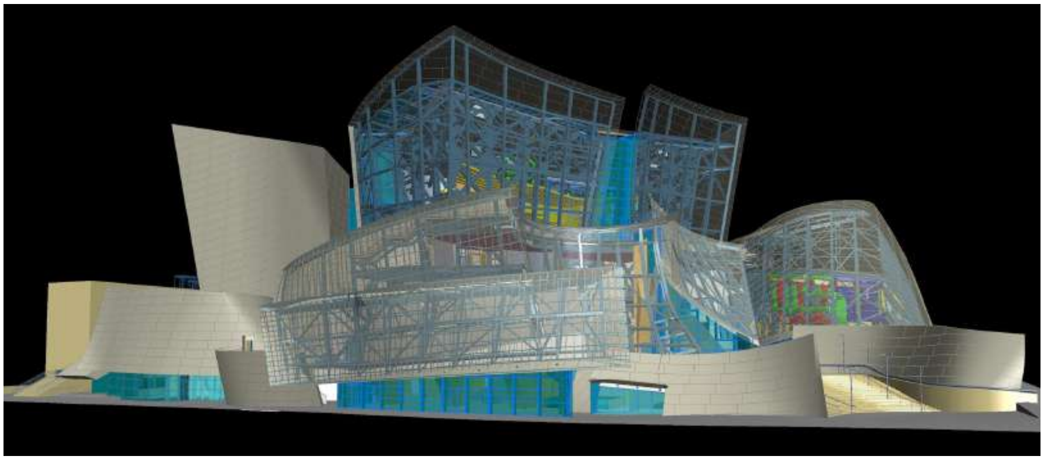
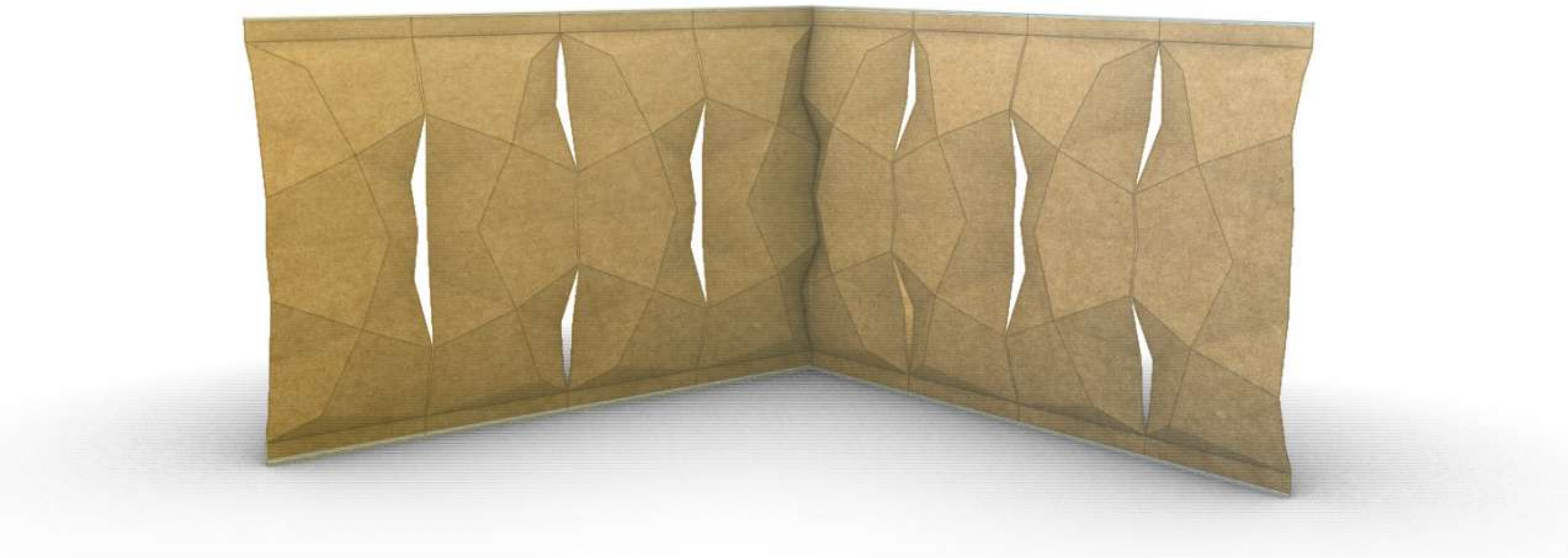


Figure 9
Walt Disney Concert Hall digirtal study with CATIA



varied. Blade-based cutting machines are known as 'cutting plotters'. They consist of an element that can slide on the table holding the accessory for cutting/ engraving or creasing in two separate steps. In the case of laser cutting, the machines have a similar set-up, with the difference that the moving element carries a laser. Laser processing creates a burn along the cutting curves and the power of the laser can be adjusted to cut or engrave the surface of the cardboard in a single pass. In some cases, engraving may replace creasing by helping the material to fold more easily. The advantages of digital manufacturing include the ability to optimize cutting of elements within the sheet while minimizing waste, an operation known as 'nesting'. This may be performed manually by the operator or automatically through the use of specific algorithms that recursively position the pieces within a work area, with consideration for the minimum distance between the various pieces.

Figure 10
Origami stand Di Battista

Figure 11
Diamond box Unicam and Di Battista logos are laser engraved

FOLDING

Folding gives objects made with this technique a softness that contrasts with the natural rigidity of the cardboard. This category also includes geometries inspired by the Japanese tradition of origami. It is precisely from origami that the folding techniques have inherited the alternating division of the structure into mountain and valley folds.

Each fold creates a flexible hinge, and the different compositions between rigid elements and hinges define possibilities for resisting different stresses. Folded sheets can take the shape of single or double curves, defining one or more main axes of inertia. A folded structure may be composed of one or more sheets, which in turn must be connected using adhesives or other types of bonding materials.

The overriding feature of elements created through folding is the dynamism of the shapes, which may be changed multiple times to form different configurations (open-closed).

The folding technique allows the simple creation of enclosed spaces and it is therefore mainly used to create elements of separation and pavilions.

Origami stand Di Battista - Graziano Enzo Marchesani

One of the first experiments carried out during the doctoral work was a request from the company Di Battista to create elements for its stand at the Tipicità 2018 trade fair *Fig. 10*. The project involved the application of corrugated cardboard panels folded in a many-sided pattern. The segments were simply creased and light pressure was applied so the structure could take the desired shape. For greater structural resistance, the cardboard fluting was situated vertically. The parts were held fixed at the top and bottom by a metal frame.

DIAMOND BOX - GRAZIANO ENZO MARCHESANI

The Diamond box stemmed from the need to make a small cardboard container that could be produced quickly without the use of adhesives *Fig. 11*. The diamond cut is inspired by the Yoshimura origami pattern. The production process for this box is completely digital and can be scaled parametrically based on the thickness of the material. No punch is needed but a laser cutter is used. This technology also enables graphics to be engraved without the need for printing. The use of laser engraving rather than creasing gives the box a unique appearance during folding, where the internal fluting is visible. The structure is held together through a male-female joint using the two ends of the box.

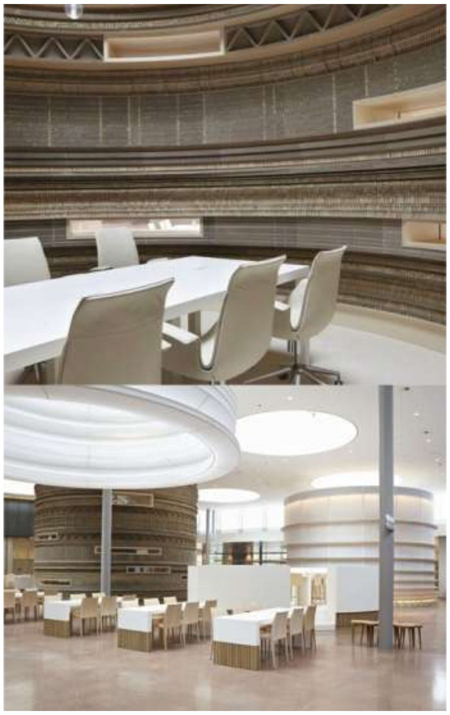


Figure 12
Rabobank Headquarters carboard interiors Sander Architecten

Figure 13
Easy Edges forniture Wiggle Side Chair and Wiggle Stool Frank Gehry, 1972

LAYERING

In the layering technique, materials are overlapped to give the object a feeling of heaviness and solidity that cannot be achieved through any other technique.

Layered objects are generally made by 'slicing' the volume to be created with a pitch equal to the cross-section of the material. The sections thus obtained are placed side by side and held together with adhesives.

By eliminating voids inside the structure, this technique enables the construction of elements that are very resistant to compression in all directions.

The layering operation is not reversible and, given the strong resistance to compression, is used above all to create small furnishing elements.

Easy Edges forniture - Frank Gehry

In the early 1970s, architect Frank Gehry created a furniture series called Easy Edges *Fig. 13*. Famous items in the collection include the Wiggle Side Chair and the Wiggle Stool, a seat and a small table, respectively. The entire series was made by gluing together shaped cardboard sheets, alternating the orientation of the fluting. Although apparently simple, this operation yields solid, durable elements by filling as much volume as possible. The lines in the series are soft and reminiscent of a tatami mat, contrasting aesthetically with their structural strength.

Rabobank Headquarters interiors - Sander Architecten

Sander designed the interior of the Rabobank building entirely out of cardboard and washi paper. The large space is left open without divisions to accommodate the flow of people, except for two small cylindrical rooms which create reserved spaces *Fig.12*. The walls of one are made of washi paper and the other is made of

Figure 14
The MC 302 chair designed by Nordwerk

Figure 15
HyPar-Table designed by Nordwerk

several layers of corrugated and honeycomb cardboard. The use of different types of cardboard creates different textures, varying the visual and tactile appearance of the walls. The various cardboard layers are simply shaped, overlapped, and glued together. The cross section of the walls increases as they rise, yielding a space that looks cylindrical on the outside and tapered on the inside. There are also small glazed slits with wooden frames to diffuse the light.

INTERLOCKING

The interlocking technique, commonly known as 'waffling' lends objects a great three-dimensional appearance, and the interplay of solids and voids endows them with aesthetic and functional lightness. This technique enables the production soft, rounded shapes using rigid materials.

Waffle structures are built by placing two-dimensional elements originating from the section of a volume side by side. The interlock is created by cutting one or both sides at the joint so that the elements can be embedded either totally or partially. There is no need for adhesives and assembly is quick and reversible.

When subjected to loads transverse to the main direction of inertia, these structures are weak at the nodes, which act like flexible hinges, so the use of these structures must clearly be limited to supporting loads acting along the main axis of inertia. However, due to the poor capacity of the panel to resist compression in the direction of corrugation, it is easy to find examples where the structure is designed to support only its own weight. In cases where this technique is used for load-bearing structures, the ratio between the spacing and the thickness of the profiles is sized appropriately, strongly limiting the feeling of lightness.

The waffle joint technique is therefore used to make small furniture elements and exhibition halls.

Figure 16 and 17
Honeycomb cardboard pavillion designed by cartonLab

Figure 18
Giant cardboard apple trees cardboard pavillion cartonLab

Nordwerk MC 302 and HyPar-Table - Nordwerk Design

The MC 302 chair and HyPar-Table are two furniture items designed by Nordwerk *Fig. 14 and 15*. They are made using the waffle joint technique. The studio created these elements out of cardboard and provides technical drawings free of charge so interested individuals can make their own version of these objects using materials other than cardboard.

Honeycomb cardboard – cartonLab

This pavilion is made of cardboard panels produced by Nidokraft, which also promotes the project *Fig. 16 and 17* To create the construction, large sheets of honeycomb cardboard were shaped using a CNC milling machine. The entire pavilion is self-supporting and was built without the use of adhesives. The authors themselves compare the work to a large jigsaw puzzle because of the size of the panels. The entire pavilion occupies an area of approximately 30 m^2.

Giant cardboard apple trees – cartonLab

This stand was exhibited at the Paris International Agricultural Show 2020 ***Fig. 18 an 19***. The design represents a 'cardboard apple tree forest'. The interlocking roof above is only for aesthetic purposes; it is supported by a metal structure. The vertical elements representing the tree trunks are self-supporting structures resting on the ground and connected to the roof by a cardboard insert.

CONCLUSIONS

The cardboard industry produces it mainly for packaging, but it can also be used as an insulator and cladding due to its mechanical, acoustic, and thermal properties.

The key to making good cardboard has a good paper production process. This process starts with wood, uses recycled material, and goes through several steps, including debarking, pulp reduction, washing, pressing, drying, calendering, and sheet reduction.

Turning paper into cardboard involves squeezing the paper between two rollers to create a corrugated shape and then glueing one-liner at a time until the finished product is complete. Recycled material is often used in this process to avoid waste.

Paper is often used in geometric shapes for specific purposes. The average lifespan of cardboard objects depends on how they are used - for example, furniture objects in industrial design, arts and crafts, or everyday objects have an average lifespan of five years, while exhibition pavilions, stage sets, and objects designed for

Figure 19
Giant cardboard apple trees cardboard pavillion cartonLab

temporary use have a lifespan of one year. Architecture and buildings may have a lifespan between twenty and fifty years. Momentary structures for emergency use made of cardboard are thought to last around five years.

Computer-aided design (CAD) has revolutionised architecture and design, making it possible to create buildings and designs that would be difficult or impossible without the help of computers. Computers are essential for designing and constructing buildings. Digital manufacturing techniques allow for quick and precise prototyping, which can be used to study large-scale works. Architects need to learn a new language to use these techniques, which involve translating three-dimensional drawings into digital data for machines to interpret. Design professionals use digital technologies to study and test different combinations of processes and materials. They have now found which processes work best for a given material and can create compositions through assembly, modelling, ornamentation, or parts organisation. Digital manufacturing techniques offer new possibilities for shaping materials. With these techniques, it is possible to give architecture a new quality and artisanal look.

Computer-aided design (CAD) has revolutionised architecture and design, making it possible to create buildings and designs that would be difficult or impossible without the help of computers. Digital manufacturing techniques allow for quick and precise prototyping, which can study any scale works. Architects need to learn a new language to use these techniques, which involve translating three-dimensional drawings into digital data for machines to interpret. Design professionals use digital technologies to study and test different combinations of processes and materials. They use processes to work best for a given material and can create compositions through assembly, modelling, ornamentation, or parts organisation. Digital manufacturing techniques offer new possibilities for shaping materials. With these techniques, it is possible to give architecture a new quality and artisanal look. Cardboard is a versatile material that can be cut and engraved, folded, layered, and interlocked using different digital manufacturing techniques. Digital manufacturing techniques like laser cutting or engraving can be used to cut and engrave cardboard, then folded and assembled into several products. The folding technique creates softness and dynamism in shapes that can be changed multiple times. It is mainly used to create elements of separation and pavilions. The layering technique is a way to create a heavy and solid object by stacking materials on top of each other. Cardboard sections can be held together with adhesives, and the object is resistant to compression in all directions.

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Computers are useless.

They can only give you answers.

Pablo Picasso

Parametric design in the complex era

IMPROVING THE MECHANICAL PERFORMANCE OF PAPERBOARD USING DIGITAL TECHNIQUES

The term origami refers to the art and technique of folding paper according to a pattern to create three-dimensional objects of different shapes. The word comes from the Japanese ORI 'fold' or 'folding' and KAMI 'paper'. Paper folding originated in China over two thousand years ago, where the first examples are found, but it was in Japan that the technique was refined, becoming a true art form tied to the Shinto religion and its customs. In the culture of ancient Japan, paper lost its material value to become something divine, and for the person folding the paper, the act was a moment of spirituality. More recently, this art has spread to the West especially due to the exhibitions of Japanese artist Aikira Yoshizawa. His work attracted the interest of mathematicians, engineers, and architects, who then began to focus more on folding techniques, opening the way to new experiments. Yoshizawa is also remembered for establishing a standard in fold notation, the 'Yoshizawa-Randlett' system, which is still used today to describe folding operations (Yoshizawa et al., 2019). By definition, origami is created by folding a sheet of paper without cutting or gluing, iterating the process several times until the desired figure is obtained. This technique yields shapes that can dialogue with the language of architecture. Folding paper leads to a direct and intuitive understanding of the geometry and rigidity of a structure. By folding and manipulating paper, the hands and eyes spontaneously understand the potential of different shapes (Buri and Weinand, 2008).

Operations with paper can lead to complex shapes, but simplifying the 'dynamics of folding' reduces it to just two actions: folding in one direction or the other, creating so-called 'mountain' and 'valley' folds. By alternating the types of fold, three-dimensional geometries can be created out of a flat sheet of paper in the form of corrugated surfaces or single- and double-curved shells. Through folding operations, lightweight structures can be produced to withstand high stresses. The principle of folding is widespread in nature, though its potential has rarely been used in architecture because of the geometric and mathematical difficulty in describing these surfaces. The digital world can, however, compensate for these shortcomings by making it possible to tessellate and triangulate shapes (Trautz and Herkrath, 2009). In architectural research and design, origami is studied both as a purely formal investigation and as 'computational design algorithms' in which every aspect of the realization of a shape can be controlled. Moreover, through reverse engineering, the technique of digital origami can help decompose complex

Figure 1

Miura-Ori pattern

freeform objects by suggesting interesting construction alternatives (Sorguç et al., 2009).

Through the application of a folded geometry, paper, which is by nature a soft material, becomes 'solid'. In the same way, this technique may also be applied to more resistant materials such as cardboard, producing structures that are more durable than those made of paper. The limitations that arise when folding a thick material such as cardboard can be overcome by creasing (or engraving). Where the material needs to be folded, the thickness is reduced by weakening the structure to create flexible hinges and facilitate folding. In more extreme cases, where the thickness of the material is much greater than an ordinary sheet of cardboard, the thickness cannot be ignored when creating a folded structure, and it actually becomes a strength when making structures on human scales (Butler et al., 2019; Lang et al., 2020; Tachi, 2011).

The production of folded surfaces may be divided into three types, each of which leads to different configurations. The first type — chaotic — involves a very dense and apparently disordered tessellation similar to a crumpled sheet of paper. This type of folding produces completely freeform surfaces suitable for reconstructing a geometry from its volume. In this type, the division yields the shape and it is impossible to define the relationships between the folded parts a priori. The second type — shaped — involves folds specially designed to achieve an individual spatial configuration. The third type — structured — is determined by the orderly tessellation of the sheet, yielding different configurations depending on the fold geometry, which can only later be traced to the architectural elements created (Casale and Valenti, 2013). Over the years, studies by mathematicians and computer scientists have produced various structures of the latter type in order to understand their properties. Unlike origami created to construct just a single shape, these patterns are more flexible, and their spatial repetition can lead to interesting geometries in the field of architecture.

Miura-Ori or herringbone

The Miura pattern takes its name from its creator, Japanese astrophysicist Koryoto Miura, who designed a solar panel in 1995 to be used in space *Fig. 1*. The advantage was that the panel could be closed upon itself, thereby reducing its size for transport. For the kinematics, Miura drew inspiration from the world of origami, building a panel composed of identical pieces. Today, this name refers to the entire category of patterns made of square elements repeated in a mirror image. The most common pattern consists of parallelograms, which is why it is also known as the herringbone pattern.

In this pattern, the folds are distributed in two directions in the following way:

> *•Along the main direction, the folds maintain the same sense (mountain or valley) throughout the sheet.*
>
> *•Along the secondary direction, the folds alternate in each segment.*

Questo cinematismo prevede la planarità di ogni elemento in tutte le possibili configurazioni per questo motivo è realizzabile anche con pannelli rigidi. Lo sviluppo spaziale del pattern MIURA-ORI produce un elemento bidimensionale il cui spessore è dato dall'angolo di piega. L'oggetto, chiudendosi sul piano, tende ad

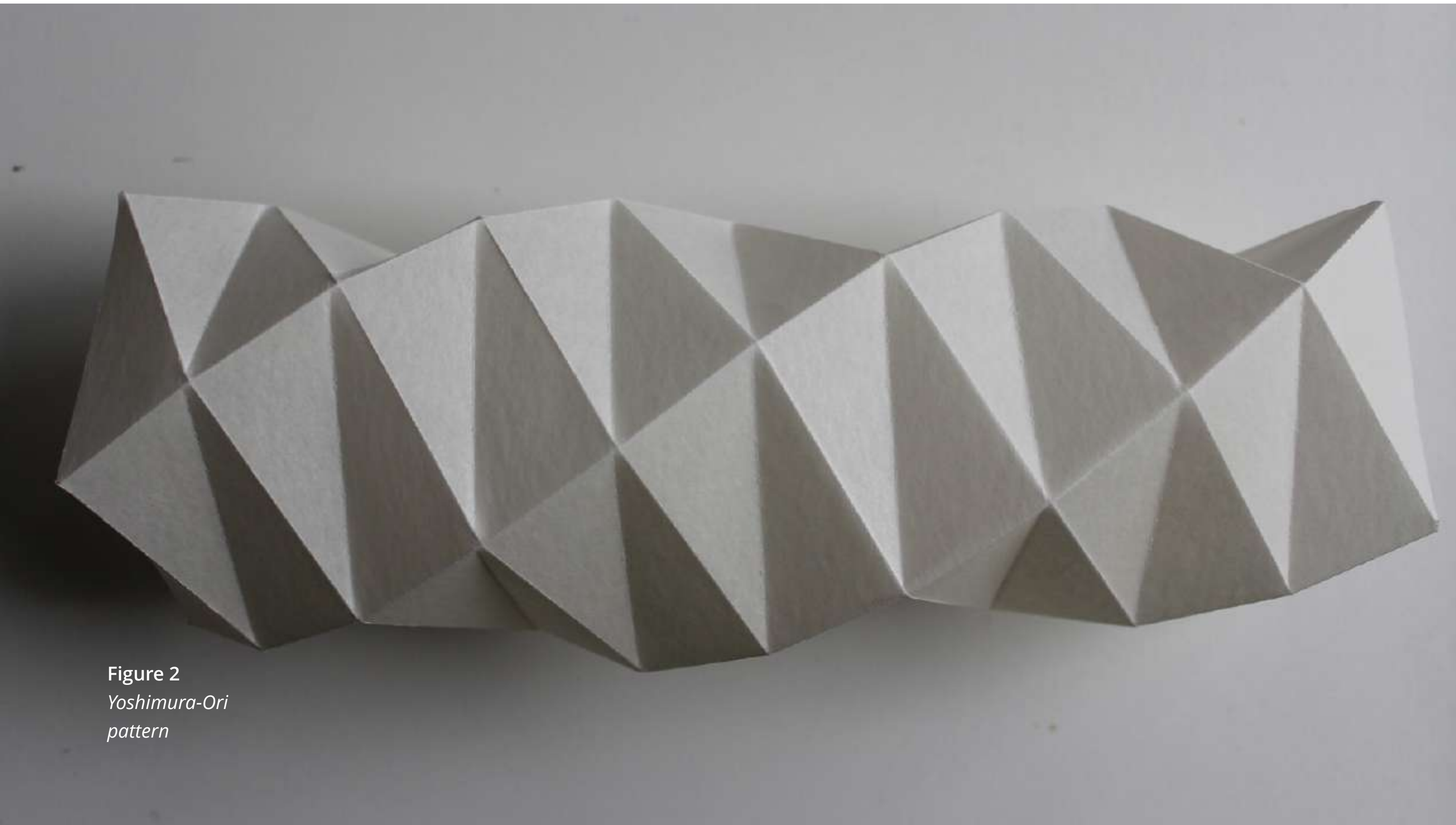
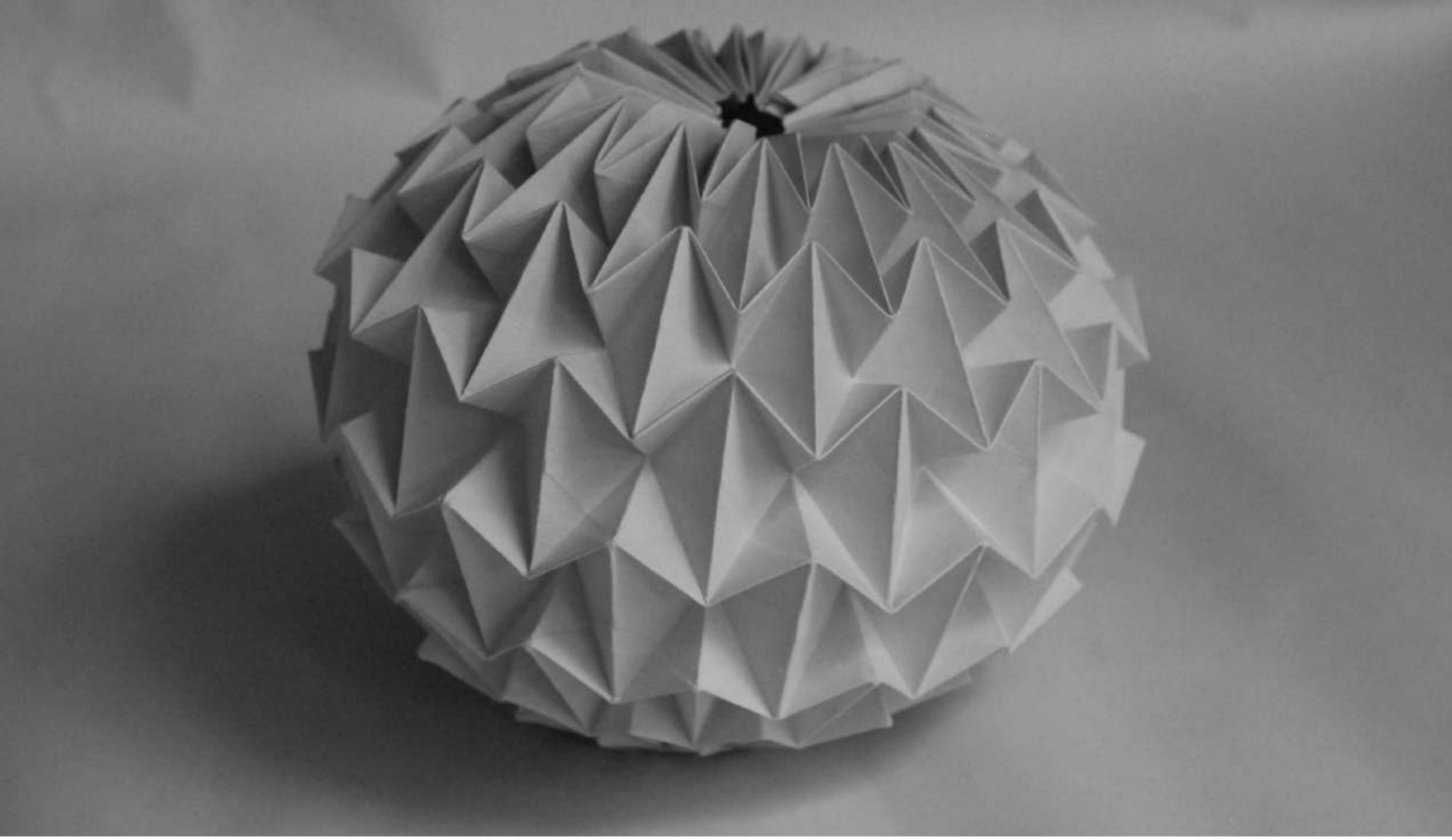


Figure 2
Yoshimura-Ori pattern



accorciarsi contemporaneamente nelle due direzioni principali. La misura in cui questa geometria può essere compattata è proporzionale allo spessore del materiale con cui verrà realizzato l'oggetto: l'angolo di piega è inversamente proporzionale allo spessore.

Yoshimura-Ori or diamond

The Yoshimura pattern takes its name from the Japanese researcher Yoshimaru Yoshimura who published a study in 1955, first in Japan and then in the United States, on the instability of cylindrical geometries made with this pattern (Yoshimura, 1955) ***Fig. 2***.

The pattern contains an alternation of specular triangles. The segments of the tiles can be divided by simply decomposing the triangles into legs and hypotenuse, each of which arbitrarily takes a mountain or valley fold. It is also called a 'diamond' because of the triangular cut that is obtained, which resembles the facets of a gem.

Like the Miura pattern, the kinematics here also requires its constituent elements to be flat in any state of configuration. The spatial development of the Yoshimura pattern produces elements which, when tightened, curve in on themselves to create an open or closed shell. Depending on the proportions between the elements of the triangles in the pattern (legs and hypotenuse), one dimension or the other may be emphasized.

Magic ball

The magic ball pattern is a configuration that originates from the alternation of two patterns ***Fig. 3 and 4***:

- *The first pattern starts with the division of a quadrangular polygon divided by diagonals to form four triangles arranged with the common vertex at the centre*

Figure 3 and 4
Magic ball pattern

of the original polygon.

• The second pattern also stems from a shape similar to the first, but its division involves two opposing triangles at the centre surrounded by four triangles at the corners.

In this configuration, the mountain and valley folds are alternately assigned to orthogonal segments.

The spatial development of the Magic Ball pattern (and its variants) produces geometries that completely depart from the plane, creating spherical or hemispherical elements. The kinematics achieves such shapes through a large number of degrees of freedom, but this, however, results in poor structural strength.

Ron Resch patterns

Ron Resch patterns refer to the patterns created by artist and computer scientist Ronald Dale Resch. His research in the field of art has produced many interesting shapes, the most famous and interesting of which are the Barbell pattern and the Waterbomb pattern. Resch created very complex patterns in which he played with the alternation of mountain and valley folds.

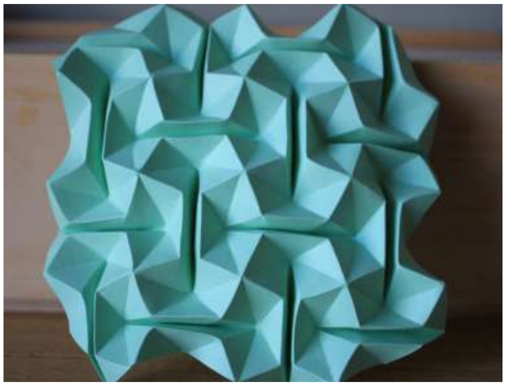
Ron Resch barbell

This configuration consists only of triangles forming a fractal path that covers the entire surface *Fig. 6 and 7*.

The spatial development of the Barbell pattern produces a structure that develops on the plane and, unlike the Miura pattern, its contraction is limited by the geometry even before it is limited by the thickness of the material.

Ron Resch waterbomb

Two variants of this pattern are possible, starting with a triangular *Fig. 8* or quadrangular



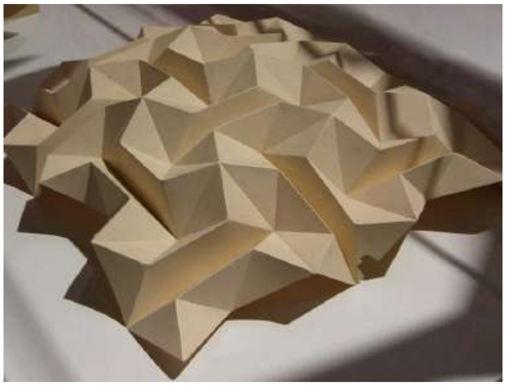


Figure 6 and 7
Ron Resch barbell patterns

Figure 8
Ron Resch waterbomb triangular version

Figure 9
Ron Resch waterbomb quadragular version

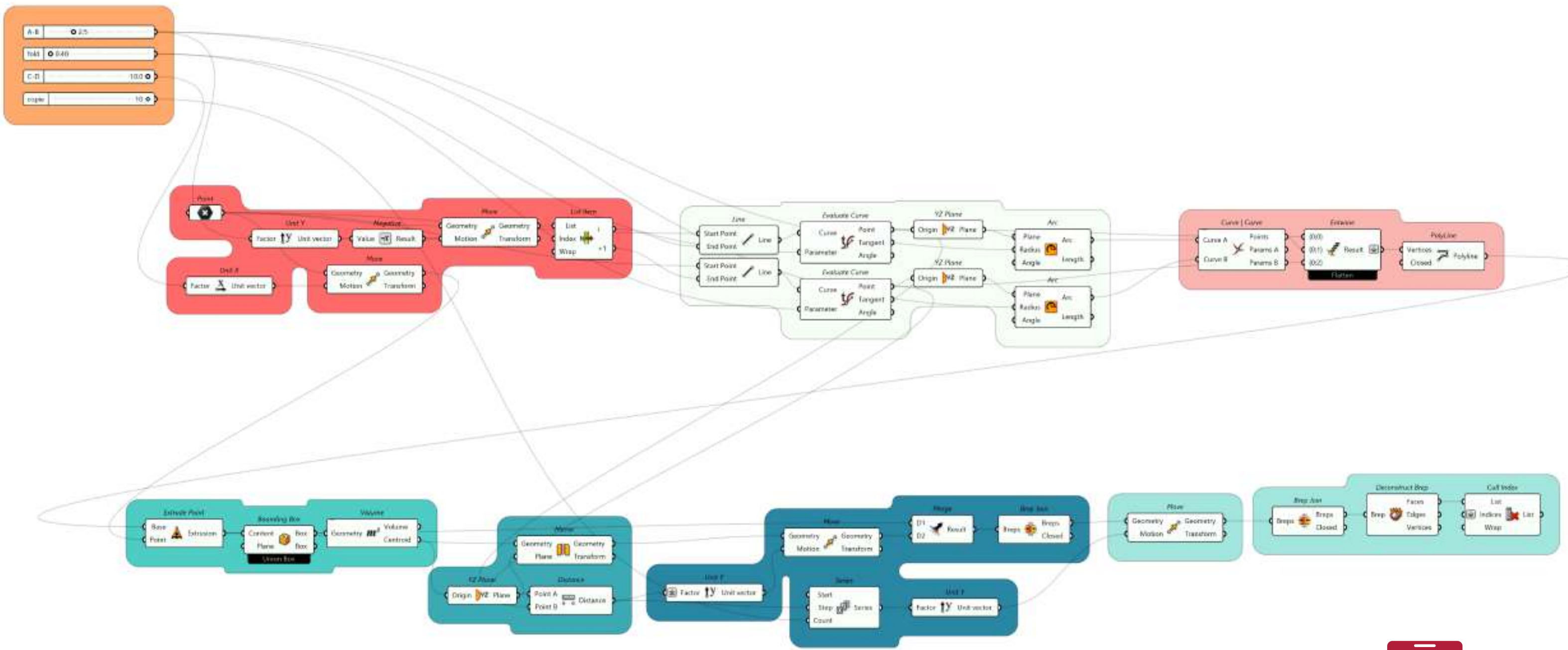


Figure 10
An example of a rigid origami algorithm: Diamond pattern

division *Fig. 9*. In both cases, the basic shape is duplicated and staggered, leaving a space identical to the starting shape, but on a smaller scale.

Both variants of the Waterbomb pattern produce geometries that can be distributed on a plane or made to conform to a cylindrical or even hemisphere structure. The structural resistance is related to the final configuration of the object and the strength of this pattern certainly lies in its versatility.

EVOLVE DIGITAL GEOMETRY

In order to study, design and calibrate these folded objects, it is very important to digitize the geometries using systems that can reproduce the structures as faithfully as possible. The digital world presents various opportunities that make this aspect quicker and cheaper than in the past, which would have involved physically building each version of the studio model.

The use of a procedural and parametric design tool is useful when creating a digital model whose structure can change over time. In recent years, the use of the graphical development environment Grasshopper has been established, which allows specific tools to be built to suit all design requirements. Designing a procedural and parametric system consists of breaking down and ordering the entire problem into sub-problems that are easier to address. This development environment involves a series of specific components that capture input, process it, and return a result that can be input at other stages in a chain until the process is complete. The parametric-geometric approach, which is the most immediate, is based on generating shapes by setting rigid mechanics between the parts conditioned only by rotational movements (Casale and Calvano, 2012; Casale and Valenti, 2013; Curletto, 2016; Zhang et al., 2019). A second approach, simulation, exploits the large computational capabilities available today to model a real physical environment in which the structures can move. This system is based on the use of the Shape Op libraries developed by the Computer Graphics and Geometry Laboratory at EPFL (Bouaziz et al., 2012; Deuss et al., 2015), subsequently integrated into the Kangaroo Physics tool in Grasshopper by Daniel Piker. With this approach, the application of forces on a virtual sheet of paper can be simulated so that it folds as it would in reality.

In digitizing the folding model, the process can be simplified by considering the surfaces to have no thickness, and then integrating this feature at a later stage in order to verify the operation realistically. Another problem often encountered when designing folded surfaces (or panels in general) is the flatness of the parts. Shapes that are not flat induce deformations which can, in some cases, compromise the final results of the project. For this reason, the shape should be checked at the end of the process.

Parametric/geometric approach

Constructing a folded structure using the parametric-geometric approach implies that each element is related to the next by pivoting along the hinged side. Each rotation of the first element is countered by a rotation of the second element in the opposite direction *Fig. 10 and 11*. The relationship between the parts must be maintained, even with elements connected in more than one direction, which implies advance knowledge about the plane of rotation and the rotational relationship between the elements to allow for the correct kinematics.

The process of producing algorithms based on this approach involves the identification of a basic module (extracted from the entire pattern) to which kinematic motion is applied. The complete module can then be duplicated to create the folded surface.

The advantage of this approach lies in the result, which consists of flat elements that are not deformed because they have undergone only rigid movements at each stage of the process. The parametric-geometric approach requires few computational resources, but a great deal of effort to understand the geometric systems involved in the folding. The Miura and Yoshimura patterns are the most suitable for this technique because of their simplicity.

Simulations

The simulation approach implies the application of complex mechanical dynamics and kinematics using technologies that can simulate them. The Kangaroo Physics tool, which can be used within Grasshopper, was created for simple management of complex mechanical systems *Fig. 12*. Constructing a folded surface with this tool closely resembles the real process of folding a sheet. Exactly as it would happen in reality, the kinematic motion is made possible thanks to a system of forces and constraints that, acting on the body, make it react by folding until the desired shape is achieved.

The algorithm used in this approach can be divided into three stages. The first stage consists in creating the geometrical pattern in its entirety and identifying the segments assigned to mountain and valley folds. In the second stage, the structural constraints and forces acting on the initial surface are defined. For folding operations, the forces are limited to the rotation of the faces around each hinge, thereby inducing the kinematic motion. The combination of forces and constraints acts on the structure by modifying its spatial conformation. The term 'constraint' implies all actions necessary to respect the established conditions, such as the flatness of the faces, respect for the length of the constituent sides, or the angles between the elements. Another possibility permitted through the system of constraints is to condition the fold to adapt to a predefined geometry (e.g. a shell) always in accordance with the feasible spatial development of the pattern. Each constraint and force must be calibrated to allow the system to function correctly. The third stage concerns the solver, i.e. the component that

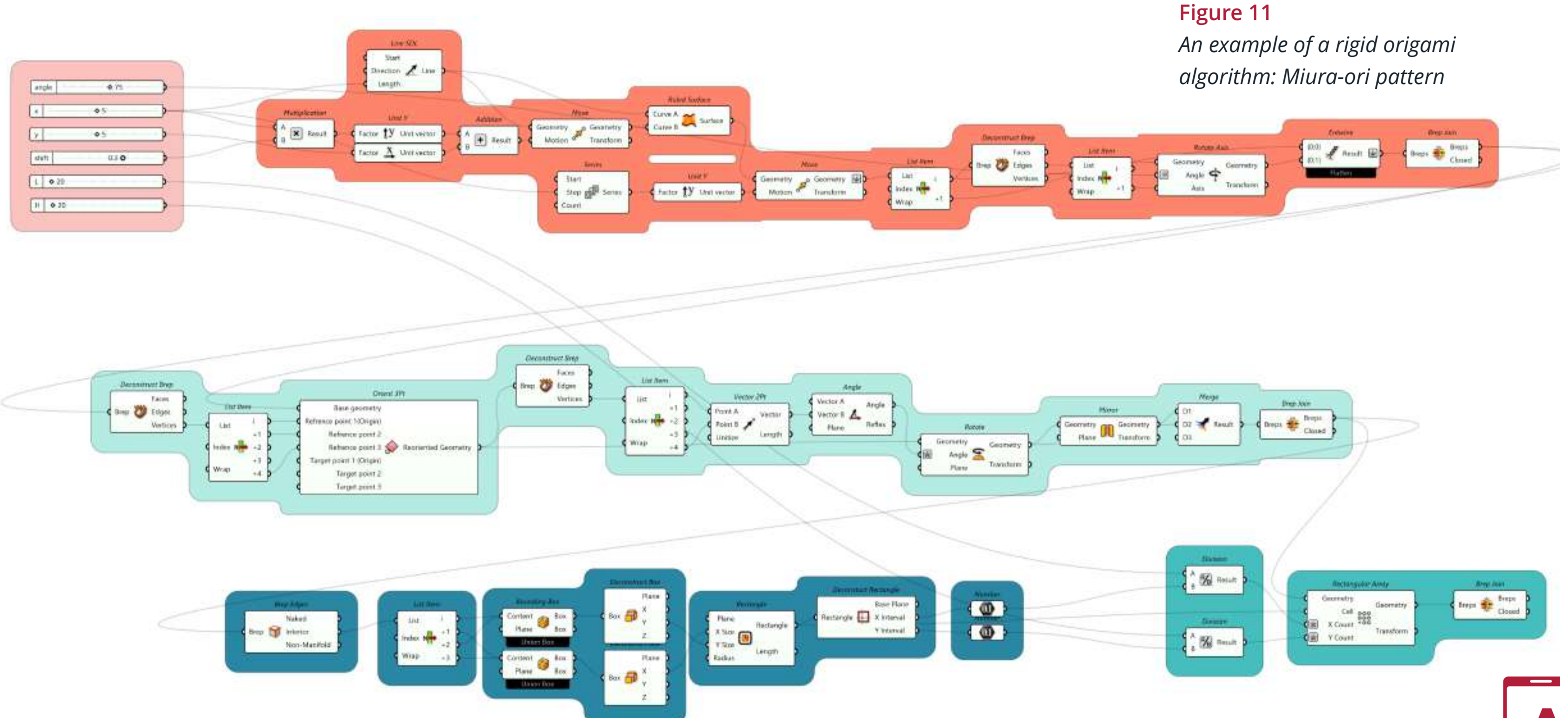


Figure 11

An example of a rigid origami algorithm: Miura-ori pattern

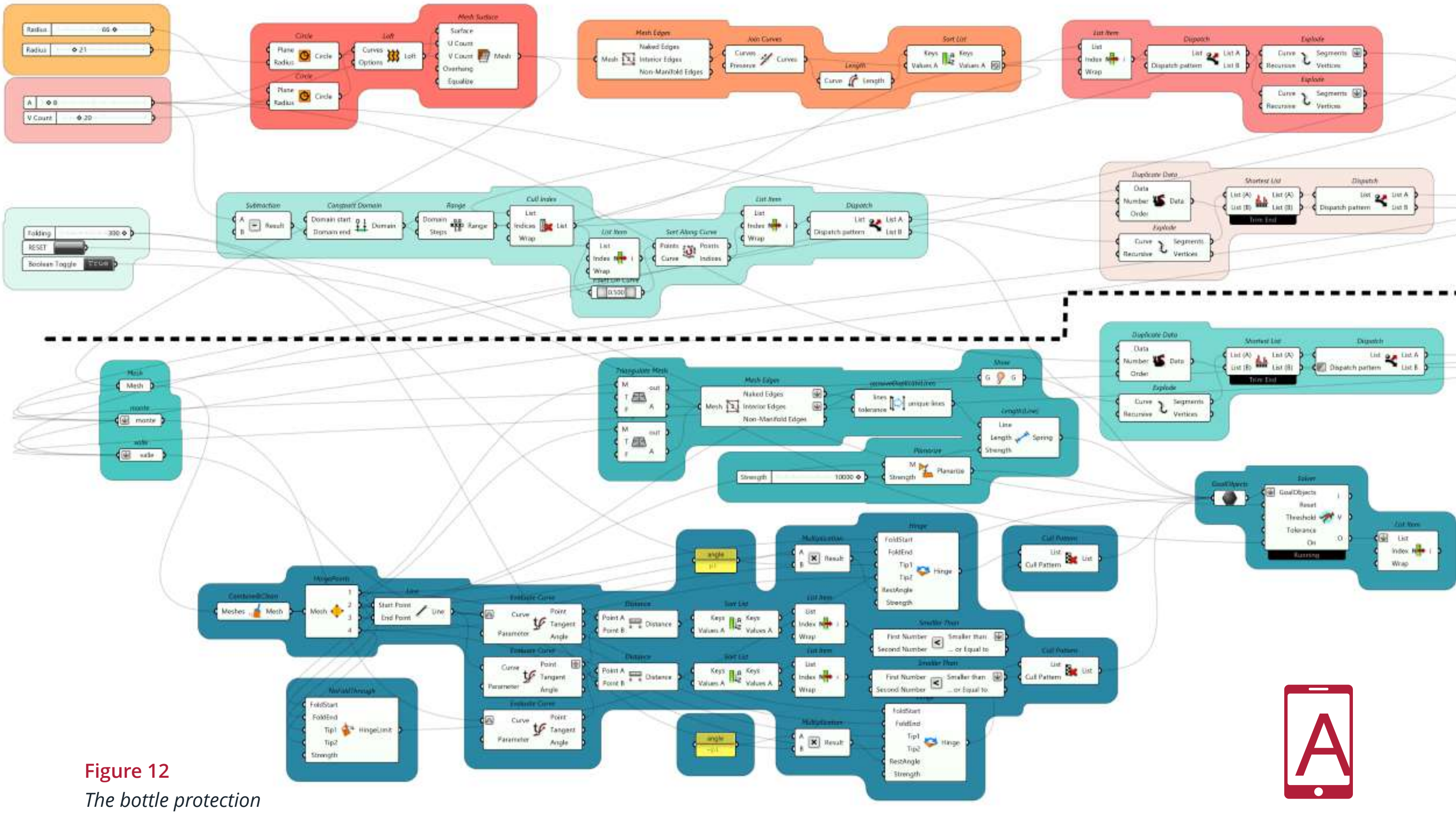


Figure 12
The bottle protection system algorithm

reiterates the calculation thousands of times until all the established conditions converge. At this point, geometric checks can also be made to verify the shape. Unlike the parametric-geometric approach, it is not essential to know the fold ratios between the elements in advance, such that folds can be easily created from more complex designs such as Ron Resch patterns.

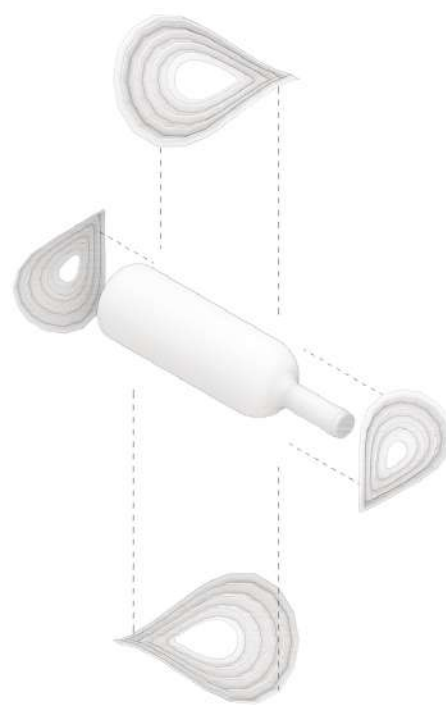
The Kangaroo software discretizes the geometries into a set of points acted upon by a system of forces and constraints. This has both favourable and unfavourable consequences. Since it is only a set of discrete points moving in a constrained manner in space, the system tolerates slight deformations of the geometry, which can be either good or bad depending on the material used to create the work. The ease of use and speed with which very complex folding systems can be defined is a major advantage. The only true disadvantage is the computational power required, which is much higher than the parametric-geometric approach.

BOTTLE PROTECTOR SYSTEM

To assess the possibilities offered by the proposed systems and in agreement with the Di Battista company, a new system was designed and created to protect the bottles for which this box factory provides packaging *Fig. 13 and 14*. The system consists of a single folded cardboard element whose shape is reminiscent of a hyperbolic paraboloid. The device was designed using the simulation approach and was cut digitally.

The concept is inspired by the Miura pattern, with the alternation of mountain and valley folds; however, the development of the pattern is periodic, forming a 'circle' on the plane. The pieces were modified from parallelograms to sections of arc. In the first stage, an algorithmic process was designed to construct circular shapes and parametrized divisions. The algorithm automatically divides the inner

Figure 13
Axonometric view of the bottle protection system



segments into groups of folds *Fig. 12*. In addition to the forces required to activate the kinematic motion, the combination of forces and constraints in the second stage includes a flatness constraint and a constraint to fix the length of the sides and diagonals of each element. The strategy of fixing the length of the diagonals prevents any changes to the internal angles of the faces. Increasing the tessellation of the circle or the number of folds affects the overall stiffness of the dissipation device.

Finally, the system automated the division between the cutting and creasing curves, which were then sent to the digital cutter for fabrication. The element was folded by hand. Using the same technique, several elements of different sizes were built to fit inside a package.

Today, the production of folded surfaces to meet various architectural and design requirements is facilitated by digital technologies. The construction of the mechanical dissipation device in cardboard was useful for gaining experience in the process of producing folds, from algorithmic applications to digital fabrication and the simulation approach greatly simplified the operations of studying the shape before manufacturing. The operation was repeated for the various elements required to protect a bottle from impact during storage or transport

PARAMETERISING COMPLEX SCENARIOS

In recent years, global climate change and its local projection have compelled careful analysis regarding the complexity of systems on

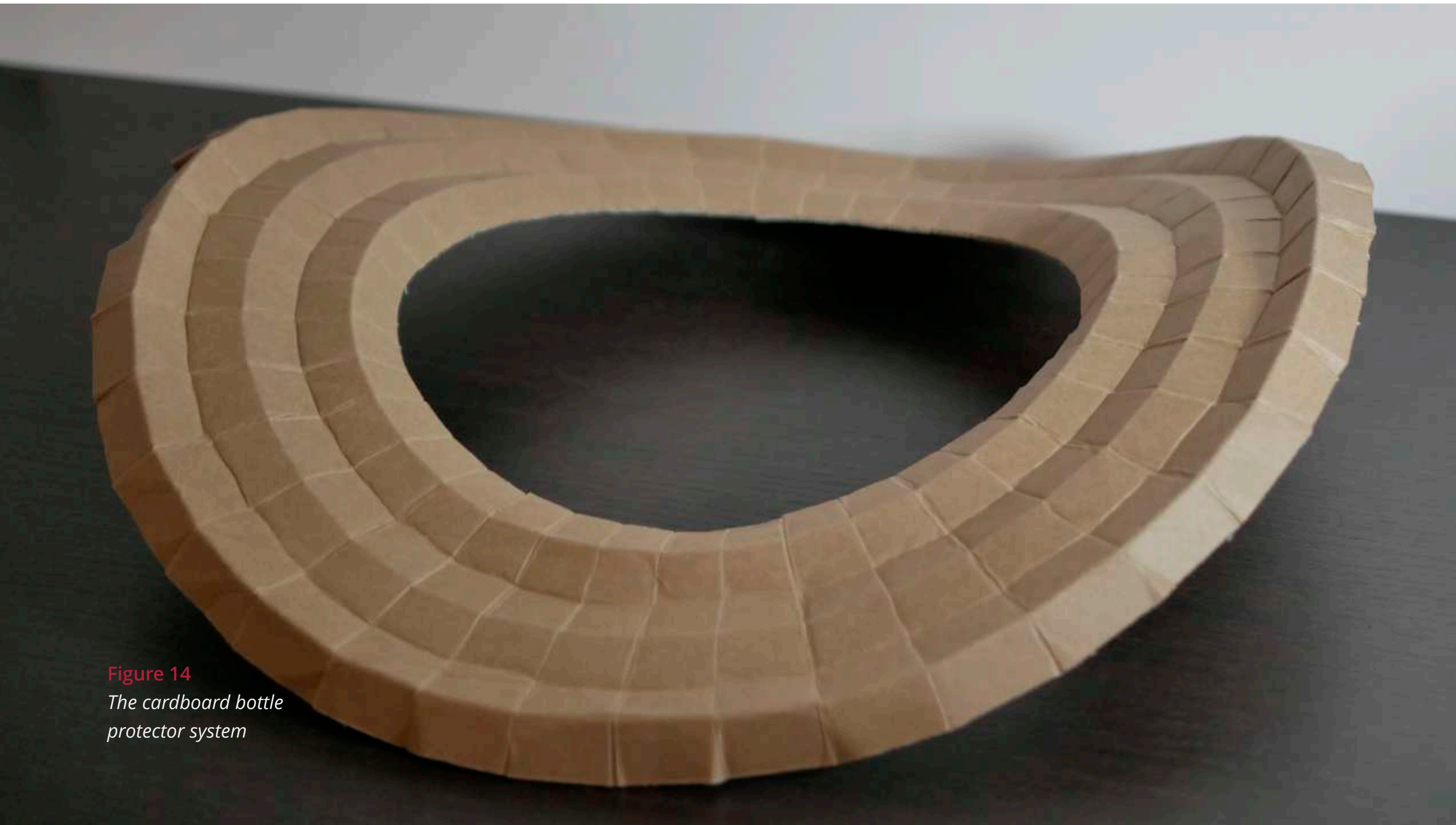


Figure 14
The cardboard bottle protector system

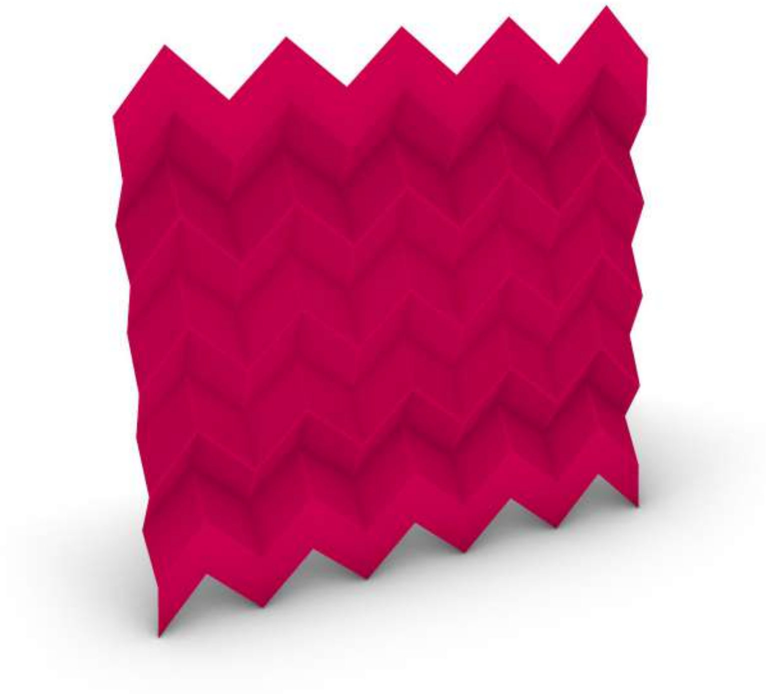


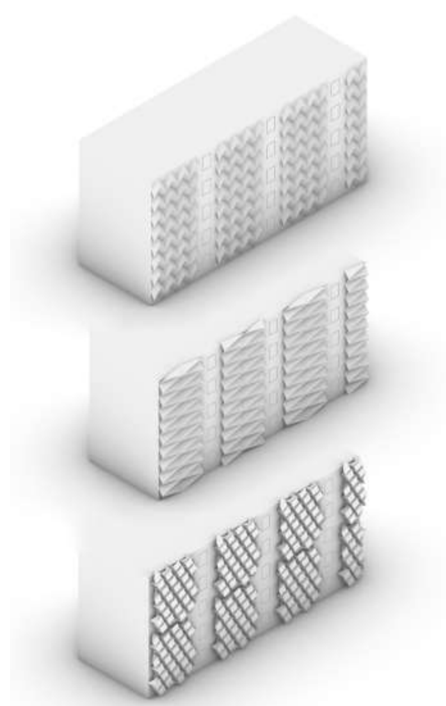
Figure 15
MIURA-ORI pattern digitisation

the small and large scales (architectural and urban), interpreting them as independent yet interacting components that increase the flow of information and design parameters. The (re)generative design of interface devices (vertical or horizontal) leads to the idea of a building as a process of becoming, whose main objective is the ecological, energy, and social improvement of the place where it stands. Today, the study of aspects tied to ecology and sustainability refers to the science of relationships and complexity fed by different interacting skills that have led to a change in paradigm. Starting in the 1970s, the step was made from Descartes's and Newton's mechanistic, deterministic vision to a vision that assumes complexity as a foundation and uses concepts such as unpredictability, nonlinearity, instability, bifurcation, homeostasis, self-study, self-organization, etc. Specified by various scientists as a theory of complexity, nonlinear dynamics, network dynamics, etc. (Morin, 2008), this new paradigm contrasts with the mechanistic idea of nature as a simple, linear machine that can be decomposed into elements reducible to the cause that preceded them in time.

The new perspective views nature as an organism, an organized system whose parts interact dynamically and whose behaviour is essentially disordered, irreversible, and connected to the arrow of time but not linearly predictable.

These considerations show that 'complex' models are characterized by their qualitative rather than quantitative character. For example, while traditional mathematics deals with quantities and formulas, the dynamic theory of systems deals with qualities and methods, shifting the attention from the objects to the relationships. In addition, 'complex' models entail nonlinearity and the fundamental role of irreversibility as a source of order and the generator of organization.

Figure 16
Application of origami patterns on architectural façades



The perception of complexity therefore leads to a holistic, ecological vision that tends to attribute phenomena observed in the various scientific fields to their own oikos (home), intended as a system of relationships and also as the root of what we now call 'ecology'. This new systemic approach is inevitably combined with the use of digital devices (computers, etc.), which are indispensable for conceiving, controlling, and interrelating complex geometries. It represents a tool in much contemporary research for studying and controlling structures that, once realized, reveal themselves to be capable of self-organization and self-growth (Schumacher, 2010) analogous to the capabilities of living organisms (Tucci, 2008). These structures are therefore capable of reacting to information from the external environment, establishing interactions with the outdoors through the continuous modification and adaptation of their state. They can respond to atmospheric forcing and external stress by adapting their shape and spatial and functional configuration to respond to changing environmental requirements.

In some examples of architectural complexity, there is instead a tendency to dematerialize, to create 'vaporized' buildings (Rahm, 2014), indeterminate forms realized as if the process of formation were perennially progressing. The key aspects of this concept are then attention for the communicational values and sensory and intellectual relationships suggested by the object, an openness to nature, dematerialization of the mass of the walls through membranes and sensors that detect and transmit information, and recourse to the metaphor of fluidity, which represents life itself, in continuous transformation. In contrast to physical masses, the building skin increasingly tends to become a 'threshold' rather than a barrier, with the purpose of not only 'closing' and 'containing' but also 'opening' and extending' in response to stimuli from the exterior. These reactive architectural surfaces can change the way in which we relate to the built environment and the way in which construction of the environment relates to the user.

As with many other designers in contemporary architecture, Toyo Ito's 'Blurring Architecture' — fluid synergies between form and matter, appearance, and performance — gives rise to a building with light edges that can react in response to the natural environment (Ito, 2000). The concept of Blurring Architecture does not regard the form of the building as much as the idea of limits, of clear separation between interior and exterior that increasingly begs discussion, making the borders between architecture and environment, between body and space, ephemeral and soft. This 'new reality' is capable of testing not only the strength of matter, but also (as always) transmitting new physical and mental sensations, creating sensory experiences through spaces where people can move and live freely.

The objective of the research therefore is to present new environmental parametric strategies in order to improve the technological and environmental project proposals, thereby changing the modus operandi of environmental designers and architects.

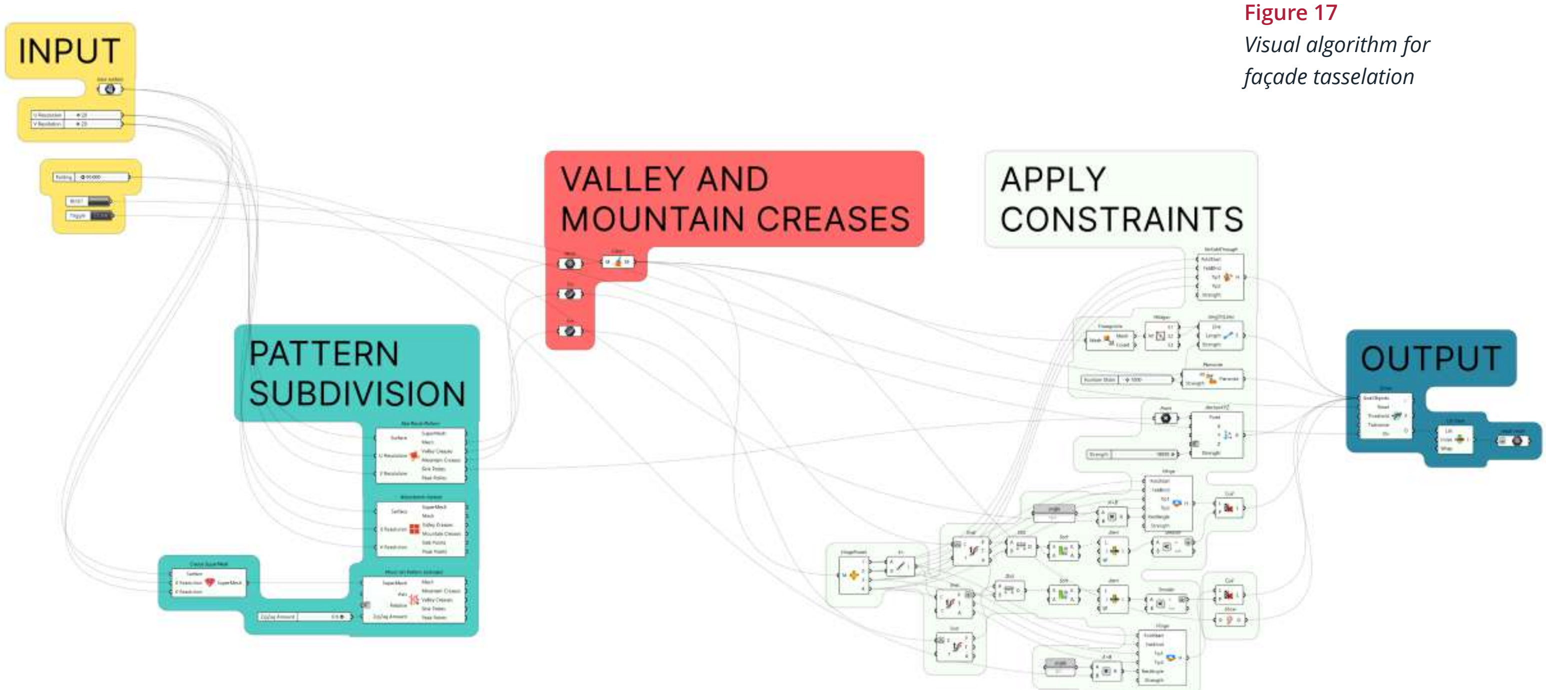


Figure 17
Visual algorithm for façade tasselation

Figure 18

Waterbomb Ron Resh's pattern digitisation

Façades coding

Contemporary research (Peters and Peters, 2018; Rahm, 2018) aims to establish continuous feedback between architecture, the environment, and users using digital tools to incorporate architecture within the natural or urban context and to integrate the experience of users themselves within the design process and the result.

Matter is not considered an inert substrate on which a form is imposed from the outside, but an active element that participates in generating the form itself. The various materials, with their different characteristics and properties, therefore become an integral part of the design process. Material information may not only be integrated in the computational design but may also act as one of its generating morphogenetic drivers. In this way, the properties and behaviours of the materials and their related characteristics of materialization are not considered limits, but rather the source of an exploratory design process.

Wood is one material that best lends itself to these design processes; with its environmental sustainability (naturally renewable and completely recyclable), thermophysical characteristics, composition, and behaviour, it lends itself to use as a 'living' construction material. In fact, its hygroscopic behaviour allows reactive architecture to be created. Another material interesting for its versatility is cardboard, which, due to its sustainability and resistance, was used by Shigeru Ban (Eekhout et al., 2008) to create environmentally conscious buildings built with innovative, solid systems, even to face natural disasters.

Luigi Moretti (1906–1973) was the first architect to talk about 'parametric architecture' (Pellitteri and Gallo, 2018) with the goal of defining an operational method that allowed the most recent acquisitions in modern scientific thought to be encompassed in architecture. Some design themes (theatres, stadiums, subway stations, etc.) could then be addressed not according to traditional typological references but by pursuing the idea of generating the form through rigorous geometric relationships among the parameters.

The parameters and their interrelation therefore become the expression, the code, of the new architectural language, the 'structure' in the original and rigorous sense of the word and define the forms that those functions satisfy. In determining the parameters and their interrelation, the most advanced techniques and tools of scientific thought should be employed, particularly logic/mathematics, operational research, and computers — especially computers — for their ability to express probable solutions to the values of the parameters and their relationships in recursive series. The development of this setup and the new procedure and theory specified in its methods and verified in the initial results is called "parametric architecture" ***Fig. 15-18***.

Architecture should therefore be proposed as a display of and for finiteness: by probing the limits they may tend towards places of 'possibility' in opaque zones, left in shadow by the design of total technological 'solarization' (Carboni et al., 2015). Even in its current strength and universality, the technique therefore, as a means through which the form is realized, does not subtract space from our creativity. It institutes processes of continuous feedback in which each architect creates an original view of the world, a vision aimed at the future but capable of constantly questioning the limits of one's own work. *Appendix E*

Parameterising "green" optimization

Green roofs and plant façades are today's new frontier in the relationship between nature and architecture. The technique has given architecture operational concreteness, offering unexpected possibilities for people's primary desire to live in and with nature. Intended thus, the plant-related element is no longer proposed just as a theatre set; rather, it becomes a component of the project just like any industrialized material. In this way, vegetation adds to the quality of the overall housing system, adding a sign of increased sharing to the principles of sustainability required by environmental challenges *Fig. 3*. The aim is to perform an optimization analysis to determine some important parameters, such density, green typologies, vertical or horizontal direction, insulation thickness etc, to define the thermal behaviour of green devices and to proposed an optimal system strategy that not only improves the outdoor thermal comfort, but also improves the urban microclimate, reducing the cooling load of the buildings. A parametric method was developed to optimize the green façade (green façade optimization, GFO) in order to consider the characteristics of the growing media, irrigation and vegetation characteristics, and to account for shading and insulation effects as well as evapotranspiration from the substrate and plants. The method uses 3D parametric tools, Grasshopper in particular, which is a graphical algorithm editor integrated with Rhinoceros, a 3D modelling program *Fig. 19 and 20*. Specifically, the research uses a variety of Grasshopper plug-ins, such as Ladybug, Honeybee and Galapagos, a mathematical computation solver. Small interventions in specific sites of the urban city can bring about a considerable improvement in the quality of life of the citizens, outdoor

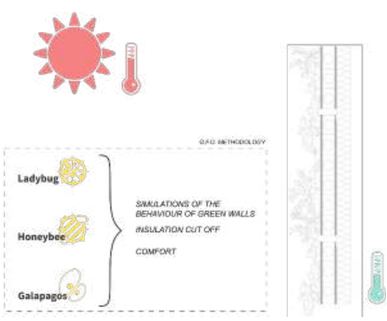


Figure 19
The G.F.O. metodology

Figure 20
Sedum green façade for microclimatic control

comfort and cooling load reduction. By implementing an optimized strategy that combines green shading, vegetation and cool materials, the city can reach its goals to-ward the city sustainability plan. The main goal of the research is to establish a thickness above which the behaviour of the green façade becomes isothermal and its performance do not improve. Future developments will show better outdoor and also indoor temperatures, with cooler environments in summer compared to the standard design solutions. The results are discussed and recommendations for simulating green devices are made. ***Appendix A***

CONCLUSION

Origami has the potential to be used as a tool for the design of lightweight and efficient structures. Its ability to create rigid three-dimensional forms from a flat sheet of material has already been explored in the field of engineering, where origami has been used to create deployable structures, such as microarchitecture or devices for satellites orbiting in space.

In order to design correctly, it is essential to accurately digitise folding objects so that they can be studied, designed and calibrated. The use of digital tools makes this easier and quicker than it would have been in the past. Additionally, simulation allows for a more realistic understanding of how the objects will fold in reality.

The geometry-based approach is a way to fold a piece of paper using a set of specific geometric rules. The paper is not deformed using these rules, and the final folded structure is straightforward.

The simulation approach is based on a technology that can simulate the folding of sheets of material that closely resembles the natural process. The technology uses an algorithm divided into three stages: creating the pattern, defining the forces and constraints, and solving movement equations. This approach is more flexible than traditional geometric approaches because the fold ratios between the elements do not need to be known in advance.

Designers increasingly use digital tools to create architecture that interacts with its environment and considers users' experiences. They are also using materials that have unique properties, like wood and cardboard. To create new and innovative architecture, we should use mathematical and scientific techniques to determine the best possible way to design and construct our buildings. This way of designing is defined as 'parametric architecture'.

The parametric approach can provide answers at different scales of design. It is possible to parameterise the inert elements of our architecture and the living elements, such as greenery. Green roofs and plant façades are becoming more popular because they offer a way to connect with nature while still living in an urban area. The technique has become more efficient and practical, so architects use it more often in their designs. Green spaces enrich the urban ecosystem and also help to improve the thermal comfort of the building and the urban microclimate.

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List of Figures

“It is shifting from metric design to thermal design, from structural thinking to climate oriented thinking, from narrative thought processes to meteorological thought processes.”

Philippe Rahm

Developing climate challenge tool

Various tools have been developed over the years to investigate changes in the microclimate and assess architecture projects in terms of building performance and other aspects, expanding the range of possibilities on the urban scale. With technological advances, these tools are increasingly common today and requested in preliminary project assessments in the decision-making process. Despite their growing recognition, the development of these tools has not drawn the attention of large software houses. As a result, software has been developed independently to respond to specific objectives that have difficulty communicating in a cascade with other tools, thereby greatly limiting the possibilities for investigation. Visual programming platforms[1] such as Grasshopper and Dynamo have recently been created on which independent developers have built connections with tools for energy simulations. This new scenario in which it is possible to create a workflow that provides continuity to the use of these tools promotes a more complete context that is destined to evolve and expand.

Modeling a Workflow

Using a virtual environment to investigate natural phenomena and their influence on the anthropized system requires more or less significant simplifications to be made. These simplifications are necessary for balancing the degree of complexity of the analysis, allowing for a smooth workflow. The mathematical tools used to represent physical phenomena, the computational power of modern machines, and the correct scale of representation are just some of the aspects considered when building a suitable method. In this scope, it is important to combine the different tools in a single platform such as Grasshopper, making it possible to manage external independent simulations and establish input-output exchange among them. Because it is a true development environment, Grasshopper always allows for parametric control of each phase of the process. This means that each aspect of the design should be converted into a numerical variable. For easy movement within this space, a change in design paradigm is not necessary, but it is important to support the common 'design' thought with a new 'parametric' thought. With the help of this platform, it is possible to manage third-party tools such as ENVI-met[2], EnergyPlus[3], and Urban Weather Generator[4], standardizing and visualizing the data produced. Each of these programs was developed for different reasons, with different interfaces, and without the possibility of interaction, a trend that can be completely inverted with management under a single platform. Various plug-ins called Ladybug Tools[5] have been developed for this purpose. These can be considered libraries within Grasshopper that are configured based on the need. It is important to understand the scale of the intervention from the beginning because depending on the case, some aspects can be focused on more than others, optimizing analysis times. When an overall view is maintained to assess the microclimate and effect it has on the building, the method for indoors must be used, or it can be varied according to the need.

To best understand this complex workflow, it is helpful to divide it into three phases: pre-analysis, analysis, and optimization.

Pre-analysis Phase

Once the area in question has been chosen, information regarding different aspects of the urban scenario needs to be entered. First, the geometries of the bordering buildings are entered (information that may also be collected from GIS databases). To best represent the outdoor space, the type and position of green elements and surface materials may be defined, along with permeable and impermeable areas. Finally, an additional set of data grouped under the name 'environmental data' must be found. This data is necessary for the subsequent analysis. This set is composed of time-series detections such as meteorological data and levels of atmospheric pollution. Meteorological data can be found easily (also free of charge), but often in reference to exurban contexts (commonly airports) that are not affected by the urban heat island. These may be managed by an application (on the Grasshopper platform) to automate the acquisition and manipulation of the geometric-material data, generating three different models and correlating information from different databases.

The first model is a slight simplification of the urban context to be used in the preliminary analysis with Urban Weather Generator. The model includes the volume of each building, the building materials and the context, vegetation, and environmental data, including information regarding the location of the source.

The second model is a representation (greatly simplified on a three-dimensional grid) to be used with ENVI-met. The model includes the volume of each building, the building materials (including transparent partitions), ground materials, and vegetation.

The third model is a representation of 'thermal masses' of the buildings to be used with EnergyPlus. The model includes the volume of each building, possible separations according to thermal area, building materials, and the context and vegetation.

Following the order of creation, each model is sent to the reference tool, thereby proceeding to the processing phase and subsequent analysis.

Processing and Analysis Phase

The first model (sent to the U. W. G. tool) is assessed considering relationships between the height of the buildings and the distance between them, the materials used, the presence of vegetation, and sources of pollution in relation to the site where the set of meteorological data was sampled. The result of this first investigation is a set of meteorological data modified to consider the urban heat island. This new data is then used in subsequent analysis (Nakano et al., 2015). To proceed with the analysis using ENVI-met, it is necessary to prepare a subset composed of 24 hours of continuous data that include temperature, humidity, and wind speed and direction. The standardized sets of data (including the one generated by U. W. G) contain hourly data for an entire year, from which it is necessary to select the restricted subset of values. To obtain this, the consolidated method of representative day may be used (Grifoni et al., 2012; Tirabassi and Nassetti, 1999), performed on the Grasshopper platform. Through the above-mentioned algorithms, statistical information may be extracted about the representative day that will later be used in the ENVI-met analysis.

The second model for use with ENVI-met consists of a simplification of the spaces through the use of a three-dimensional grid in which the thermodynamic behaviour of the flows within the urban space are simulated. This tool may be used to asses variations in temperature, humidity, wind field, state of pollution, and in sum, the state of comfort throughout the chosen 24 hours. The set of information collected in this initial analysis will become part of the information useful for later analysis based on the third model.

The latter is an analysis that addresses the details, relying on the capacity of a computation engine called EnergyPlus, which very accurately simulates the energy conditions of the buildings, but not of the outdoor spaces, whose condition, as is clear, can influence the behaviour. For simplification, the data characterizing the outdoor area are usually approximated by acquiring the values of the set of environmental data obtained previously. The workflow developed is able to obviate this lack, providing the possibility of connecting the results of the Envi-met analysis to the EnergyPlus analysis, which will therefore return much more realistic results. The results of this processing are quick enough to allow for recursiveness of the simulation to be made in a possible third phase to optimize the results as a function of the change in geometry rather than the materials.

The ultimate output of the analysis consists of maps coloured by gradients that quantify each atmospheric forcing as well as the state of comfort that can be estimates starting from said forcing, allowing the microclimate context to be quickly interpreted.

The adoption of a parametric workflow allows for fluid management of the simulation tools, which are indispensable for clarifying how the microclimate evolves and how the architecture, and even more, the adoption of territorial strategies influence it.

Appendix B

DESIGN AN URBAN CLIMATE ANALYSIS TOOL

The form of the city, its structure, density, and morphological and material characteristics are elements that have always been investigated when analysing the evolution of cities and the change in evolution. The study of the interconnection between morphology, climate, and energy has, over time, characterized a large part of the history of cities and architecture (Barucco and Trabucco, 2007; Givoni, 1998; Landry and Franco, 1995; Olgyay et al., 2015; Pascali, 2008; Rogora, 2012). In particular, urban morphology, which studies the form of the city, has guaranteed solid support for the analysis of the main factors that determine the spatial structure, its changes over time, and the sometimes violent alterations in a given built landscape. The morphology of contemporary cities has changed along with changes in the resident societies and activities distributed throughout the territory, generating de-urbanization and re-urbanization processes. It is an intricate urban system that is also closely tied to the (increasingly evident) local projection of global climate change.

Figure 1
Rome
urban network A

Figure 2
Rome
urban fabrics B

Figure 3
Barcellona
urban fabrics A

Figure 4
Barcellona
urban fabrics B




Figure 5
Athens
urban fabrics A

Figure 6
Athens
urban fabrics A

Figure 7
New York
urban fabrics

Figure 8
Oxnard
urban fabrics

The great weight of these demands and current transformations necessarily also leads to a change in the tools that are used today to study and analyse urban phenomena and strategies for intervention on an urban and architectural scale. As of today, however, these have unfortunately been shown to be insufficient in guaranteeing the achievement of those objectives tied to energy and the environmental quality of the city. What is necessary are tools that are capable of modelling the city's complexity (Barucco and Trabucco, 2007), intended as a combination of elements that generate the built space according to a logic of aggregation that can be identified via parameters. Parametric models allow information to be associated with digital simulation models, which can be considered 'information containers' that are quick to use and can be consulted in real time. Parametric modelling is based on the formalization of limits and elements that connect and systematize formal and relational variables, e. g., climate, environment, energy. These programmes, i.e., Grasshopper and its plug-ins, are able to manage means of vertical representation for the built environment and, in parallel, are also capable of horizontal aggregation according to the most varied logic, thereby allowing the complex urban density to be characterized. These considerations give rise to the need to propose a new tool based on the association of information. The tool is capable of drawing the complex city, tying it to all external demands (climate forcing, energy limits, changes in materials, etc.) and quickly reading the characteristics of the urban fabric and conditions of environmental comfort generated. Therefore, a parametric tool is proposed to generate urban volumes (replacing the classical technique of manual drawing), quickly modifying the geometries and material characteristics of the given portion of city and allowing for the analysis and comparison of multiple scenarios. The workflow developed is composed of three phases developed in the Grasshopper environment. The first phase regards the composition of the urban aggregate. The entire process to generate the urban geometries requires the geometries of the outermost urban perimeter and the main practicability under the form of open fragments. This phase entails the definition of the urban geometries. Starting from the outermost perimeter, which should contain all the buildings and roads, the set of main streets present in the territory is defined, thus forming the agglomerates, secondary streets, and green areas. The entire process is regulated by a series of parameters:

- *Maximum side of the block*
- *Ratio of shape of the plots*
- *Offset from the front main street*
- *Offset from other streets*
- *Side of the internal plot*
- *Size of the internal courtyard*
- *Range of heights of the buildings*

This tool assigns these characteristics to uniform zones, allowing for their modification in real time ***Fig. 9***.

The second phase uses the Urban Weather Generator (UWG), which is connected to Grasshopper through the Grasshopper Dragonfly plug-in (Mackey et al., 2017). The UWG is a tool developed by Massachusetts Institute of Technology to analyse local effects generated by urban geometries on urban comfort and energy consumption. This tool simulates the atmosphere/built environment and is capable of assessing the urban heat island effect and modifying a file of generic meteorological data (here called 'rural') to create a file of 'urban' meteorological data. Its task is to transform meteorological data usually obtained from exurban stations (e. g., airports) into meteorological data adhering more to the morphological and material characteristics and use of the city. The data is processed using a variety of parameters, for example,

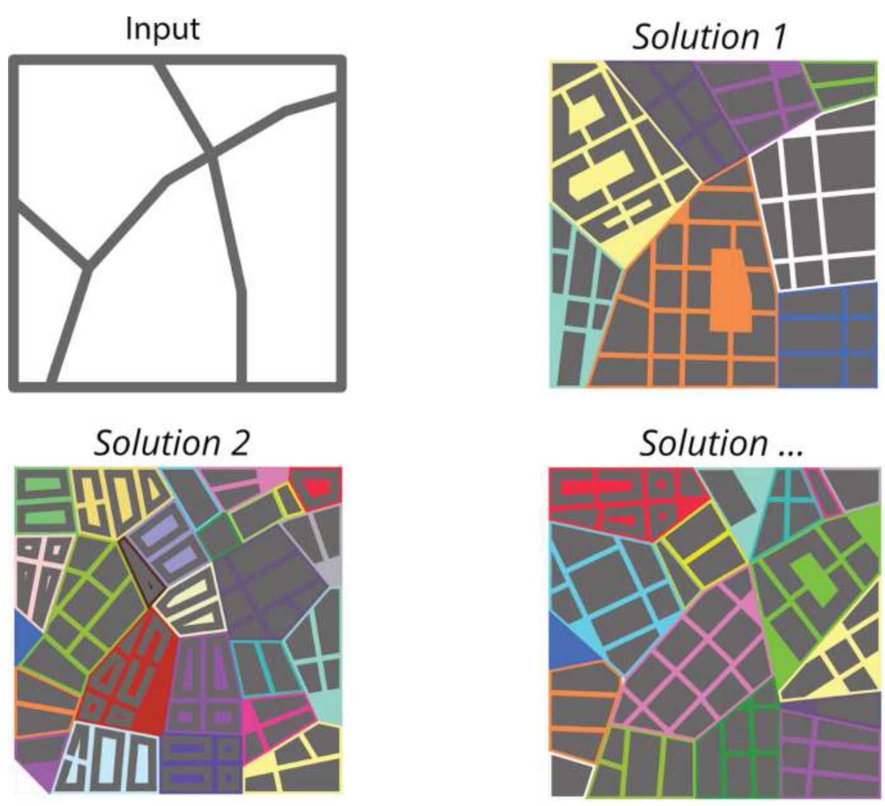
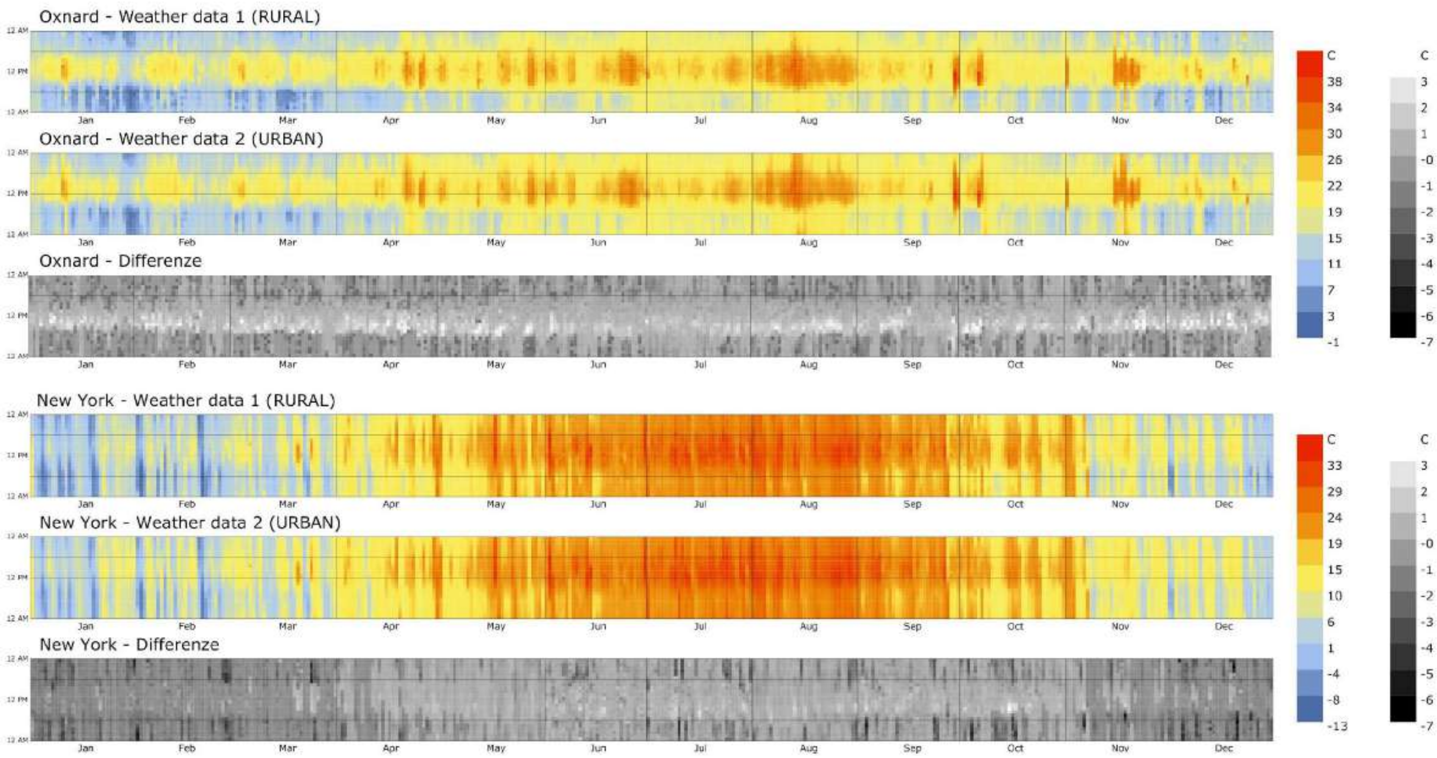


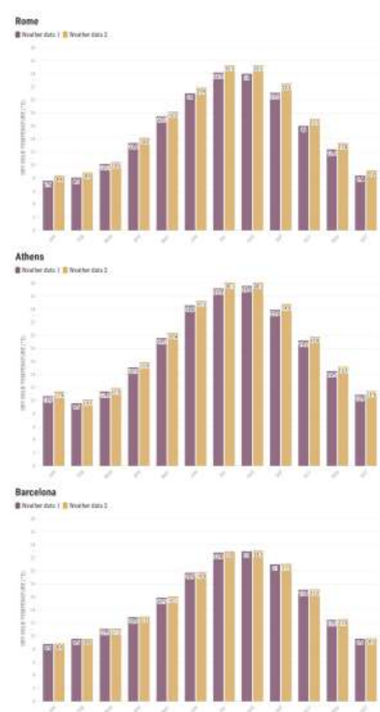
Figure 9
Potential configurations generated by the algorithm



material properties (solid, roofs, walls), the urban form, the generation of anthropogenic heat (in the street and within buildings), and the presence of green areas. The UWG is not limited to calculating traditional factors like the sky view factor or the vertical ratio of the urban canyon; it expands the analysis, calculating various relationships between the built environment and the territory. In particular, it considers three factors: site coverage ratio, façade-to-site ratio, and average building height. The parameters used, which are reported in Table 1, describe homogeneous urban fabrics using indices of the surface density in the vertical and horizontal directions, 'rapidly' adapting to different urban fabrics ***Fig. 1-8***. The built environment is characterized from the energy point of view, considering (with respect to the type and age of buildings) the relationship of glass surfaces, the albedo of horizontal and vertical surfaces, and, finally, the presence of a garden roof. In addition, the UWG characterizes the city based on the presence of urban greenery (horizontal or vertical), the amount of impermeable surface area, and road traffic present in the area of study. By interrelating all this information, the model transforms the 'rural' meteorological data into 'urban' climate data that better agrees with the microclimate of the city. 3) The third phase is to manage energy/environmental aspects via the Ladybug plug-in for Grasshopper (Sadeghipour Roudsari and Pak, 2013) in order to calculate the universal thermal climate index (UTCI), a quantity representing perceived outdoor comfort. Values of the temperature perceived by the subject using the study area are returned in degrees Celsius. Environmental comfort is defined within the band from 19°C to 26 °C, while values between 26°C and 28°C define the comfort zone for brief periods. This process allows for an understanding of how geometric and material aspects affect the microclimate and, as a consequence, the environmental comfort and empathic perception of the place, i.e., 'architectural empathy' (Mario Cucinella Architects, 2016; Wölfflin et al., 2009).

Figure 10
Visual description of annual results and their delta for Oxnard - New York

Figure 11
Comparison between weather data 1 and 2



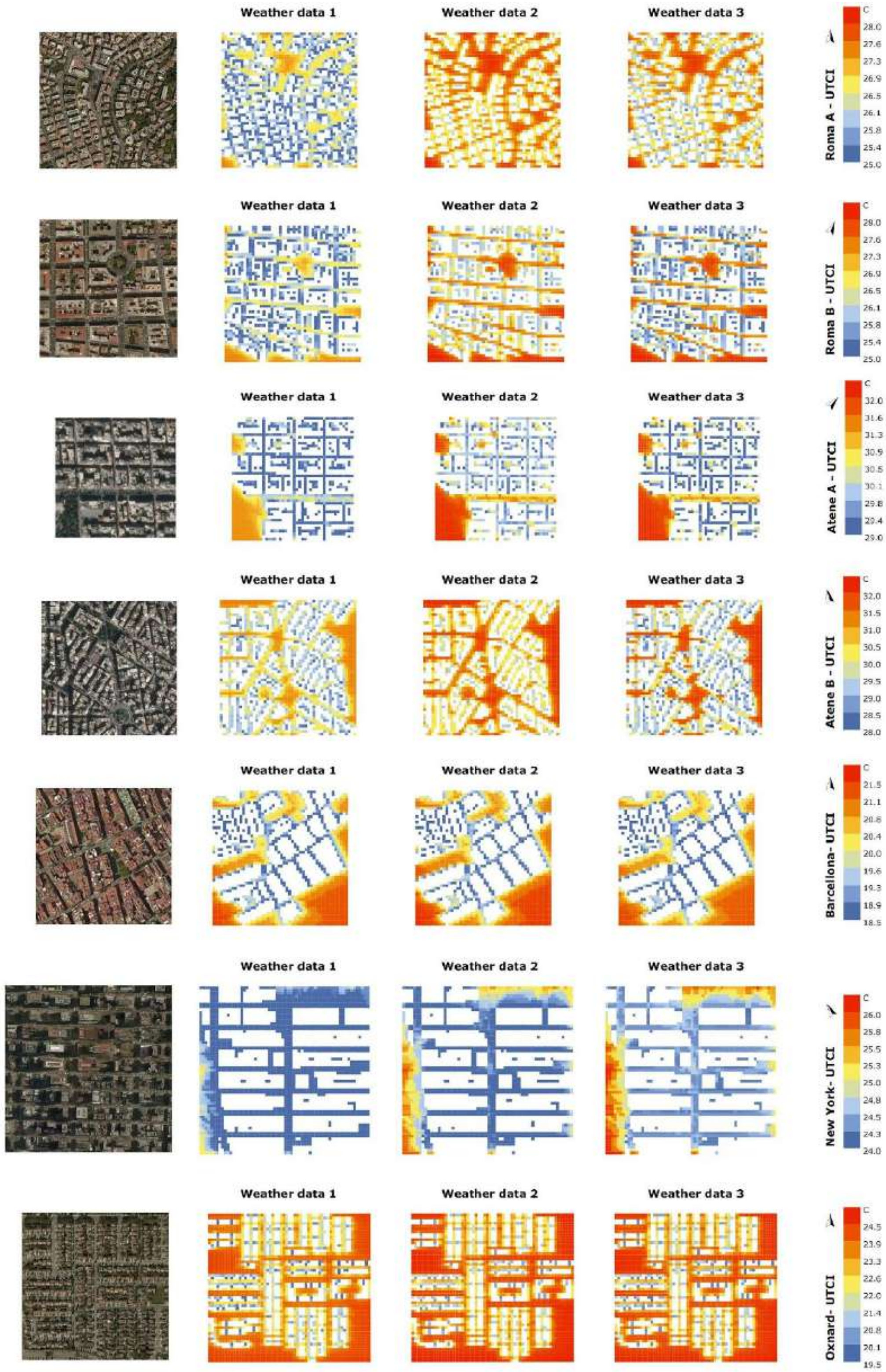


Figure 12
All compared results

	Rome A	Rome B	Athens A	Athens B	Barcelona	New York	Oxnard
Average Bldg Height	15 m	13 m	12 m	10 m	17 m	106 m	6 m
Site Coverage Ratio	0. 47	0. 49	0. 38	0. 41	0. 47	0. 6	0. 39
Façade-to-Site Ratio	1. 25	0. 96	0. 8	0. 94	0. 82	7. 78	0. 6
Tree Coverage Ratio	0. 04	0. 03	0. 01	0. 01	0	0	0. 06
Grass Coverage Ratio	0. 3	0. 03	0. 12	0. 1	0. 06	0	0. 8

Tab1

The data necessary for this analysis are:

- *Dry bulb temperature*
- *Wind speed 10 m above the ground*
- *Relative humidity*
- *Average radiant temperature*
- *User-related data (age, gender, height, weight, metabolism, clothing)*

The first three are provided by values of the meteorological profile modified by the UWG in the preceding phase. The average radiant temperature is calculated numerically (according to UNI-EN 27726 standards) and represents the temperature of an artificial, thermally uniform environment that would exchange the same thermal radiant thermal energy with the human body as is exchanged in the real environment. Once the values of the UTCI are obtained at various points and visualized as a colour gradient on the urban map, one can identify the effects of the urban heat island present the city and design strategies for climate mitigation.

Urban climate tool application

The methodology developed was applied to the case studies, which were chosen based on their geometric and environmental characteristics. In particular, urban fabrics were sampled pertaining to cities with a Mediterranean climate (Csa in the Köppen climate classification: Rome, Athens, Barcelona, Oxnard) (Peel et al., 2007) and a humid subtropical climate (Cfa classification: New York). The cities in the first group have a primarily horizontal development, while New York is obviously the symbol of a typically vertical urban fabric. The city with the highest presence of green areas (and therefore greater permeability) is Oxnard, while New York is the most impermeable. Once all the urban fabrics were reconstructed, they were characterized from the material point of view and various climate files were produced and used in subsequent phases to assess outdoor comfort (by determining the UTCI). Each sample covers a surface area of about 500 m 2, and each city was evaluated for its own hottest week (hot week scenario), defined based on the climate file ***Fig. 9***.

For each sample, the UTCI was evaluated starting from the original climate file (weather data 1) and then compared with values obtained with the 'urban' climate file modified using the UWG (weather data 2). The climate file was then modified further to create a paradoxical condition in which the city, while maintaining the same formal characteristics and geometric ratios, presents a paradoxical condition wherein all materials have an albedo equal to 1 (maximum reflectance) and there is total green- roof coverage (weather data 3).

Tool application results

The analysis shows that this methodology allows the local climate characteristics to be assessed quickly and expeditiously. Different effects of the urban heat island were revealed depending on the season (winter/summer). These effects are represented by the UTCI, which allows users' perception of comfort, i.e., the perceived well-being of the place, to be evaluated. This also represents a competing element in defining the architectural empathy. In winter, the urban heat island is effective in fabrics with greater vertical density, such as New York ***Fig. 11 and 12***, which has a façade-to-site ratio ***Tab. 1*** that is much higher than the other portions of city considered. In summer, however, a higher horizontal density exacerbates the intensity of the urban heat island effect and, as a consequence, also the negative effects tied to urban overheating.

In Europe, it is clear how, for this type of simulation, it is now impossible to overlook the use of the climate file without the necessary proper characterization. The increases, even if a little less than the American cities should be considered limiting cases: Oxnard, with its moderate horizontal density (low, sparse buildings), does not show appreciable variations in perceived urban comfort between the urban and peri-urban areas throughout the year, nor are there evident improvements in the paradoxical case. In New York, on the other hand, the urban heat island effect creates a slight increase in summer temperatures, but seems to draw greater benefit in the winter when the urban temperature increases punctually, creating a thermal gradient of 6–7°C ***Fig. 10***. The annual value is about 1°C.

This research proposes an in-depth, quick method of analysis, a workflow, to delineate an urban design that is sustainable and controlled energetically because it is capable of simulating the effect of design proposals on the urban heat island. The method proposed aims to decode the highly complex city system, considering meteorological data, technological aspects, and architectural empathy. The resulting isopleths and graphs are meant to act as support for design, providing a preliminary detailed analysis and becoming a fundamental means to design climate and technological devices that can improve the urban context analysed. Since this is an open, complex analysis capable of determining additional effective solutions and output that can be validated, this work represents the first step in defining a tool that is even more effective in hypothesizing interventions that consider the parametric variables referring to the dynamics of urban transformations, such as economic and social factors. ***Appendix C***

DESIGN A MICRO-CLIMATE CARDBOARD CONTROLLER DEVICE

Algorithmic and parametric procedures allow complexity to be managed relatively easily: they are versatile and expandable and enable multiple factors that have a reciprocal and simultaneous influence to be addressed. The logical/mathematical capabilities of computer tools thus allow the most correct and efficient solutions to be obtained with respect to all the parameters considered. The computer therefore 'minimizes a parametric functional', wherein 'functional' implies the space of the phases of possible choices based on the input parameters and 'minimize' means obtaining the best choice in terms of efficiency (environmental comfort, energy efficiency, functional requests, environmental impact, structural efficiency, etc.). This is where the designer intervenes; with multiple parameters involved, the designer's task is to choose from among the different possible solutions. It is in this choice that the designer's capacity unfolds, in architectural thought that is not only efficient but also capable of innovating, thrilling, and involving.

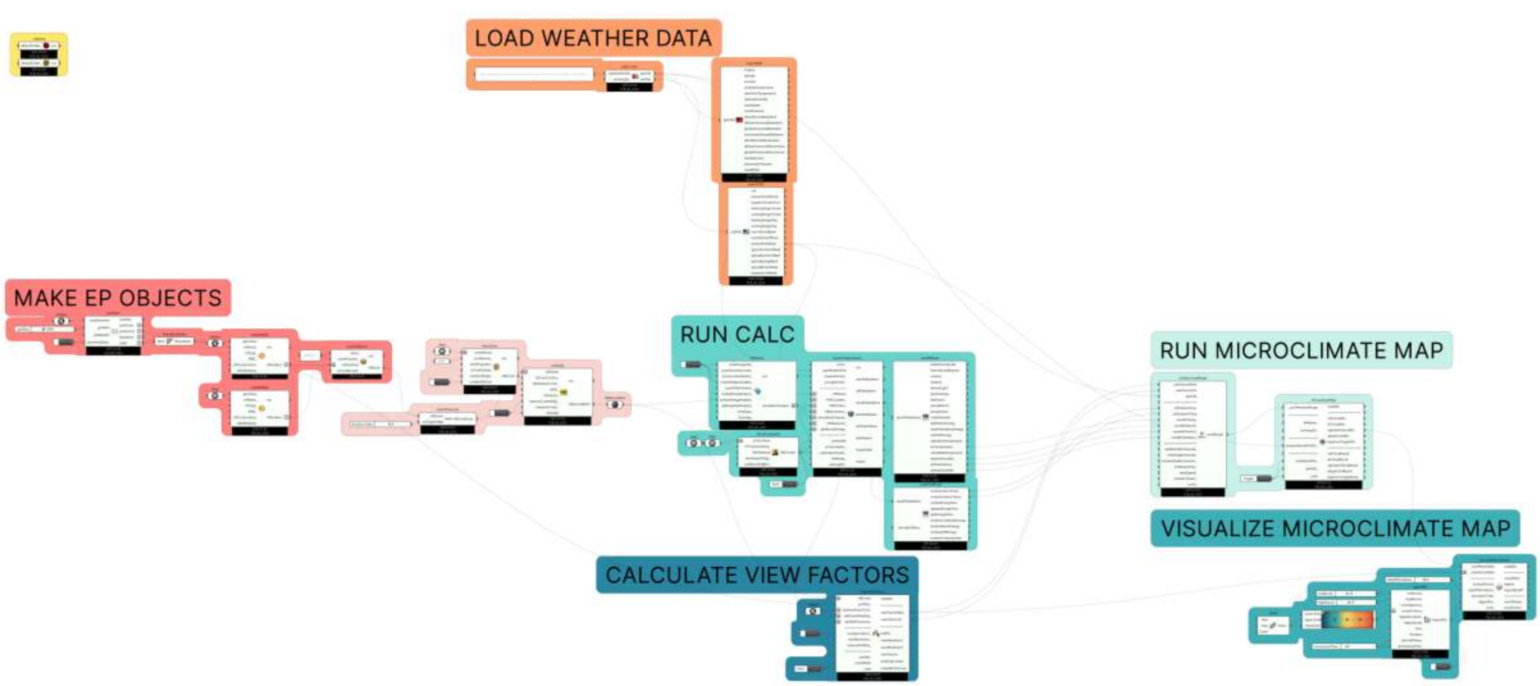
In this research a new methodology to manage and assess the complexity of environmental design is presented. To create the workflow, various tools are used and managed in a single platform called Grasshopper1. This platform is a development environment in which programs can be packaged independently according to continuous feedback actions: input commands assigned in the first phase generate output that feeds the input information again in an iterative manner.

Since Grasshopper is a true development environment, it allows for parametric control of each aspect of the process ***Fig. 13***. This means that each aspect of the design should be converted into a numerical variable, translating common 'design' thoughts into new 'parametric' thoughts. With this platform, tools such as ENVI-met[2], EnergyPlus[3], and Urban Weather Generator[4], can be managed by means of the various plugins for Ladybug Tools[5] (libraries configured within Grasshopper as needed).

The workflow can be divided into three phases: the first, pre-analysis; the second, processing and analysis, and the third, optimization.

Once the area of study has been chosen, the first phase entails the insertion of information on the urban scale using data collected from available GIS[7]

Figure 13
Grasshopper process algorithm



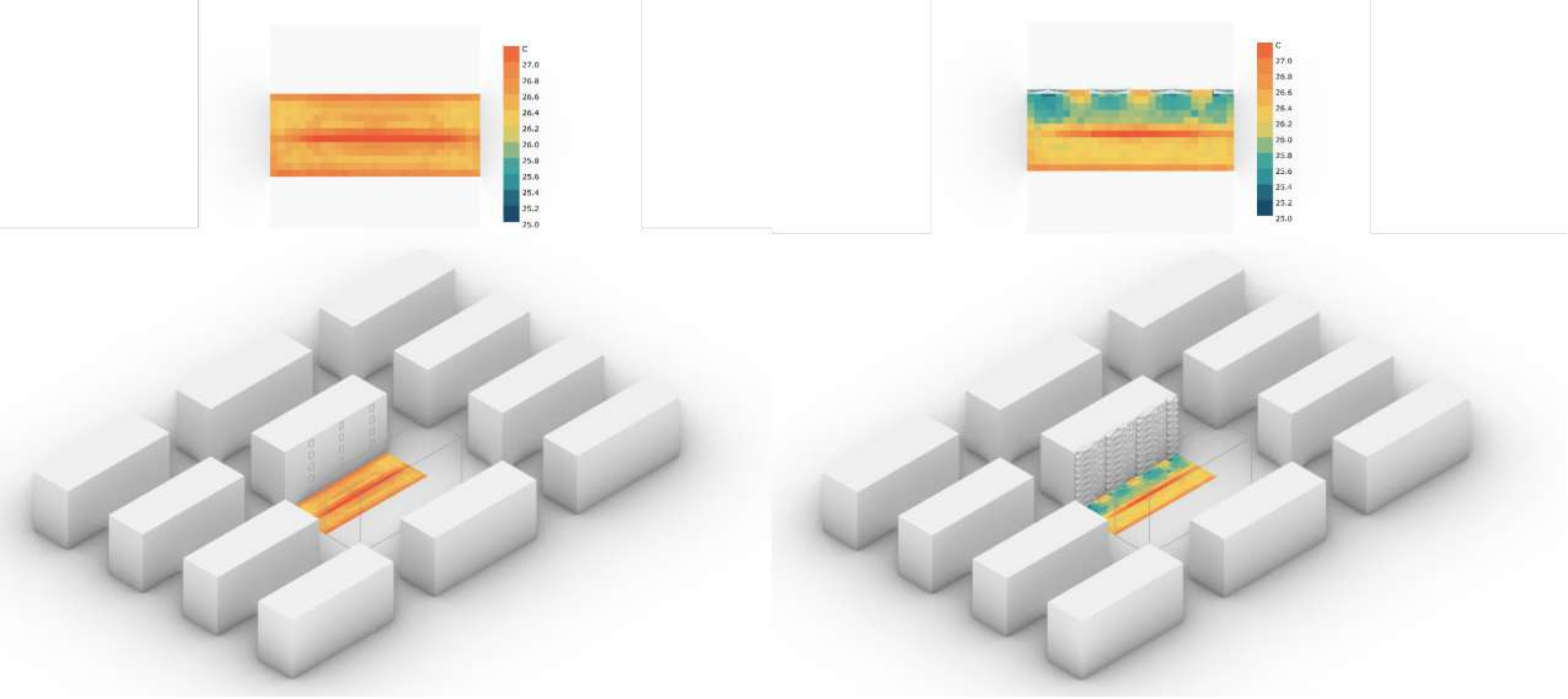


Figure 14
Making outdoor comfort from the façade

databases (building volumes, land elevation, and cladding and roofing materials).

For contiguous buildings, where analysis is made on a more detailed scale, BIM[8] (Building Information Modelling) databases may be used, which contain information about the technological details (connection with the ground, windows and doors, roofs, etc.). To best represent the exterior space, the type and position of green elements and the surface materials can be defined, along with permeable and impermeable areas.

Finally, it is necessary to use environmental data represented by the meteorological variables and levels of atmospheric pollution on an hourly basis.

In the second phase, this information is fed into the Grasshopper platform, which automates the acquisition and manipulation of the geometric/metric data, generating three different models and correlating information from very different databases:

The first model is a simplification of the urban context for use in the preliminary analysis with Urban Weather Generator to modulate the environmental data. The result of this initial investigation is a set of meteorological data modified to consider greater adherence of the environmental data in an urban context. It is characterized by typical phenomena tied to climate change as effects of the urban heat island. The output data is used by the other models.

The second model entails exemplification of the urban layout (according to a three-dimensional grid) for use with the ENVI-met tool to generate the thermal fluid-dynamics analysis in the outdoor environment. With this model, variations in temperature, humidity, the wind field, pollution levels, and the state of comfort or discomfort in the representative scenario can be assessed. The output is used in the last model.

The third model represents the 'thermal masses' of the buildings for use with EnergyPlus to generate the non-stationary thermal analysis. EnergyPlus very accurately simulates the energy state of the buildings, which is combined with analysis of the conditions at the edge of the outdoor environment (from the previous phase). The workflow thus developed allows the results of the outdoor analysis made with ENVI-met to be tied to the indoor simulations made with EnergyPlus, returning information that is much more complete. The time to calculate the results of this last phase is short enough to allow for recursion of the simulation to optimize the results.

The last phase is represented by the optimization of the systems in which the values (geometric, material, etc.) of the parameters characterizing the technological devices can be identified using recursion to maximize their efficiency. The generation of the variables is not random, but rather managed through the use of particular genetic algorithms capable of improving the results, which are evaluated with each variation. These tools allow for assessment, for example, by progressively refining the solution to very complex problems entailing one or more objectives.

Case Study and Discussion

The case study is cardboard façades with different patterns inserted in a typical Italian climate context. To highlight the urban heat island phenomenon, Palermo was considered as is often done for its warm urban area *Fig. 14*.

Under the Köppen Climate Classification, Palermo is defined as Csa, 'hot summer subtropical', a climate often referred to as 'Mediterranean'.

The choice of cardboard originated in the challenge of designing architectural elements capable of controlling the microclimate within the urban space, considering the complexity of the system. The study of cardboard architectural elements grew out of the technological need for a light material that could be formed into complex geometries inspired by the Japanese tradition of origami. Cardboard is a light material traditionally used in architecture for its structural characteristics; here, however, it is used for its physical/technical characteristics (capacity to adequately reflect solar radiation, preventing urban overheating and ensuring impermeability with a surface treatment).

To design these elements, a parametric approach was used to translate complexity into potential, tradition into innovation. With the computerized parametrization of the geometries, it was then possible to easily modify the geometries of the system to find the best energy performance and possibility of realization by means of digital manufacturing.

Figure 1 shows an analysis of the façade to improve the state of outdoor comfort acting as a reflective membrane for solar rays within an urban canyon in Italy. With the optimization algorithms, it was possible to study the correct fold of the façade element to maximize the comfort level. The Figure shows the difference in temperature (bluer colours represent greater comfort) between the bare façade and the façade with the optimized cardboard element. The façade with the cardboard element clearly produces a lower temperature in the immediate area. This shows how it was possible use the recursive parametric analysis to analyse the façade element to reduce the temperature by about 1ºC evaluated for the UTCI (Universal Thermal Climate Index), reaching the thermal comfort zone (between 9 and 26 degrees Celsius).

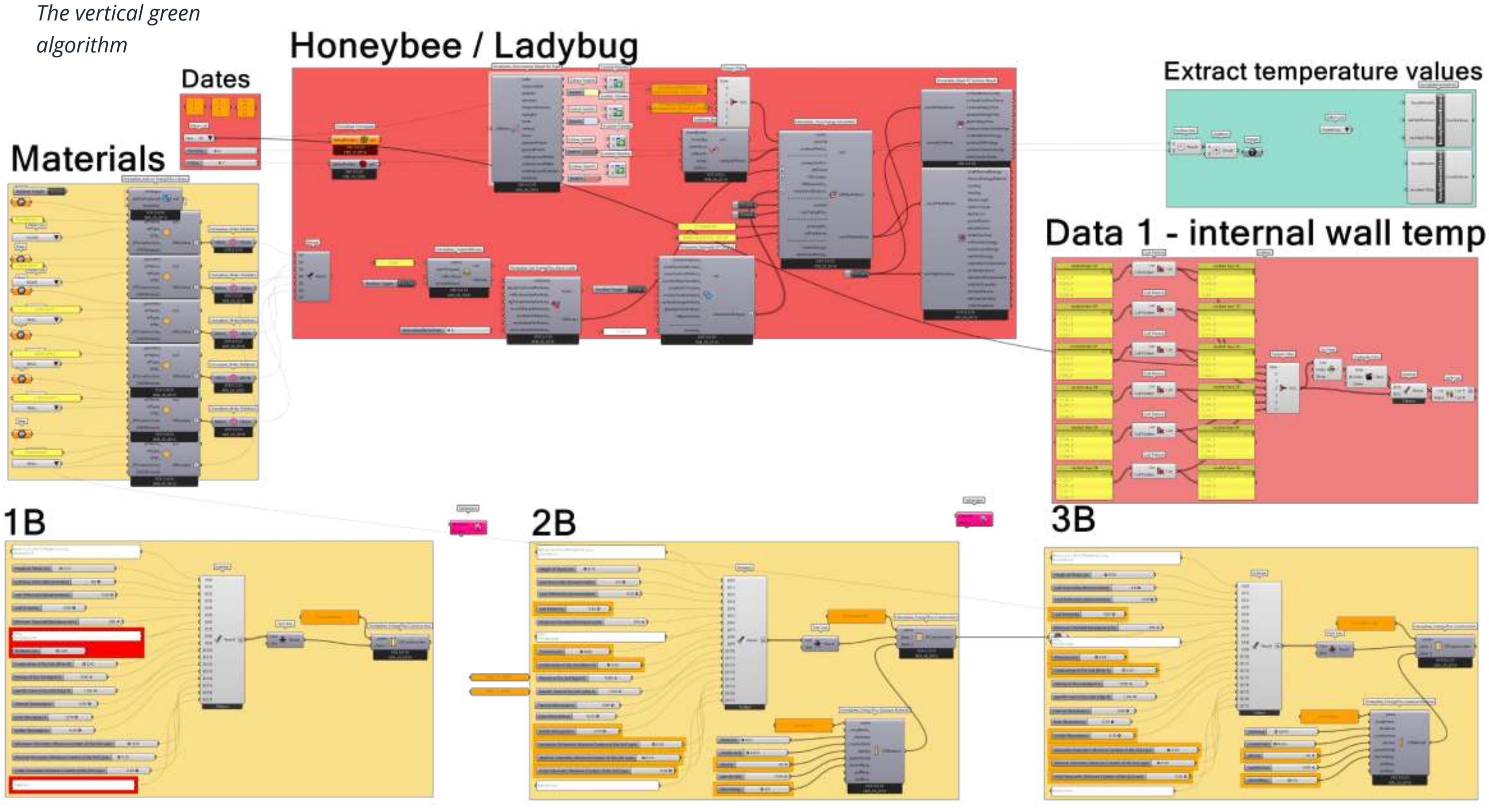
Figure 3 shows three possible modular variants to be applied on the façade (Miura Ori, Ron Resch, and Yoshimura patterns). Following our analysis, the pattern on the right was found to be the most favourable in terms of improving the thermal comfort in front of the façade. This was the pattern used for the analysis in Figure 1.

Toward (Re)generative Urban Design

In recent years, global climate change and its local projection have compelled careful analysis regarding the complexity of urban systems. These systems are complex and composed of multiple independent yet interacting components that increase the flow of information and design parameters. This complexity is represented by the autopoietic capability of exterior architectural structures, that is, the ability to react to information from the outdoor environment by continuously modifying and adapting their state. It follows that the skin increasingly tends to become more of a 'threshold', a (re)generative and adaptive interface that regulates and minimizes the flows of information that cross it. It is therefore no longer an element of separation but of connection between urban volumes and empty spaces. In this way, the relationship between building and public space becomes the design of spaces for interaction, that is, in-between social interaction. A link is made between the quality of 'between building' spaces, the quality of life within buildings, the possibility for users to establish social activities, and the possibility of designing comfortable places.

Environmental aspects are gaining importance in the design of anthropized ecosystems. The material and morphological

Figure 15
The vertical green algorithm



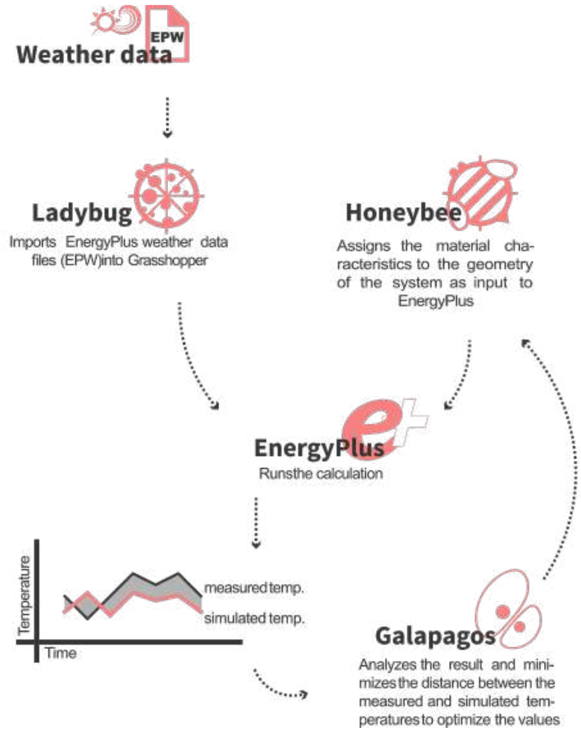


Figure 16

The vertical green workflow scheme

characteristics can be associated in complex relationships that generate and influence design solutions on various levels, solutions capable of adapting over time to respond to environmental questions while also activating and supporting social mechanisms for community growth.

(Re)generative design allows computer systems to be used to define architecture whose essence does not lie in techniques per se, but in the awareness of the consequences that the use of techniques may have on the perception and use of open space and architectural structures. In addition, it allows processes for evaluating the design choices to be accelerated due to the association of material, geometric, and environmental characteristics. ***Appendix E***

DESIGN AND OPTIMIZE A GREEN FAÇADE SOLUTION

A parametric method was developed to optimize the green façade (green façade optimization, GFO) in order to consider the characteristics of the growing media, irrigation and vegetation characteristics, and to account for shading and insulation effects as well as evapotranspiration from the substrate and plants. The method uses 3D parametric tools, Grasshopper in particular, which is a graphical algorithm editor integrated with Rhinoceros, a 3D modelling program ***Fig. 16***. Specifically, the research uses a variety of Grasshopper plug-ins, such as Ladybug, Honeybee and Galapagos, a mathematical computation solver. Small interventions in specific sites of the urban city can bring about a considerable improvement in the quality of life of the citizens, outdoor comfort and cooling load reduction. By implementing an optimized strategy that combines green shading, vegetation and cool materials, the city can reach its goals to-ward the city sustainability plan. The main goal of the research is to establish a thickness above which the behaviour of the green façade becomes isothermal and its performance do not improve. Future developments will show better outdoor and also indoor temperatures, with cooler environments in summer compared to the standard design solutions. The results are discussed and recommendations for simulating green devices are made.

The simulation can be summarized in the following five steps ***Fig. 15***.

- *First phase: single layer (outside) with a RoofVegetation/ EnergyPlus material that considered the soil and green layer;*
- *Second phase: exterior layer as in phase 1, as well as an internal layer with a 3-cm-thick insulating material;*
- *Third phase: exterior layer as in phase 1, as well as an internal layer with a thicker (7 cm) insulating material.*

Input to the simulation includes the characteristics of the material in the RoofVegetation module. Different aspects of the green roof are specified, such as root depth, thermal properties, the density of leaf coverage, plant height, and stomatal conductance, as well as soil humidity and irrigation. The complexity of the calculation system in RoofVegetation module means that a large number of parameters are required to describe the details of the green roof construction system. The RoofVegetation module only deals with the soil substrate, i.e., the last component of the roofing unit. It generally includes the drainage, insulation, and anti-root layers, which are modelled in the EnergyPlus “Materials” sheets.

The last phase (3) was selected for validation, considering all of the previous material values with the depth of the insulating layer changed from 3 to 7 cm. A period during daylight hours was considered because most of the urban mitigation potential of green walls can be observed at that time. Due to selected monitored data, a direct comparison was considered to validate simulated data. July 2011 and 2012 were considered and three days were selected as similar study scenarios. The third scenario (Phase 3, 12 July 2012) represents boundary conditions for the validation, so that only one diurnal behaviour can be used. Numerous studies have shown that a direct comparison point-by-point is feasible when small amounts of carefully selected data are compared.

The Importance of Insulation Thickness in Green Façades: A Parametric Optimization Study

The main goal of this research was to understand the importance of insulation thickness in a green façade. A new parametric optimization methodology called GFO (green façade optimization) was therefore developed and validated using real data monitored in an experimental box located near Madrid (Spain). The GFO methodology was developed to find all the unknown variables that well-known thermal simulation tools need to simulate the thermal behaviour of green façades. Comparison of the simulations to experimental data allowed the model to be validated. The model was then used to simulate the behaviour of the green wall, varying the insulation thickness from 3 cm to 13 cm. ***Appendix A***

Footnotes

1. *Visual programming languages generate software by means of a simplified interface in which the user assembles suitable ‘function blocks’ on the screen in a visual syntax rather than by writing textual code.*
2. *ENVI-met is a program that simulates urban environmental phenomena and assesses the effects of the atmosphere, vegetation, architecture, and materials (www.envi-met.com).*
3. *EnergyPlus is a complete program for building energy simulations that engineers, architects, and researchers use to model energy consumption for heating, cooling, ventilation, and lighting. Its development is financed by the US Department of Energy’s (DOE) Building Technologies Office (BTO) (www.energyplus.net).*
4. *Urban Weather Generator is a robust, reliable program for studying the effect of the urban heat island. It grew out of the Urban Microclimate Project developed by a research group at MIT (https://urbanmicroclimate.scripts.mit.edu).*
5. *Ladybug Tools is a collection of free applications to support design; they serve as an interface for different energy simulation systems (www.ladybug.tools).*
6. *Grasshopper is an integrated development environment (IDE) that runs within the Rhinoceros 3D n. The program was created by David Rutten at Robert McNeel & Associates. (http://www.mcneel.com/)*
7. *Geographic information system (generally abbreviated to GIS), is a computerized information system that allows the acquisition, recording, analysis, visualization, restitution, information derived from geo-referenced geographical data*
8. *Building Information Modeling (generally abbreviated to BIM) indicates a software method for design, planning and construction management of building.*

CONCLUSION

Instruments that help assess microclimates and building projects are commonly used today, but software companies have not supported their development. Independent developers have created their tools to meet specific needs. The platforms like Grasshopper and Dynamo allow developers to connect different tools, promoting a more comprehensive context. In order to study the effects of complex phenomena on an anthropised system, accuracy sacrifices may be necessary to maintain a balance between complexity and workflow smoothness. Various tools can be used in a single platform to run simulations independently and exchange data. With the help of plug-ins called Ladybug Tools, it is possible to manage third-party tools such as ENVI-met, EnergyPlus, and Urban Weather Generator. It is essential to understand the scale of the intervention from the beginning to optimise analysis times.

The form of a city, its structure, and how it changes over time are important factors to consider when analysing its evolution. The current city transformations are so large and complex that traditional methods for studying and intervening in cities are no longer adequate. We need new methods that can model the city's complexity. Parametric models can create digital simulations of cities that can be quickly consulted and modified in real-time. Parametric modelling is a way to create models of the city by defining limits and relationships between variables, and this allows for the quick creation of different scenarios to see how the city would respond to different conditions. The research proposes a quick, in-depth method of analysis to help create a sustainable and controlled urban design. The proposed method considers meteorological data, technological aspects, and architectural empathy to create isopleths and graphs supporting design. This work represents the first step in defining a tool that can more effectively hypothesise interventions considering economic and social factors.

Going down in scale, Designing architecture that interacts with the environment is becoming more critical as climate change increasingly affects all. In order to design buildings and public spaces that are more comfortable and accommodating for social interaction, we need to be aware of the consequences of our design choices. Computer systems can help us do this by accelerating the design process and evaluating different possible solutions. Complexity management can be achieved through parameterisation, i.e. the definition of a set of rules that allow complexity to be managed in a controlled and predictable manner. Parametrisation allows complexity to be reduced to a set of controllable variables, making it possible to manage complexity in an orderly and rational manner. A parametrisation is, therefore, a fundamental tool for governing complexity and managing complex organisations effectively.

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“I believe that the material doesn't need to be strong to be used to build a strong structure. The strength of the structure has nothing to do with the strength of the material.”

Shigeru Ban

Prototype

THREE-DIMENSIONAL ARCHITECTURAL FAÇADES

The last research step was carried on in collaboration with the University of Cyprus in Nicosia, where different geometric solutions were studied to interpret their behaviour towards solar radiation. The study was conducted on samples made in the university's laboratories through rapid prototyping techniques. The prototypes were subjected to heating with infrared lamps placed at certain angles and analyzed with a thermal imaging camera to verify their level of heating and determine which samples could heat more and which less.

Traditionally, façades were perceived to cope with aesthetic features, or in order to create a thermal barrier between the indoor and the outdoor, thus paying less attention to how their surface thermo-physical performances could affect the outdoor microclimate. Common sense and tacit knowledge have led to building surface finishes and 3d forms that were based on local technology. Each material was assembled and treated in a way that thermodynamically positively created tempered indoors.

Nowadays, non-conventional and complex 3D façades in macro-level are of increasing interest, with many examples referring to different types of geometries, which are represented, among others, as wave-like, bio-inspired and origami ones (Schultz and Katz, 2018). To some extent, their application serves environmental needs, for instance, daylight control, in buildings where façades are implemented through static and dynamic systems. Towards this direction, different materials were applied, ranging from a shape memory alloy to clay and cement-based ones, to name a few.

More specifically, examples of investigation on how building façade geometrical variations impact the local urban climate are little or non-existent. Thus, despite the rapid increase in the capabilities of technology and the advent of 3D modular units and building components' shape customization, the architectural scene have shown several 3D façades populating cities, there is no clear explanation on how such geometries relate to outdoor comfort.

DESIGN ARCHITECTURAL FAÇADES

3D façades in macro scale are based on their geometric control both locally, i.e. at the macro scale unit and in particular at the level of transformation, enabling their protrusion from a certain flat surface, and globally at the level of their overall control, as single or double-curved surfaces.

Figure 1
Plain façade behaviours

The classification of the geometries of the 3D façades based on the above observation, allows a range of types of façades to come to the fore, although in a practical and feasible level, which is representative of many buildings today, these are distinguished in tho main architectural languages.

Curve-like - The first category deals with 3D façades that follows a single or double curvature of their surface in global level, that is slightly transformed from a flat vertical surface to a curve-like one but without strong changes of unit elements in the local level, neither imperceptible projection of their macro 3D façade elements. This architectural language can be observed in examples like de Cope building in Utrecht and the 20 Hotel OMM in Barcelona. This category of 3D façades shall be called "curve- like" façade.

Wave - like - The second architectural language of 3D façades again follows single or double surface curvature in global level but with the more distinguished transformation of their unit elements, which at the local level have more intense projections than the flat state, but maintaining a rhythm of recesses and protrusions in a way that bears the characteristics of origami structures, for instance in the example of Argo Building in Colombia or the Beijing Greenland Centre in Beijing. This category of 3D façades shall be called "wave-like" façade.

Pixelated geometries - The third category refers to 3D façades, which in the global level are presented as a curve or flat ones with strong differences in the protrusion of the units that constitute them. Examples of such buildings are The Street in India and the Unicato Residential building in Poland. Due to the strong differences in regard to the protrusion of their façade elements shall be called 'pixelated' façade.

The curve-like, the wave-like and pixelated geometries, despite their complexity, are today accessible via the rapid diffusion of computational design and digital fabrication, which are opening the possibility of their design development and then their construction in actual and macro scale. Although such techniques have not been applied to the examples demonstrated herein, the construction and control of custom 3D façade units using emerging technologies, provide the opportunity for more direct control of their performance in order to respond to the local environmental conditions and users' needs. In particular, the construction of 3D façade units in macro scale, due to their increased complexity compared to conventional designs, requires the introduction of new techniques and materials, opening the opportunity for overcoming the difficulties arising during the construction of one-of-solutions. Also, it allows affordable and economically effective production techniques of complex shapes to come to the fore compared to conventional construction approaches applied in the case of mass customization of 3D façade components.

Towards this direction, a number of computer numerical control (CNC) and robotic fabrication techniques have been applied in the physical production of 3D façade systems, debating at the same time the effectiveness of this application. In the early example by Bock (2008), the digital design and prefabrication of pre-cast 3D façade elements were demonstrated, debating the advantages of robotic technology in the construction of highly customized façades at affordable construction costs, constant quality and ergonomic working conditions (Bock, 2008). Nowadays, several examples of 3D façade construction in macro scale can be found in practical and research direction, using automation and robotic techniques that include techniques for 3D printing, moulding but also forming 3D components in large scale. In parallel, methods for façade installation and assembly, but also off-site automated prefabrication and on-site application of such systems are discussed in several studies.

Their potential to provide solutions that minimize time-consuming and costly approaches (Chen et al, 2019), in particular using widely used materials like concrete, with the aim of overcoming difficulties arising in construction industry towards digitization of processes and products have been also discussed. Leveraging the potential of mass customization for the production of concrete building components, modular units and digitally fabricated 3D façades in macro scale can thus be made for given locations and the specificity of the site in order to contribute to control the microclimatic conditions of outdoor spaces.

What seems to be an topic with high currency is to link todays capabilities in the making of 3d façades to outdoor microclimatic control.

SHAPING GEOMETRY FAÇADE FOR CLIMATE CONTROL

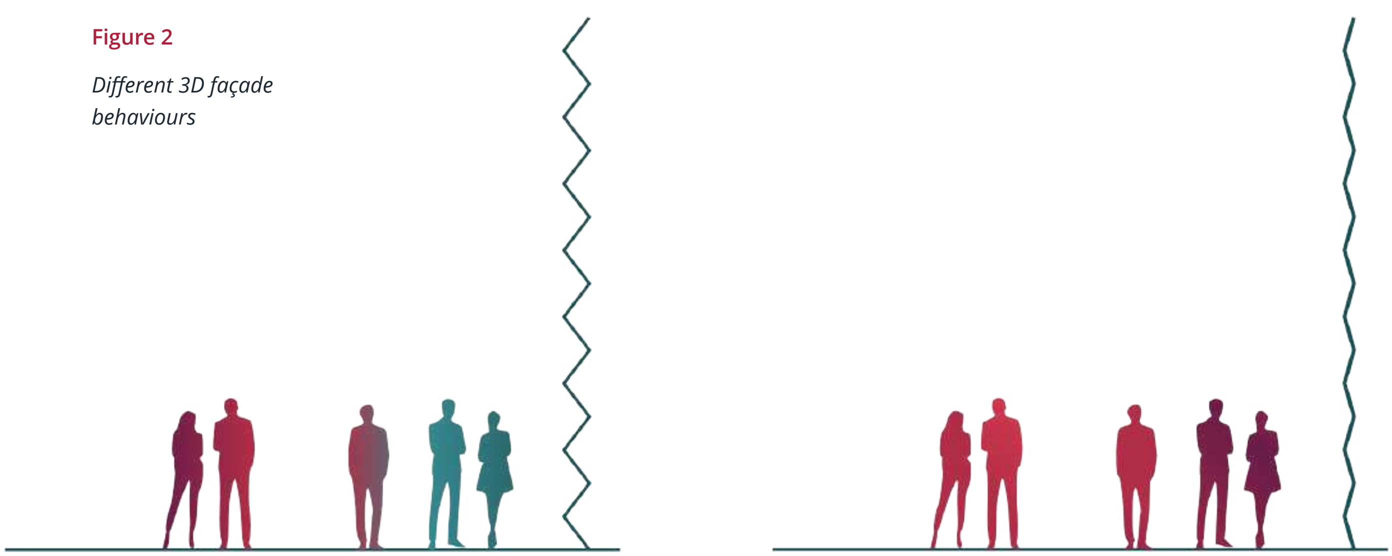
In summer, solar absorption by urban surfaces is the dominant cause of the UHI effect. The efforts to mitigate the formation of heat in urban canyons should be from one side based on controlling the absorption and emissivity of solar radiation. On the other side, it should be based on thermal reflection. Until now research has been discussing heat mitigation solely focusing on “cool” materials—those with high solar reflectance and high infrared emittance applied to building envelopes (roofs and walls) and urban structures (roads, squares and footpaths).

Highly reflective materials are usually used to decrease solar radiation absorbed by horizontal urban *Fig. 1*. However, the use of cool materials on building façades is shown to be less effective than in roofs because of the multiple reflections between the walls, and the ground implies a consequent entrapment of the solar radiation in urban canyons.

However, the 3D geometry of buildings’ façades should affect the amount of shortwave radiation absorbed by the buildings *Fig. 2*. Furthermore, shortwave radiation is reflected or even multi-reflected when buildings face each others like in canyon. Longwave solar radiation is also a primary type of local thermal exchange in such urban contexts. Here, façade emissivity becomes a significant parameter influencing the local microclimate (Doya et al., 2012; Han et al., 2015) These causes assign a primary role to tall building façades, and their influence varies according to solar angles and the geometry of façade. Therefore, it is logical to conclude that small design variations of façade can substantially impact the local thermodynamic exchanges. Clarifying the link between emissivity, reflectivity and the impact on radiant temperature as a function of building façade geometry is therefore considered of primary importance to grant a favourable

Figure 2

Different 3D façade behaviours



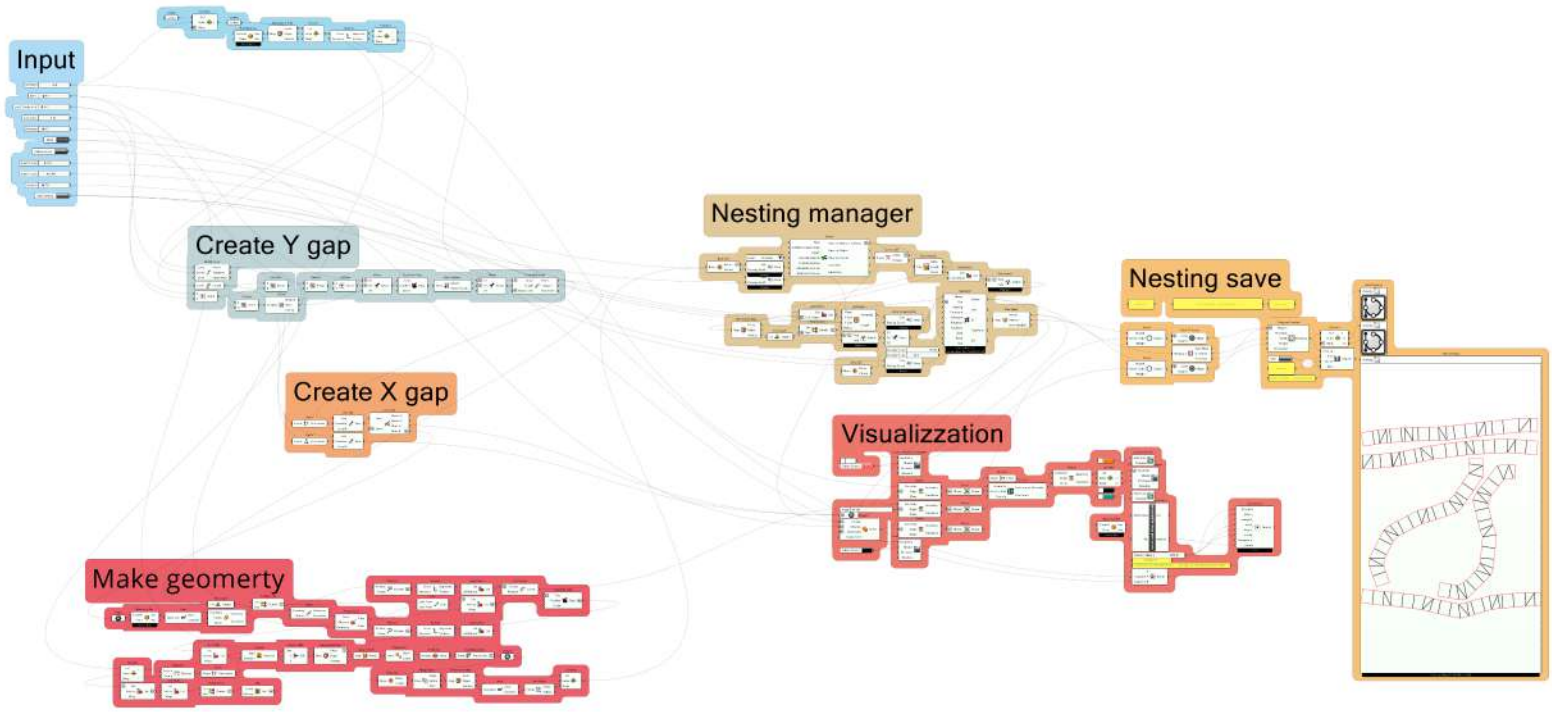


Figure 3

The algorithm for making cardboard façade

outdoor microclimate.

The hypothesis to be verified is that the geometrical variation of tiles' surfaces could lead to self shade, which is one means of controlling their temperatures. Furthermore, by orienting surface directions a second interesting hypothesis to be verified is that these surfaces can selectively exchange short and longwave radiations withe the body of pedestrians as well as with the sky. Overall, such characteristics, if varied can lead to the main hypothesis to be verified that assume that façades' surfaces can be efficient in controlling summer heatwaves and can overall contribute to temperate winters by geometrical means of their tile surfaces. In short, façade can become a resilience factor. *Appendix H*

DEVELOPMENT METHODS

In order to rework three-dimensional surfaces into cardboard objects, a specific algorithm was constructed to control the digital and laboratory realisation phase *Fig 3*. The tool has been developed with the Grasshopper platform and contains a stage for surface geometry and a stage for automated nesting operation required for laboratory production. In the first stage, surfaces are subdivided according to the main directions into continuous or discontinuous elements. The two methods of approximating surfaces generate linear or curved elements. This decision impacts the cutting layout on the cardboard sheet. The prototyping using a digital cutter in the final phase. The algorithm approximates the geometry with broken lines shaping positive and negative bulges.

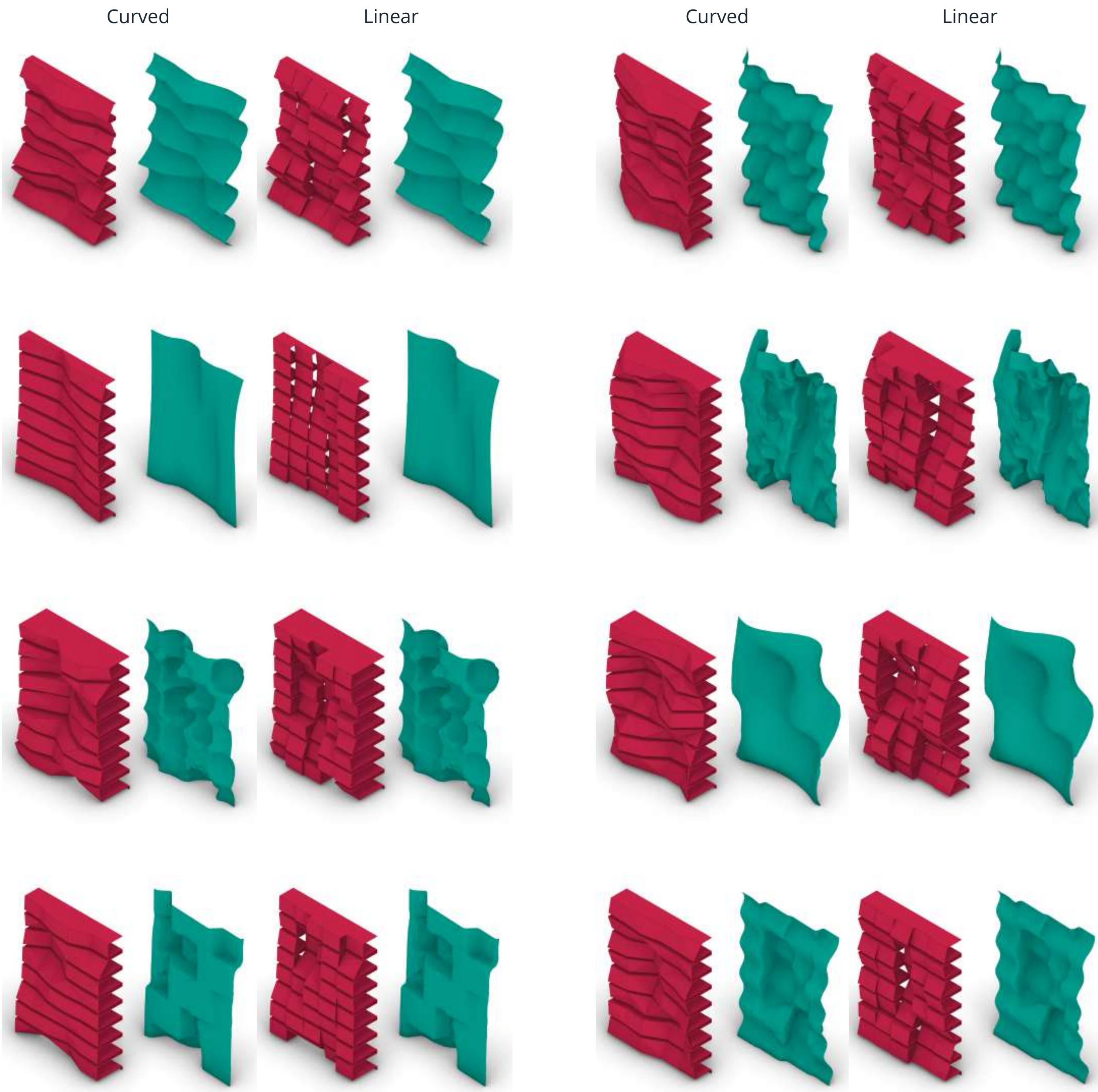


Figure 4
Surface approximation using the curved and linear method

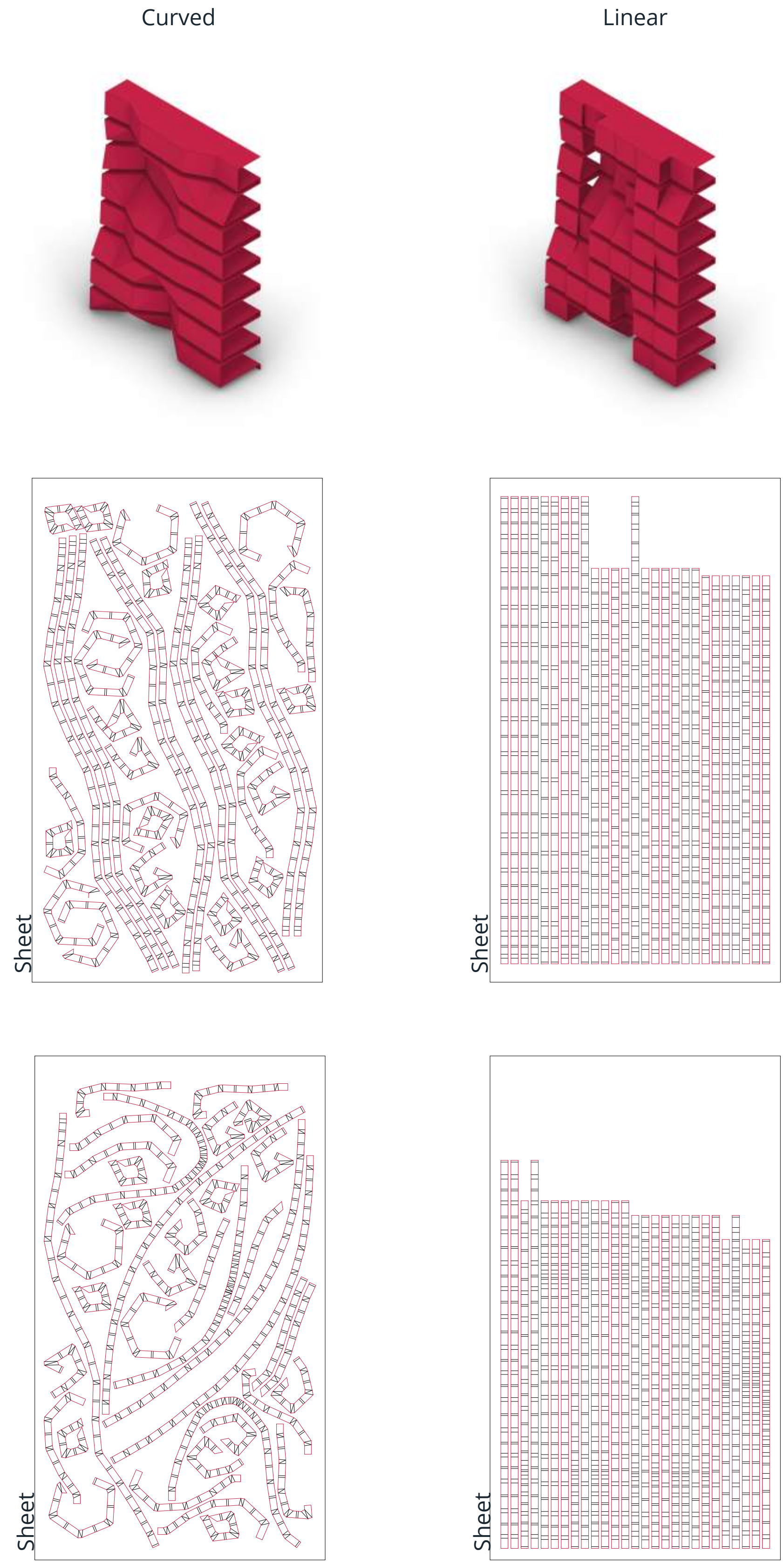


Figure 5
Surface approximation using the curved and linear method

The parameters controlling the alternation of the bulges determine their distance in the principal directions.

This algorithm can approximate infinite solutions from arbitrary geometries. The cases shown are derived from the modification of curve-like, wave-like and pixelated geometries *Fig 4*.

PROTOTYPE PRODUCTION

These geometries, thus created, can be used as elements to be affixed to traditional façades to make them three-dimensional. The algorithm that manages the geometries can construct sheets containing the cutting and creasing information that the digital cutter can interpret *Fig 5*. The algorithm develops the cardboard strips on the plane and automatically places the various pieces next to each other, maintaining the minimum distance required by the operator so that the cut is clean and, at the same time, tries to use all the spaces on the sheet, minimising waste.

Figure 6
Insutated solution

Figure 7
Green solution

The result of this operation changes depending on whether a linear or curved geometry is used. In the first case, the strips to be cut will be arranged longitudinally along the sheet, while it is impossible to predict the result in the curvilinear case in which the algorithm takes a long time to rotate the elements on the sheet in order to guarantee optimal use of it. Finally, it is possible to optimise cutting and creasing operations by sorting the resulting segments according to their position to reduce the movement of the digital cutter's cutting head and reduce working time.

Fold the strips along the creasing lines and attach them to rigid support to complete the product.

The three-dimensionality of a cardboard wall can allow outdoor microclimate control and acquire a second function, such as that of an insulating coat for the building it is leaning against, exploiting the interstices of the geometry by inserting plant-based insulation ***Fig 6***. Another solution to improve the outdoor performance of this wall is to integrate it with live greenery ***Fig 7***. Many of the configurations presented have the right geometrical conditions to accommodate a type of vegetation that does not need soil (tillandsia). As has been amply demonstrated in the literature, greenery on walls provides a dual benefit by improving both outdoor and indoor comfort. any possible solution involving cardboard or other materials will have to include a water-repellent surface treatment.

CONCLUISION

The traditional use of façades was to cope with aesthetic features or create a thermal barrier between the indoor and the outdoor. However, there is a growing interest in non-conventional and complex 3D façades that serve environmental needs such as daylight control. The research wants to answer how building façade geometrical variations impact the local urban climate.

3D façades are based on their geometric control, which allows them to protrude from a flat surface. The classification of the shapes of the 3D façades makes possible a variety of types of façades.

The use of computational design and digital fabrication has made complex geometric shapes more accessible, which could be used to construct 3D façades. New techniques and materials will be needed to build these shapes at a larger scale, but the potential benefits outweigh the difficulties. Some advantages of using these techniques include producing highly customized façades at affordable construction costs, regular quality, and ergonomic working conditions.

The UHI effect is mainly caused by solar absorption by urban surfaces in summer, and efforts should be made to control the absorption and emissivity of solar radiation and reflect thermal energy. The shape and orientation of buildings' façades affect how much shortwave radiation they absorb, which affects the local microclimate. The research aim is to lead self-shading to the surfaces, which can help to control the temperature of the building. Furthermore, if the surface directions are varied, the tiles can selectively exchange radiation with pedestrians and the sky. it may be concluded that the surfaces of façades can be effective in controlling summer heatwaves and temperate winters. The described algorithm controls the way a three-dimensional surface is reworked into a cardboard object. The surface is subdivided into elements according to its main direction, and the two approximation methods determine whether the elements are linear or curved. The algorithm allows for an infinite number of solutions to be generated from arbitrary geometries. A cardboard wall can be used to control the microclimate and serve as an insulating coat for the building it leans against by using the spaces between the cardboard to insert plant-based insulation. Another solution to improve the external performance of a cardboard wall is to integrate it with greenery, which benefits both the exterior and interior comfort of the building. Any possible solution involving cardboard or other materials will need to include a water-repellent surface treatment.

ACKNOWLEDGEMENTS

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I would also like to thank my family, who without this would not have been possible.

Figure 8
A front view of a prototype device

Figure 9
Another view of a prototype device

Figure 10, 11, 12
Side view of a prototype device

List of Figures

Appendix

Poster exhibition on "World Forum on urban Forest" - Mantova 2018
Roberta Cocci Grifoni, Maria Federica Ottone, Graziano Enzo Marchesani, Dajla Riera
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A - DEVELOPING A PARAMETRIC URBAN FOREST TOOL

Keywords: Green façades, Parametric optimization, Energy-efficient design

Abstract

Green roofs and plant façades are today's new frontier in the relationship between nature and architecture. The technique has given architecture operational concreteness, offering unexpected possibilities for people's primary desire to live in and with nature. Intended thus, the plant-related element is no longer proposed just as a theatre set; rather, it becomes a component of the project just like any industrialized material. In this way, vegetation adds to the quality of the overall housing system, adding a sign of increased sharing to the principles of sustainability required by environmental challenges. The aim of this work is to present an optimization analysis to determine some important parameters, such density, green typologies, vertical or horizontal direction, insulation thickness etc, to define the thermal behaviour of green devices and to proposed an optimal system strategy that not only improves the outdoor thermal comfort, but also improves the urban microclimate, reducing the cooling load of the buildings. A parametric method was developed to optimize the green façade (green façade optimization, GFO) in order to consider the characteristics of the growing media, irrigation and vegetation characteristics, and to account for shading and insulation effects as well as evapotranspiration from the substrate and plants.

The method uses 3D parametric tools, Grasshopper in particular, which is a graphical algorithm editor integrated with Rhinoceros, a 3D modelling program. Specifically, the research uses a variety of Grasshopper plug-ins, such as Ladybug, Honeybee and Galapagos, a mathematical computation solver. Small interventions in specific sites of the urban city can bring about a considerable improvement in the quality of life of the citizens, outdoor comfort and cooling load reduction. By implementing an optimized strategy that combines green shading, vegetation and cool materials, the city can reach its goals to-ward the city sustainability plan. The main goal of the research is to establish a thickness above which the behaviour of the green façade becomes isothermal and its performance do not improve. Future developments will show better outdoor and also indoor temperatures, with cooler environments in summer compared to the standard design solutions. The results are discussed and recommendations for simulating green devices are made.

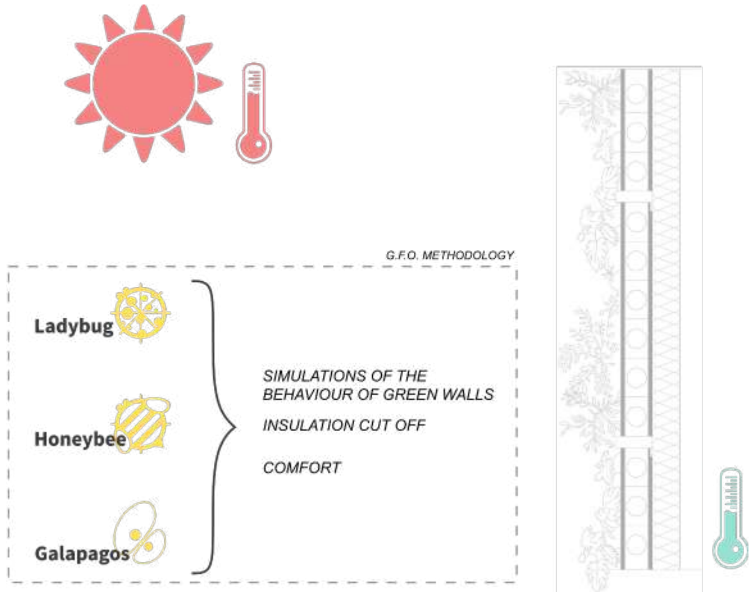

Figure 1

The G.F.O. metodology

Method

The simulation can be summarized in the following five steps.

- *First phase: single layer (outside) with a RoofVegetation/EnergyPlus material that considered the soil and green layer;*
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Conclusion

The main goal of this research was to understand the importance of insulation thickness in a green façade. A new parametric optimization methodology called GFO (green façade optimization) was therefore developed and validated using real data monitored in an experimental box located near Madrid (Spain). The GFO methodology was developed to find all the unknown variables that well-known thermal simulation tools need to simulate the thermal behaviour of green façades. Comparison of the simulations to experimental data allowed the model to be validated. The model was then used to simulate the behaviour of the green wall, varying the insulation thickness from 3 cm to 13 cm.

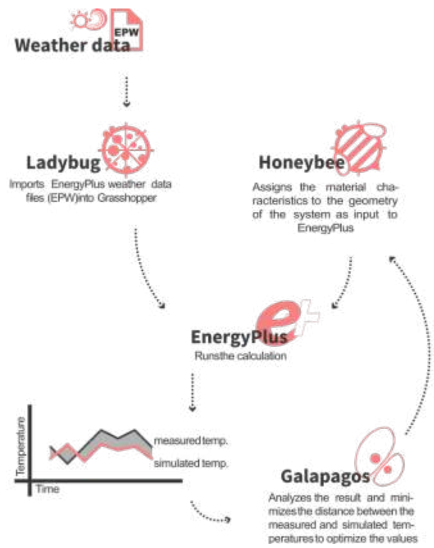
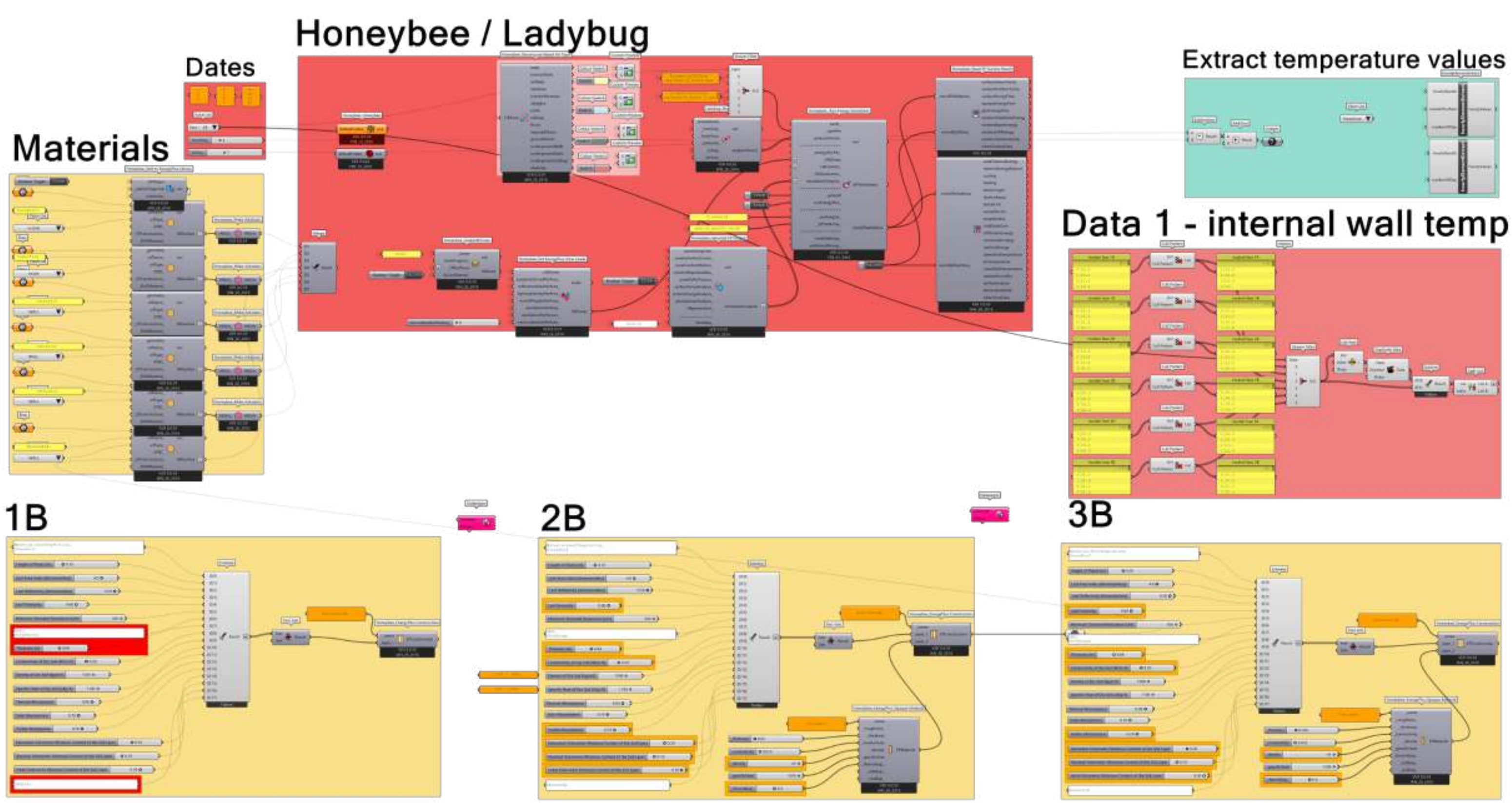


Figure 2
The workflow scheme

Figure 3
The algorithm



Contribution for the book "Emergenza clima e qualità della vita nelle città"
Graziano Enzo Marchesani
School of Architecture and Design Eduardo Vittoria, University of Camerino

B - STRATEGIES FOR URBAN MICROCLIMATIC INVESTIGATION

Keywords: Climate change, Climate workflow, Urban heat island

Introduction

For over a decade, more than 50% of the world's population has lived in cities, an estimate that tends to increase continuously. This trend is very accentuated in emerging countries and less so in countries with a more developed economy. Italian cities are not excluded from this phenomenon, growing by 8. 7% from 2001 to 2011 (ISTAT, 2017). Urbanized spaces suffer more in relation to the microclimate conditions, clean air, and environmental comfort in general. The study of microclimate characteristics on the urban scale and the strategies and technologies to modify it is therefore a fundamental task for contrasting the negative effects directly impacting the liveability and health of urban environments, as well as the quality of outdoor and indoor spaces. Many factors are involved in assessing the quality of urban spaces, including sources of noise and atmospheric pollution, health, and environmental hygiene. There are now expanding applications and spreading analyses and studies on the urban environment aimed at researching the microclimate and identifying the most effective scenarios and strategies to achieve qualitative transformations. In fact, improvement is obtained by controlling a specific microclimate phenomenon that impacts health and also energy consumption and global climate change: urban 'heat islands'.

Problems

Locally, the increase in global temperature is mostly seen in the urban space because it is subject to the urban heat island phenomenon, leading to an increase in air temperature of several degrees where the urban fabric has a higher density than the surrounding agricultural territory. The urban heat island is not problematic during the winter, when it may even protect (at least minimally) from the harshness of the winter in certain circumstances (Ottone et al., 2019). The increase in temperature undoubtedly becomes a critical factor in the warmest months of the year, however, when the temperature gradient within the city varies only minimally between day and night, even persisting for several days. These so-called 'heat waves' are monitored in Italy by the Civil Protection Service by means of the HI (heat index), i.e. a synthetic index that relates temperature and relative humidity to estimate the level of risk that these imply for the health of the population (Steadman, 1979). In Italy (and large areas of Western Europe), summer 2003 was characterized by prolonged and extreme weather conditions. During a certain period, temperature and relative humidity remained nearly constant, creating prolonged discomfort, leading to several deaths and questions tied to personal health. This has repeated with increasing frequency and intensity over the years (Conti et al., 2005). Beyond affecting the quality, liveability, and usability of open spaces, the urban heat island also has specific effects on the conditions of indoor spaces, leading to a higher use of energy for mechanical cooling. This latter aspect is closely tied to the question of climate change, because it is related to the increase in energy consumption.

The Urban Heat Island

The increase in temperature in the urban area of London was first observed by the meteorologist Luke Howard in 1818, but the definition of urban heat island only appeared in the literature in 1958 in an article by Gordon Manley in the Quarterly Journal of the Royal Meteorology Society. Manley used the term 'island' to highlight the image of air temperature (mapped using isotherms) in the city compared to the 'sea' of surrounding rural areas at lower temperatures. Understandably, not all parts of the city are subject equally to this phenomenon. The indicator used to quantify this deviation is the urban heat island intensity, which is defined as the difference between the urban and rural temperature (Oke, 1982). Massive buildings, their morphology, materials, differing surface permeability, the presence of vegetation, heat emissions, and pollution from anthropic activity characterize the urban environment and interactions with atmospheric forcing such as sunlight and wind. These dynamics modify the microclimate, altering the temperature-humidity balance of the area in ways that are not easy to predict. One of the results of this imbalance is the urban heat island, which is generated in urban areas, but it is also a considerable effect of a broader climate situation. In urban areas where this phenomenon is present, temperatures higher by 5 or even 6°C compared to the surrounding rural areas can be detected (Dimoudi et al., 2013; Oke, 1995). The intensification of this phenomenon is tied to a range of factors, including materials and the dimensional relationships of the urban layout that generate radiative exchange between the surfaces and between the surfaces and the sky. The factor with the highest incidence is anthropogenic heat, that is, heat generated by emissions tied to energy-production processes, leading to the emission of atmospheric pollution. The factors combining to create the urban heat island may be traced to various changes in the urban energy balance:

- *Greater absorption of solar radiation by buildings and impermeable surfaces in general compared to the land;*
- *Less heat dissipation due to the complexity of the geometry, which promotes reflections that trap thermal radiation;*
- *Increase in thermal energy accumulation in the environment affected by the urban layout due to the elevated heat capacity of construction materials constituting the built area;*
- *Decrease in evapotranspiration from the land due to the lower presence of vegetation that would otherwise contribute positively to mitigating the microclimate;*
- *Little dissipation of infrared radiation caused by the enhanced greenhouse effect;*
- *Little dissipation in general due to masses of air that move with more difficulty through the web of the urban fabric;*
- *Heat emission due to vehicular traffic. The latter does not particularly affect the balance, but it does contributes to generating the urban heat island.*

The observation of these factors shows which contribute in different ways to the urban heat island. The first three play a particularly important role. The increase in absorption of solar ration by the built environment, the decrease in dissipated thermal radiation, the increase in stored thermal energy as a result of the elevated heat capacity of construction materials are the factors most commonly studied when designing interventions to identify and reduce the phenomenon (Ratti et al., 2003; Ottone et al., 2019). The most common strategies for 'cooling the city' entail the use of reflecting surfaces (higher albedo) and nature-based solutions (NBS). The cooling activity of NBS is based on albedo, but especially on evapotranspiration and, for trees, shading (Angelucci, 2018).

Comfort Indices

To verify how the environmental variables positively or negatively influence the state of comfort, it is useful to assess a synthetic datum that relates these variables to a person's physical state. Over time, various indices have been developed to meet this need. One of the most common indices is the PMV (Fanger, 1970), which is based on the energy balance of the human body and empirical assessments of temperature-humidity well-being tested on a wide range of people. The PMV is widespread in the literature and has also been adopted in German engineering guidelines (VDI 3787). This index considers air temperature, radiation temperature, wind speed, and relative humidity, comparing them with two parameters tied to individuals, such as clothing insulation and metabolic rate.

The PET is an index based on a model that extends the comfort calculation to the outdoor space, making it one of the most common indices used today (Höppe, 1984, 1999). It is based on the 'Munich Energy-balance Model for Individuals' (MEMI) a model that characterizes the thermal conditions of the human body. PET is calculated in two different steps. The first regards an assessment of the thermal conditions of the human body for a given simplified combination of microclimate variables (no wind or solar radiation). The second introduces values calculated for 'mean skin temperature' and 'core temperature' in the MEMI to solve the thermal balance equation.

The UTCI comfort index is the most recent index proposed. It derives from the concept of equivalent temperature described by the UTCI-Fiala thermal-physiological model (Fiala et al. 2012) combined with a complex mathematical model that describes the insulating and evapotranspiration characteristics of the clothing (Havenith et al., 2012). To calculate this index, air temperature, mean radiation temperature, wind speed, and humidity (expressed as water vapour pressure or relative humidity) are required.

The evolution of models to assess comfort has improved noticeably, refining the results and simplifying the interpretation of the data (Zare et al., 2018). The use of increasingly refined tool is even more useful for representing the impact of climate change on health (Di Napoli et al., 2018).

Tools for Investigating the microclimate

Various tools have been developed over the years to investigate changes in the microclimate and assess architecture projects in terms of building performance and other aspects, expanding the range of possibilities on the urban scale. With technological advances, these tools are increasingly common today and requested in preliminary project assessments in the decision-making process. Despite their growing recognition, the development of these tools has not drawn the attention of large software houses. As a result, software has been developed independently to respond to specific objectives that have difficulty communicating in a cascade with other tools, thereby greatly limiting the possibilities for investigation. Visual programming platforms such as Grasshopper and Dynamo have recently been created on which independent developers have built connections with tools for energy simulations. This new scenario in which it is possible to create a workflow that provides continuity to the use of these tools promotes a more complete context that is destined to evolve and expand.

Modeling a Workflow

Using a virtual environment to investigate natural phenomena and their influence on the anthropized system requires more or less significant simplifications to be made. These simplifications are necessary for balancing the degree of complexity of the analysis, allowing for a smooth workflow. The mathematical tools used to represent physical phenomena, the computational power of modern machines, and the correct scale of representation are just some of the aspects considered when building a suitable method. In this scope, it is important to combine the different tools in a single platform such as Grasshopper, making it possible to manage external independent simulations and establish input-output exchange among them. Because it is a true development environment, Grasshopper always allows for parametric control of each phase of the process. This means that each aspect of the design should be converted into a numerical variable. For easy movement within this space, a change in design paradigm is not necessary, but it is important to support the common 'design' thought with a new 'parametric' thought. With the help of this platform, it is possible to manage third-party tools such as ENVI-met, EnergyPlus, and Urban Weather Generator, standardizing and visualizing the data produced. Each of these programs was developed for different reasons, with different interfaces, and without the possibility of interaction, a trend that can be completely inverted with management under a single platform. Various plug-ins called Ladybug Tools have been developed for this purpose. These can be considered libraries within Grasshopper that are configured based on the need. It is important to understand the scale of the intervention from the beginning because depending on the case, some aspects can be focused on more than others, optimizing analysis times. When an overall view is maintained to assess the microclimate and effect it has on the building, the method for indoors must be used, or it can be varied according to the need.

To best understand this complex workflow, it is helpful to divide it into three phases: pre-analysis, analysis, and optimization.

Pre-analysis Phase

Once the area in question has been chosen, information regarding different aspects of the urban scenario needs to be entered. First, the geometries of the bordering buildings are entered (information that may also be collected from GIS databases). To best represent the outdoor space, the type and position of green elements and surface materials may be defined, along with permeable and impermeable areas. Finally, an additional set of data grouped under the name 'environmental data' must be found. This data is necessary for the subsequent analysis. This set is composed of time-series detections such as meteorological data and levels of atmospheric pollution. Meteorological data can be found easily (also free of charge), but often in reference to exurban contexts (commonly airports) that are not affected by the urban heat island. These may be managed by an application (on the Grasshopper platform) to automate the acquisition and manipulation of the geometric-material data, generating three different models and correlating information from different databases.

- *The first model is a slight simplification of the urban context to be used in the preliminary analysis with Urban Weather Generator. The model includes the volume of each building, the building materials and the context, vegetation, and environmental data, including information regarding the location of the source.*
- *The second model is a representation (greatly simplified on a three-dimensional grid) to be used with ENVI-met. The model includes the volume of each building, the building materials (including transparent partitions), ground materials, and vegetation.*
- *The third model is a representation of 'thermal masses' of the buildings to be used with EnergyPlus. The model includes the volume of each building, possible separations according to thermal area, building materials, and the context and vegetation.*

Following the order of creation, each model is sent to the reference tool, thereby proceeding to the processing phase and subsequent analysis.

Processing and Analysis Phase

The first model (sent to the U. W. G. tool) is assessed considering relationships between the height of the buildings and the distance between them, the materials used, the presence of vegetation, and sources of pollution in relation to the site where the set of meteorological data was sampled. The result of this first investigation is a set of meteorological data modified to consider the urban heat island. This new data is then used in subsequent analysis (Nakano et al., 2015). To proceed with the analysis using ENVI-met, it is necessary to prepare a subset composed of 24 hours of continuous data that include temperature, humidity, and wind speed and direction. The standardized sets of data (including the one generated by U. W. G) contain hourly data for an entire year, from which it is necessary to select the restricted subset of values. To obtain this, the consolidated method of representative day may be used (Grifoni et al., 2012; Tirabassi and Nassetti, 1999), performed on the Grasshopper platform. Through the above-mentioned algorithms, statistical information may be extracted about the representative day that will later be used in the ENVI-met analysis.

The second model for use with ENVI-met consists of a simplification of the spaces through the use of a three-dimensional grid in which the thermodynamic behaviour of the flows within the urban space are simulated. This tool may be used to asses variations in temperature, humidity, wind field, state of pollution, and in sum, the state of comfort throughout the chosen 24 hours. The set of information collected in this initial analysis will become part of the information useful for later analysis based on the third model.

The latter is an analysis that addresses the details, relying on the capacity of a computation engine called EnergyPlus, which very accurately simulates the energy conditions of the buildings, but not of the outdoor spaces, whose condition, as is clear, can influence the behaviour. For simplification, the data characterizing the outdoor area are usually approximated by acquiring the values of the set of environmental data obtained previously. The workflow developed is able to obviate this lack, providing the possibility of connecting the results of the Envi-met analysis to the EnergyPlus analysis, which will therefore return much more realistic results. The results of this processing are quick enough to allow for recursiveness of the simulation to be made in a possible third phase to optimize the results as a function of the change in geometry rather than the materials.

The ultimate output of the analysis consists of maps coloured by gradients that quantify each atmospheric forcing as well as the state of comfort that can be estimates starting from said forcing, allowing the microclimate context to be quickly interpreted.

The adoption of a parametric workflow allows for fluid management of the simulation tools, which are indispensable for clarifying how the microclimate evolves and how the architecture, and even more, the adoption of territorial strategies influence it.

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C - DENSITY - INTENSITY: MATERIAL AND IMMATERIAL ELEMENTS IN ASSESSING URBAN QUALITY

Keywords: Climate change, Technologies for the built environment, Urban heat island

Abstract

The objective of this research is to produce a critical scientific analysis of some aspects related to urban resilience to offer planners and decision-makers a deft intervention tool to mitigate high temperatures in urban areas. Densification, morphology, and materials are used to suggest strategies aimed at improving the quality of life in cities. This point of view analyses climate change and its connection to humans, urban density and its energy value, the evolution of materials, and the management of environmental comfort, considering the horizontal/vertical relationship as one of the morphological parameters capable of determining the connections between density, the form of the spaces, and the urban heat island.

Introduction

The theme of environmental sustainability in urban transformation processes has substantially modified the traditional view of cities. Architects/urban planners are progressively losing their role as directors of urban transformations, since environmental problems have introduced new aspects to address and resolve. In developing countries, where there is greater inequality and anomalies in city growth, there is now an awareness that urban design must be

undertaken with a more explicit multidisciplinary view (Balbo, 2005). 'The process of urbanization, capital accumulation, deregulation, globalization, environmental protection, and so on, are much more significant for the shaping of urban relationship than are the spatial forms of urbanism in and of themself' (Waldheim, 2006).

There is thus a need for an overall cultural renewal that ensures, on the one hand, that a precious heritage of specific contributions that have defined the qualitative characteristics of cities (form, function, etc.) in the past are not lost. On the other hand, architecture as a discipline should modify and update its own investigation methods, reviewing and reinterpreting the terms and parameters that have constituted reliable disciplinary support for many years, the exclusive prerogative of urban-planning disciplines. Starting in the 1800s with the texts by Camillo Sitte (Sitte, 1981), and continuing today with the work by Rem Koolhaas (Koolhaas,

Figure 1
Rome
urban network A

Figure 2
Rome
urban fabrics B

Figure 3
Barcellona
urban fabrics A

Figure 4
Barcellona
urban fabrics B

2002)and Bernardo Secchi (Secchi and Viganò, 2009), urban theories have increasingly described urban phenomena as a more or less definite and flexible 'design' in which the urban architect is the main advocate (or victim, as in the case of Koolhaas) of the transformations.

Albeit with different meanings and balances, such theories are mainly based on interpretational parameters referring to the form and function:

- *form and dimensions of open spaces*
- *form and arrangement of buildings*
- *communication and infrastructure routes*
- *the permitted use of areas (zoning), defined based on balances among different functions*

(residential, industrial, service, etc.). In the 1970s, theories by architects such as Aldo Rossi (Rossi, 2018), Robert Venturi & Denise Scott Brown (Venturi and Brown, 1977), and other important architect/ intellectual figures influenced entire generations of scholars, researchers, and designers who realized projects according to a one-eyed approach.

Today, this approach is no longer sufficient for making efficient interventions on cities. The increasing incidence of topics tied to environmental sustainability in processes of growth and urban transformation requires an effort to be open to cultural influence and disciplinary renewal. This study highlights how new early-investigation tools based on parametric programmes and optimization models can be moulded to build platforms of shared work that make the investigation of complex urban fabrics extremely quick, effective, and focused, with the primary goal of improving the quality of life in cities. In fact, it is believed that the investigations that are implemented and enriched are those that tend to highlight synchronization between low energy impact and quality of life, demonstrating that where passive measures are adopted to reduce the energy impact, people live better in terms of urban comfort.

Current evolution

The climate and climate change have always represented primary factors of change, not only with respect to society, but also in the appearance of the city itself (Behringer, 2013). Climate change has occurred many times throughout history, leading to changes in society, cities, and landscapes, which have been readapted and reshaped based on new scenarios that were being projected (Rahm, 2014).

Today, nothing new can be designed or existing aspects intervened on without being aware that achieving urban comfort is an unavoidable objective, just like the form, functional organization, and dimension/ proportion of the built area. From this point of view, an urban and/or architectural design can control the complexity deriving from simultaneously implementing the necessary parameters and considering all the possible variables.

This research aims to delineate a matrix of case studies — cities — whose analysis is performed in consideration of three factors deemed decisive in the evaluation of urban quality: climate, empathy, and technology. The methodology developed will allow designers to manage the complexity of non-linear relationships among the meteorological variables and geometric ratios that characterize the urban microclimate (defining the impact of urbanization on local climate conditions and mitigation factors). It will also for the management of possible technological interventions designed to modify the relationships between surface permeability/ impermeability, albedo values, and thermal fluxes.

Finally, it will address questions tied to the empathic aspect of architecture intended as an ‘emotional catalyst and an ideal transmission vehicle for content that can be

Figure 5
Athens
urban fabrics A

Figure 6
Athens
urban fabrics A

Figure 7
New York
urban fabrics

Figure 8
Oxnard
urban fabrics

shared socially (Garramone, 2013) and measured through comfort indices.

In addition to deeming necessary recourse to the inclusion of new tools and data within contemporary design parameters (Rahm, 2014), it an initial study was made within a range of indicators that refer specifically to the theme of climate change and land consumption, interweaving them with factors related to the form and dimension of the built environment.

The initial concept is that individuals inevitably establish an empathic relationship with the surrounding environment. One no longer speaks of urban space with a Modernist reminiscence, that is, a city designed mainly as a space destined for the movement of transport, which has characterized the last 150 years of planning. Rather, what prevails today is the concept of 'cities for people' (Gehl, 2017) that see '... how important it is to pay attention to people in cities in order to have vibrant, safe, sustainable, and healthy cities, all important objectives for the twenty-first century'.

A concrete example of this change in trend can be seen in the different operations that the City of Copenhagen is implementing. Through urban planning and design strategies, the focus of the built space has moved from vehicle traffic to people, to slow spaces, to spaces for interaction, to the development of green infrastructure, not only on the horizontal plane on the ground floor, but also on top of the buildings, i.e., 'green roofs'[1].

One example that combines the various parameters described above is the by Philippe Rahm, Public Air, where the City of Copenhagen requested that the entire biking and pedestrian network be redesigned in order to separate it from the flow of vehicles. Emphasis was placed on parameters such as the materials used on the ground and façades and their relationship with people. '... for example, the façades could absorb sound or the materials could be warmed in winter or at least lead to human comfort'(Rahm, 2014).

The idea of controlling the urban heat island by placing more attention on the parameters of liveability, prioritizing people, can generate interesting interventions from alternative, innovative points of view. However, weighty architectural interventions are not always needed to improve urban comfort. With a careful reading and correct analysis tools, one can understand in detail where and how to act.

One example of light intervention on the level of city impact is found in New York with its NYC CoolRoofs programme, carried out in collaboration with NYC Service and the NYC Department of Buildings[2]. The initiative involves a group of volunteers and building owners who decided to improve urban comfort by painting the roofs of some buildings with a white reflective material, reducing the absorption of heat from the Sun and consequently decreasing the internal temperature of the building by up to 30%. Thanks to the high reflectance of the colour chosen, the temperature of the surrounding area is also reduced, helping to counteract the urban heat island. 2 But how can the initial parameters be determined in order to render the most objective vision possible of the comfort of a specific area? Immaterial technology in this case is a decisive factor. An urban design should be able to make use of certain data deriving from a set of technological tools to monitor environmental and human phenomena. The data can then be processed in complex preliminary analysis that encompasses the varied information deriving from different areas. Immaterial technology is the fruit of this new millennium, permeating the city in each of its areas and delineating a new infrastructure that is important both for design analysis and for the good liveability and functionality of the space. This system of invisible control is — and will be even more in the future — present in every dimension of urban and private space as a necessary tool to foresee and design the city.

There is a shift, therefore, from a smart city to the 'senseable city' defined by Carlo Ratti: 'Optimization plus humanization do not give access to a metropolitan- seized computer nor to a network-based far west. It is the convergence of bits and

	Rome A	Rome B	Athens A	Athens B	Barcelona	New York	Oxnard
Average Bldg Height	15 m	13 m	12 m	10 m	17 m	106 m	6 m
Site Coverage Ratio	0. 47	0. 49	0. 38	0. 41	0. 47	0. 6	0. 39
Façade-to-Site Ratio	1. 25	0. 96	0. 8	0. 94	0. 82	7. 78	0. 6
Tree Coverage Ratio	0. 04	0. 03	0. 01	0. 01	0	0	0. 06
Grass Coverage Ratio	0. 3	0. 03	0. 12	0. 1	0. 06	0	0. 8

Tab1

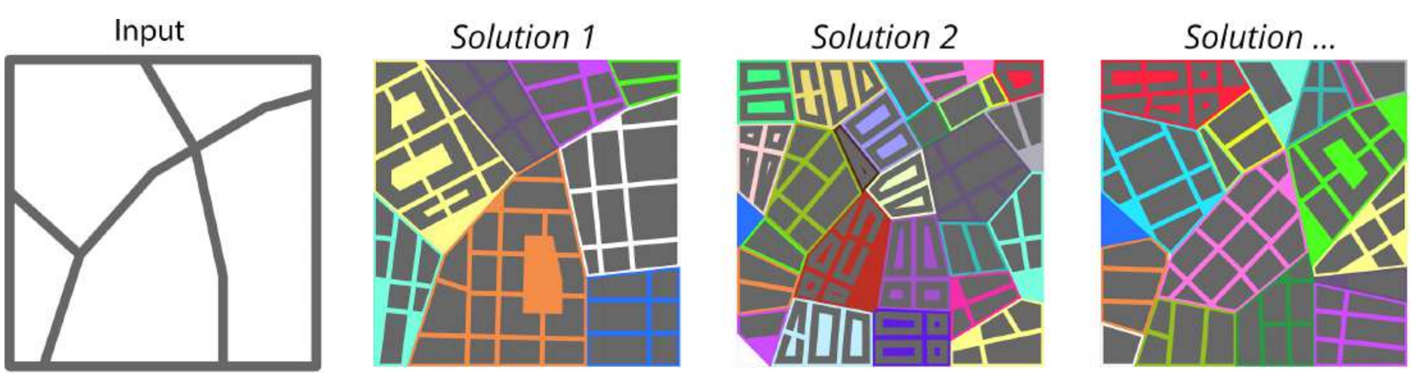
atoms; systems and citizens interact' (Ratti et al., 2016)". If technology is integrated within the urban fabric, it becomes the means to transmit real, usable data regarding flows of vehicles, people, and the climate. Environmental data implemented with current information-transmission technologies could be strengthened and used easily, taking the place of the sparse surveying stations spread over the territory. In the future, a person living in the city could be a vector and transmitter of data in specific places, mapping the entire urban space with high precision.

Materials and methodology proposed

The form of the city, its structure, density, and morphological and material characteristics are elements that have always been investigated when analysing the evolution of cities and the change in evolution. The study of the interconnection between morphology, climate, and energy has, over time, characterized a large part of the history of cities and architecture (Barucco and Trabucco, 2007; Givoni, 1998; Landry and Franco, 1995; Olgyay et al., 2015; Pascali, 2008; Rogora, 2012). In particular, urban morphology, which studies the form of the city, has guaranteed solid support for the analysis of the main factors that determine the spatial structure, its changes over time, and the sometimes violent alterations in a given built landscape. The morphology of contemporary cities has changed along with changes in the resident societies and activities distributed throughout the territory, generating de-urbanization and re-urbanization processes. It is an intricate urban system that is also closely tied to the (increasingly evident) local projection of global climate change.

The great weight of these demands and current transformations necessarily also leads to a change in the tools that are used today to study and analyse urban phenomena and strategies for intervention on an urban and architectural scale. As of today, however, these have unfortunately been shown to be insufficient in guaranteeing the achievement of those objectives tied to energy and the environmental quality of the city. What is necessary are tools that are capable of modelling the city's complexity (Barucco and Trabucco, 2007), intended as a combination of elements that generate the built space according to a logic of aggregation that can be identified via parameters. Parametric models allow information to be associated with digital simulation models, which can be considered 'information containers' that are quick to use and can be consulted in real time. Parametric modelling is based on the formalization of limits and elements that connect and systematize formal and relational variables, e. g., climate, environment, energy. These programmes, i.e., Grasshopper and its plug-ins, are able to manage means of vertical representation for the built environment and, in parallel, are also capable of horizontal aggregation according to the most varied logic, thereby allowing the complex urban density to be characterized. These considerations give rise to the need to propose a new tool based on the association of information. The tool is capable of drawing the complex city, tying it to all external demands (climate forcing, energy limits, changes in materials, etc.) and quickly reading the characteristics of the urban fabric and conditions of environmental comfort generated. Therefore, a parametric tool is proposed to generate urban volumes (replacing the classical technique of manual drawing), quickly modifying the geometries and material characteristics of the given portion of city and allowing for the analysis and comparison of multiple scenarios. The workflow developed is composed of three phases developed in the Grasshopper environment. The first phase regards the composition of the urban aggregate. The entire process to generate the urban geometries requires the geometries of the outermost urban perimeter and the main practicability under the form of open fragments. This phase entails the definition of the urban geometries. Starting from the outermost perimeter, which should contain all the buildings

Figure 9
Potential configurations generated by the algorithm



and roads, the set of main streets present in the territory is defined, thus forming the agglomerates, secondary streets, and green areas.

The entire process is regulated by a series of parameters:

- *Maximum side of the block*
- *Ratio of shape of the plots*
- *Offset from the front main street*
- *Offset from other streets*
- *Side of the internal plot*
- *Size of the internal courtyard*
- *Range of heights of the buildings*

This tool assigns these characteristics to uniform zones, allowing for their modification in real time ***Fig. 9***.

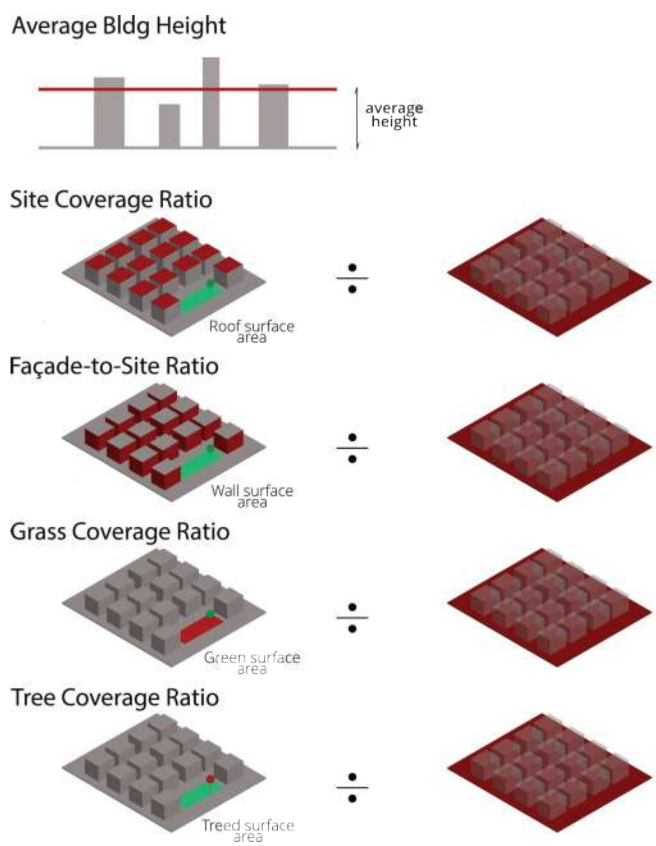
The second phase uses the Urban Weather Generator (UWG), which is connected to Grasshopper through the Grasshopper Dragonfly plug-in (Mackey et al., 2017). The UWG is a tool developed by Massachusetts Institute of Technology to analyse local effects generated by urban geometries on urban comfort and energy consumption. This tool simulates the atmosphere/built environment and is capable of assessing the urban heat island effect and modifying a file of generic meteorological data (here called 'rural') to create a file of 'urban' meteorological data. Its task is to transform meteorological data usually obtained from exurban stations (e. g., airports) into meteorological data adhering more to the morphological and material characteristics and use of the city. The data is processed using a variety of parameters, for example, material properties (solid, roofs, walls), the urban form, the generation of anthropogenic heat (in the street and within buildings), and the presence of green areas. The UWG is not limited to calculating traditional factors like the sky view factor or the vertical ratio of the urban canyon; it expands the analysis, calculating various relationships between the built environment and the territory. In particular, it considers three factors: site coverage ratio, façade-to-site ratio, and average building height. The parameters used, which are reported in Table 1, describe homogeneous urban fabrics using indices of the surface density in the vertical and horizontal directions, 'rapidly' adapting to different urban fabrics ***Fig. 1-8***. The built environment is characterized from the energy point of view, considering (with respect to the type and age of buildings) the relationship of glass surfaces, the albedo of horizontal and vertical surfaces, and, finally, the presence of a garden roof. In addition, the UWG characterizes the city based on the presence of urban greenery (horizontal or vertical), the amount of impermeable surface area, and road traffic present in the area of study. By interrelating all this information, the model transforms the 'rural' meteorological data into 'urban' climate data that better agrees with the microclimate of the city. 3) The third phase is to manage energy/environmental aspects via the Ladybug plug-in for Grasshopper (Sadeghipour Roudsari and Pak, 2013) in order to calculate the universal thermal climate index (UTCI), a quantity representing perceived outdoor comfort. Values of the temperature perceived by the subject using the study area are returned in degrees Celsius. Environmental comfort is defined within the band from 19°C to 26 °C, while values between 26°C and 28°C define the comfort zone for brief periods. This process allows for an understanding of how geometric and material aspects affect the microclimate and, as a consequence, the environmental comfort and empathic perception of the place, i.e., 'architectural empathy' (Mario Cucinella Architects, 2016; Wölfflin et al., 2009).

The data necessary for this analysis are:

- *Dry bulb temperature*

Figure 10

Dimensional ratios



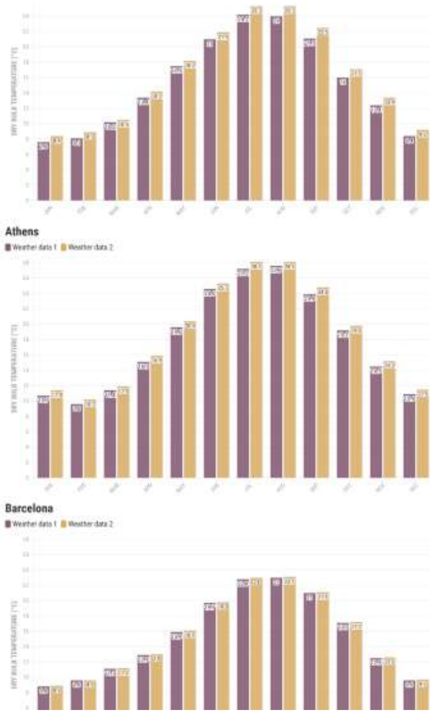


Figure 11
Visual description of annual results and their delta for Oxnard - New York

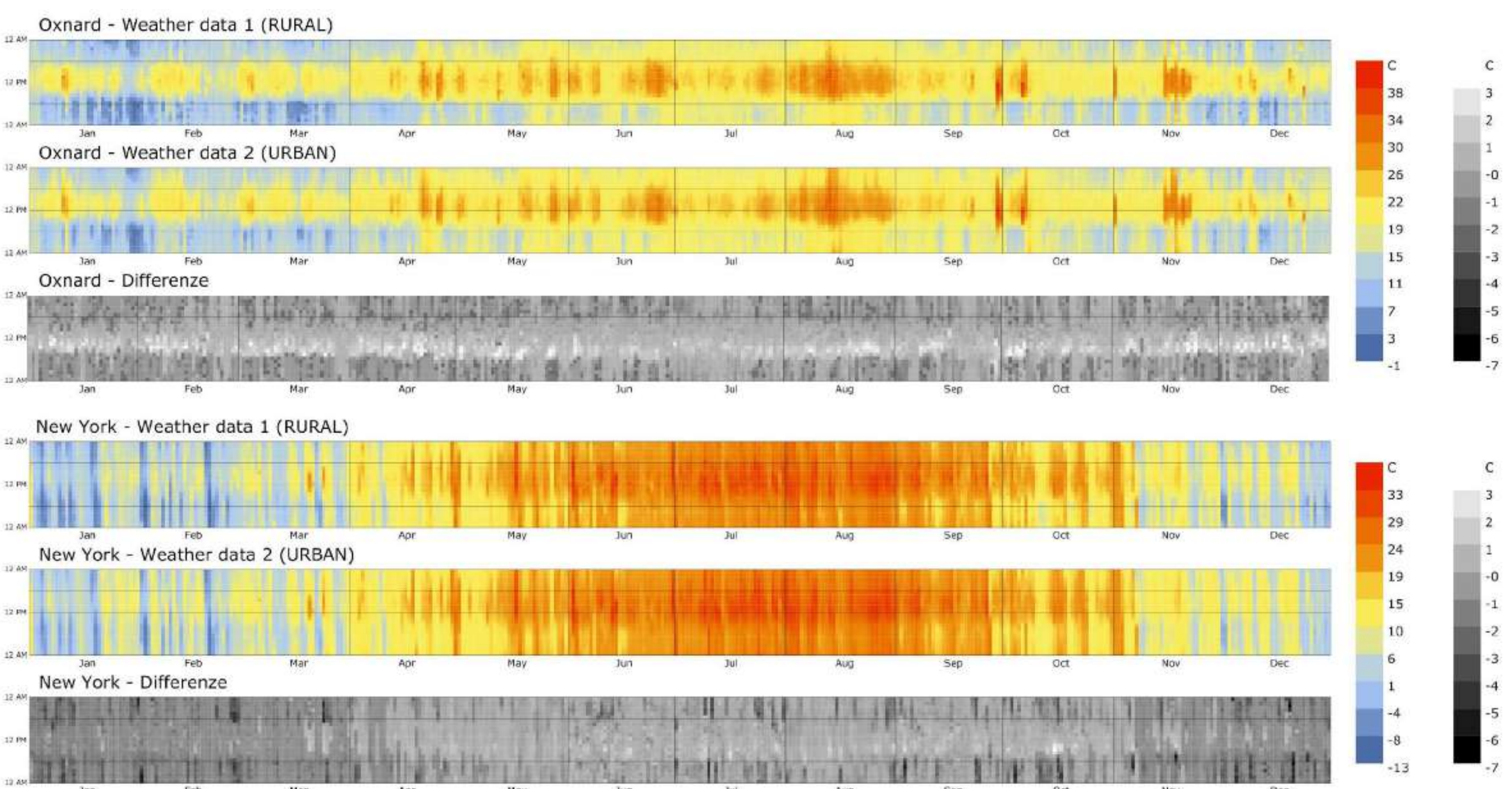
Figure 12
Comparison between weather data 1 and 2

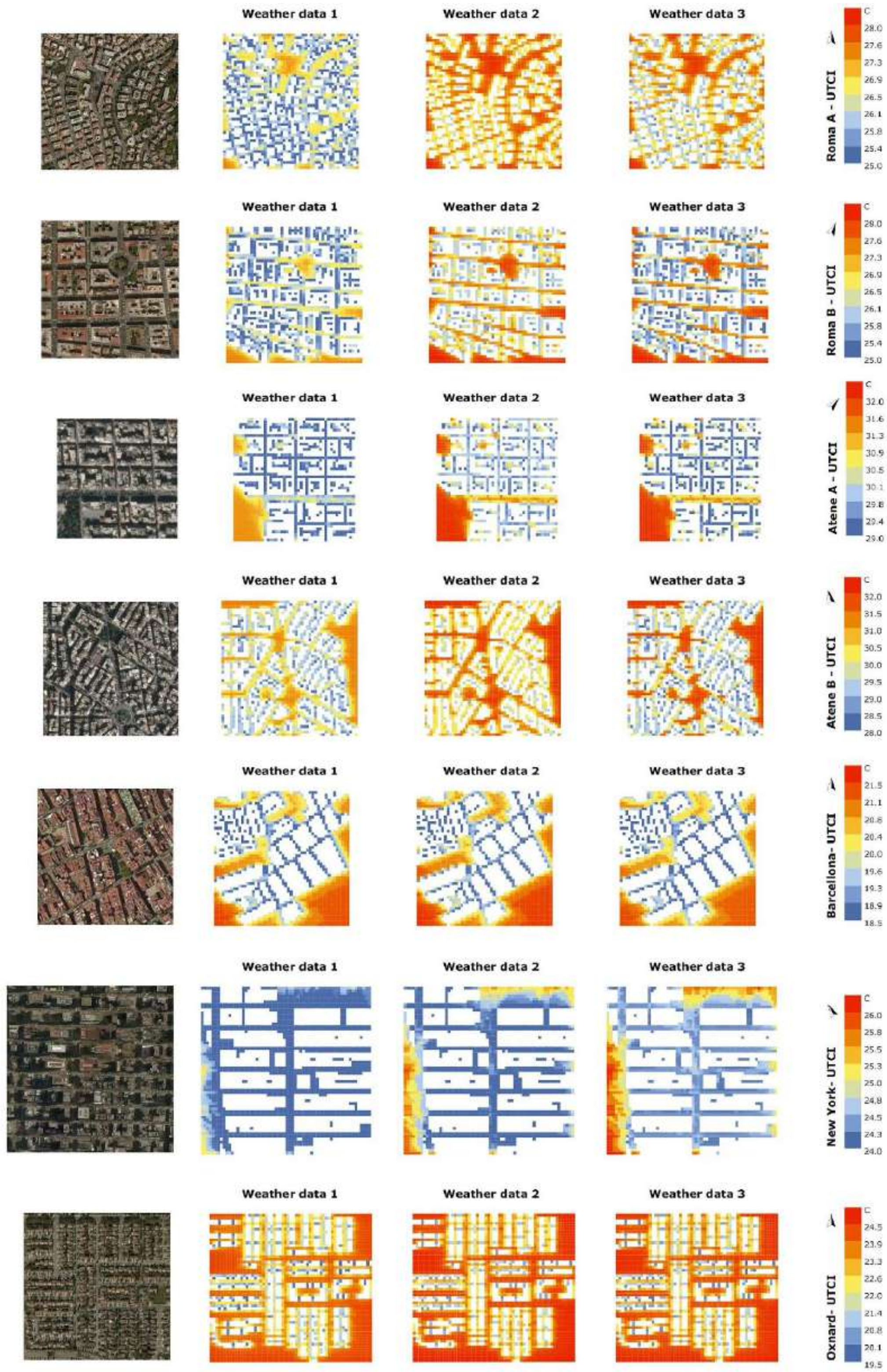
- *Wind speed 10 m above the ground*
- *Relative humidity*
- *Average radiant temperature*
- *User-related data (age, gender, height, weight, metabolism, clothing)*

The first three are provided by values of the meteorological profile modified by the UWG in the preceding phase. The average radiant temperature is calculated numerically (according to UNI-EN 27726 standards) and represents the temperature of an artificial, thermally uniform environment that would exchange the same thermal radiant thermal energy with the human body as is exchanged in the real environment. Once the values of the UTCI are obtained at various points and visualized as a colour gradient on the urban map, one can identify the effects of the urban heat island present the city and design strategies for climate mitigation.

Application of the methodology and analysis of case studies

The methodology developed was applied to the case studies, which were chosen based on their geometric and environmental characteristics. In particular, urban fabrics were sampled pertaining to cities with a Mediterranean climate (Csa in the Köppen climate classification: Rome, Athens, Barcelona, Oxnard) (Peel et al., 2007) and a humid subtropical climate (Cfa classification: New York). The cities in the first group have a primarily horizontal development, while New York is obviously the symbol of a typically vertical urban fabric. The city with the highest presence of green areas (and therefore greater permeability) is Oxnard, while New York is the most impermeable. Once all the urban fabrics were reconstructed, they were characterized from the material point of view and various climate files were




Weather data 1
Weather data 2
Weather data 3
Roma A - UTCI
C
28.0
27.6
27.3
26.9
26.5
26.1
25.8
25.4
25.0
Weather data 1
Weather data 2
Weather data 3
Roma B - UTCI
C
28.0
27.6
27.3
26.9
26.5
26.1
25.8
25.4
25.0
Weather data 1
Weather data 2
Weather data 3
Atene A - UTCI
C
32.0
31.6
31.3
30.9
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30.1
29.8
29.4
29.0
Weather data 1
Weather data 2
Weather data 3
Atene B - UTCI
C
32.0
31.5
31.0
30.5
30.0
29.5
29.0
28.5
28.0
Weather data 1
Weather data 2
Weather data 3
Barcellona- UTCI
C
21.5
21.1
20.8
20.4
20.0
19.6
19.3
18.9
18.5
Weather data 1
Weather data 2
Weather data 3
New York- UTCI
C
26.0
25.8
25.5
25.3
25.0
24.8
24.5
24.3
24.0
Weather data 1
Weather data 2
Weather data 3
Oxnard- UTCI
C
24.5
23.9
23.3
22.6
22.0
21.4
20.8
20.1
19.5

Figure 13

produced and used in subsequent phases to assess outdoor comfort (by determining the UTCI). Each sample covers a surface area of about 500 m 2, and each city was evaluated for its own hottest week (hot week scenario), defined based on the climate file *Fig. 9*.

For each sample, the UTCI was evaluated starting from the original climate file (weather data 1) and then compared with values obtained with the 'urban' climate file modified using the UWG (weather data 2). The climate file was then modified further to create a paradoxical condition in which the city, while maintaining the same formal characteristics and geometric ratios, presents a paradoxical condition wherein all materials have an albedo equal to 1 (maximum reflectance) and there is total green- roof coverage (weather data 3).

Results

The analysis shows that this methodology allows the local climate characteristics to be assessed quickly and expeditiously. Different effects of the urban heat island were revealed depending on the season (winter/summer). These effects are represented by the UTCI, which allows users' perception of comfort, i.e., the perceived well-being of the place, to be evaluated. This also represents a competing element in defining the architectural empathy. In winter, the urban heat island is effective in fabrics with greater vertical density, such as New York *Fig. 11 and 13*, which has a façade-to-site ratio *Tab. 1* that is much higher than the other portions of city considered. In summer, however, a higher horizontal density exacerbates the intensity of the urban heat island effect and, as a consequence, also the negative effects tied to urban overheating.

In Europe, it is clear how, for this type of simulation, it is now impossible to overlook the use of the climate file without the necessary proper characterization. The increases, even if a little less than the American cities should be considered limiting cases: Oxnard, with its moderate horizontal density (low, sparse buildings), does not show appreciable variations in perceived urban comfort between the urban and peri-urban areas throughout the year, not are there evident improvements in the paradoxical case *Fig. 8*. In New York, on the other hand, the urban heat island effect creates a slight increase in summer temperatures, but seems to draw greater benefit in the winter when the urban temperature increases punctually, creating a thermal gradient of 6–7°C *Fig. 12*. The annual value is about 1°C.

Conclusion

This research proposes an in-depth, quick method of analysis, a workflow, to delineate an urban design that is sustainable and controlled energetically because it is capable of simulating the effect of design proposals on the urban heat island. The method proposed aims to decode the highly complex city system, considering meteorological data, technological aspects, and architectural empathy. The resulting isopleths and graphs are meant to act as support for design, providing a preliminary detailed analysis and becoming a fundamental means to design climate and technological devices that can improve the urban context analysed. Since this is an open, complex analysis capable of determining additional effective solutions and output that can be validated, this work represents the first step in defining a tool that is even more effective in hypothesizing interventions that consider the parametric variables referring to the dynamics of urban transformations, such as economic and social factors.

Footnotes

1. *An account of these changes can be found in the numerous initiatives promoted by the Copenhagen City*

Administration and the report 'Green Roofs Copenhagen' promoted by Copenhagen Together. This report illustrates the tendency for change in the city, starting from the requirement for green roofs in most new local plans as of 2010 and including a list of different current or completed interventions whose main theme is urban renewal on a human and sensory scale. http://en.klimatilpasning.dk/media/704006/1017_sJ43Q6DDyY.pdf

2. *The programme supports the City's objective of reducing carbon emissions by 80% by 2050 (80 x 50), as indicated in 'One New York: The Plan for a Strong and Just City' by Mayor de Blasio. The initiative is a partnership between the NYC Department of Small Business Services, the Mayor's Office of Sustainability, the Mayor's Office of Recovery and Resiliency, and Sustainable South Bronx, a division of The HOPE Program. http://www.nyc.gov/html/onenyc/downloads/pdf/publications/OneNYC.pdf*

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D - MASS AND LIGHTNESS: URBAN QUALITY ALONG THE AURELIAN WALLS IN ROME: WALKING THROUGH WALLS

Keywords: Climate change, Outdoor comfort, Urban heat island, Urban regeneration

Abstract

This study focuses on the system of the Aurelian Walls with reference to Rome's regulatory plan, which indicates its role as green infrastructure in service of the areas adjacent to the historical centre of Rome. A proposal is made to reinforce the system with an environmental focus as an opportunity to regenerate open spaces for interaction, using the mass of the walls as an environmental device as well as a memory and symbol of historical Rome. The objective is to reuse the wall as an urban contour line to generate humidity and thermal comfort by virtue of the insertion of green elements and functional devices in areas of the city pervaded by stone, cement, and asphalt.

Introduction

In Rome, land consumption occurs exponentially, with an estimate of three-square metres per minute (ISPRA, 2019). In the most recent regulatory plan, the tools for implementation have identified a partial response to this phenomenon, instructing the private sector to build new living structures and services within consolidated neighbourhoods and substituting buildings that no longer respond to current standards, especially with regard to structural, energy, and environmental aspects. This building replacement, however, which has created a very strong increase in accommodation in quarters immediately adjacent to the historical centre, has not corresponded to an adequate response in terms of open space and areas for 'being'.

Rome is one of few large cities in the world whose city walls are maintained practically intact, constituting a large urban façade about 19 kilometres long marked by 14 main gates ***Fig. 1***.

The city walls currently constitute one of the areas of strategic planning proposed by the new General Regulatory Plan (GRP) of the City of Rome ***Fig. 2***. This is of great importance, because the Aurelian Walls are not only considered a historical construction, the object of restoration measures and maintenance, but also primary urban infrastructure. They represent an environmental device capable of playing an important role in enhancing the urban form and affecting the microclimate.

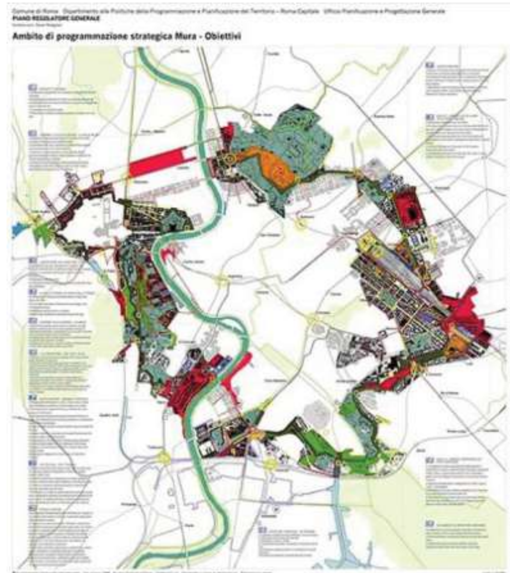


Figure 1
Outline of the Aurelian Walls

Figure 2
General Regulatory Plan of Rome

In 2014, a study group called Wall_Walk formed spontaneously (https://wallwalkproject.wixsite.com). Through conferences and workshops, the group promoted theoretical and planning considerations regarding the Aurelian Walls, identifying 'sensitive' areas to experiment with in recovering public spaces along these ancient city walls. Starting with this experience, and with a critical historical reflection on the theme of public spaces in Rome (Gadeyne & Smith, 2013), the need emerged to consider the walls as an environmental system dedicated to public space with the objective of improving the quality of life in neighbourhoods adjacent to the walls. Today, the walls form a nearly invisible tract because, despite their strategic position, they are mixed in with degraded areas of the city. Among the areas identified, examples of the lack of enhancement include the area near the Basilica of St. John Lateran, the San Lorenzo quarter and Porta Maggiore, Testaccio, and still others.

Reuse of this infrastructure will allow the city walls to be interpreted as an urban contour line used to mitigate the microclimate with the careful insertion of green elements and functional devices in areas of the city primarily characterized by impermeable materials. It is precisely in these spaces that a point-like investigation is proposed. Echoing Manuel Sola Morales' concept of 'urban acupuncture' in reference to urban regeneration, the interventions here are modified as 'environmental acupuncture' (De Solà-Morales, 2008). Therefore, starting from the climate as a fundamental component of well-being in urban living, the mass, orientation, materials, their thermo-physical characteristics, and green systems are considered as a set of requirements that are unavoidably connected and indispensable for controlling the microclimate in these areas (Xiaodong, et al, 2019; Bartesaghi Koc, et al., 2018; Battista, et al., 2016).

In considering the mass of the walls, particular attention is focused on the orientation and capacity of the wall to accumulate energy and then release it with a useful time shift, using it appropriately during winter or summer periods (Dietrich U., 2018). The walls thereby acquire a new environmental function and evolve from a system of defence to a climate-mediating element capable of contrasting phenomena such as heat waves or the urban heat island (UHI).

With these premises, a methodological strategy is proposed. This is based on the analysis of the thermo-fluid dynamics (environmental tomographies) of urban areas targeted by the precise insertion of micro-places created for the context, which then generate macro-places and provide useful planning indications to mitigate the microclimate of open spaces and attenuate the UHI (Taha, et al., 1988; Oke, 1982). Environmental tomography is a method of investigation based on urban sections on different scales. The scope is to use vertical sections to identify and analyse the close relationships between the urban open space and buildings, considering the microclimate conditions of the site, i.e. the specifics of the individual places, in relation to the structure of the urban settlement or landscape via a tool for computational fluid dynamics analysis (CFD) (Cocci Grifoni & Ottone, 2013; Cocci Grifoni, et al., 2017)

This method allows the values of temperature and predicted mean vote (Fanger, 1972), a thermal-comfort index, registered in summer periods to be compared in the conditions before and after intervention. The interventions considered entail the use of vertical and horizontal green elements (Manso and Castro-Gomes, 2015; Olivieri, et al., 2017; Santamouris, 2014; Alcazar Saiz, et al., 2016;), the planting of appropriately chosen trees (Brandt, et al., 2016; Klemm, et al., 2015), and the use of temporary architectural devices capable of mitigating overheating and generating urban quality in the areas most exposed to degradation. The tomographic rendering of the results clearly shows the mitigating effects of the designed intervention.

Since these interventions rest on pre-existing elements subject to restrictions, the idea of using temporary elements in addition to green elements aims to respond to both the intangibility of a historical monument and to a strong demand for urban and architectural quality intended in its broadest sense. The aesthetic aspect, made through a dimensional choice suitable for the context and a careful study of materials, is also considered a necessary part of the proposal's validity.

The urban system as a complex system

The climate is changing and resilience to climate change is becoming a necessary element of global and local policies. This approach entails a search for synergy between actions to mitigate climate change, and adaptation where possible. The best-known impact of the process of urbanization on the local climate is the urban heat island. In this phenomenon, higher temperatures are produced in urban areas than in the surrounding suburbs and rural areas, with a consequent difference in temperature that can regularly reach 5–6°C at night (Dimoudi, et al., 2013; USGCRP, 2017; Oke, 1995) On a temperature contour map, the UHI appears as an area (island) surrounded by adjacent

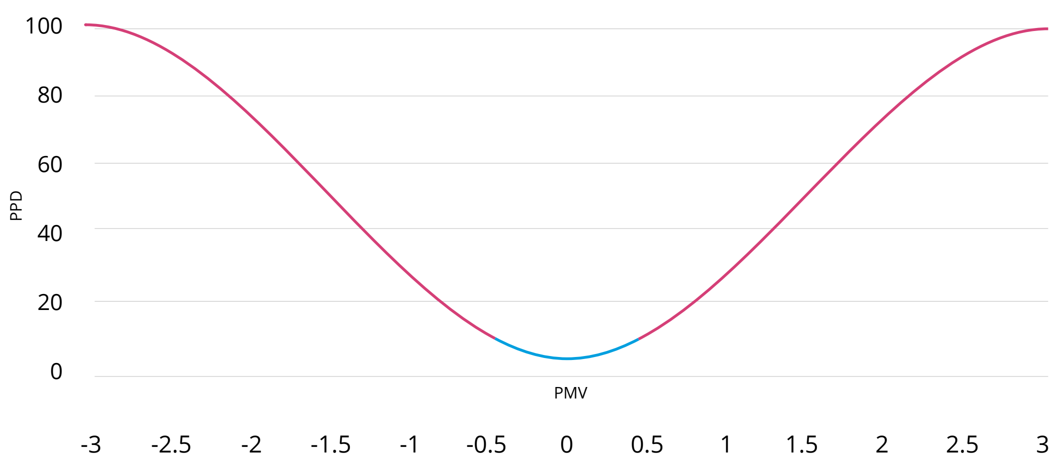
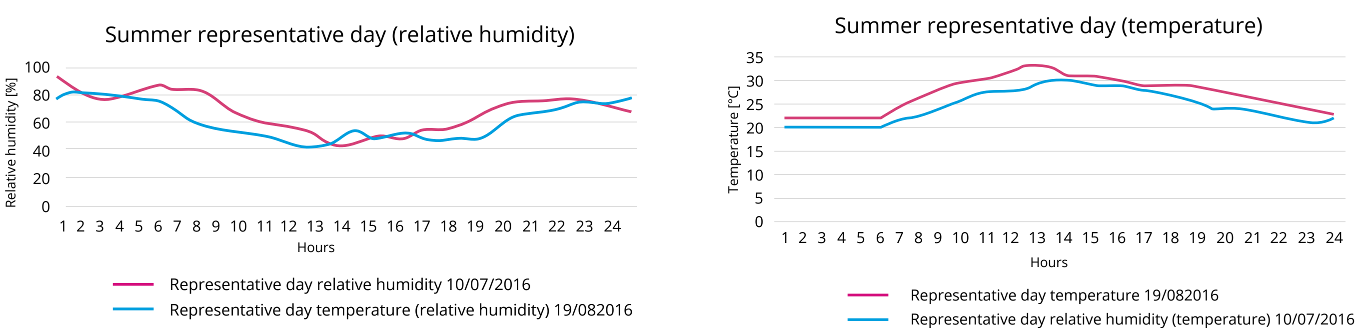


Figure 3
PMV as a function of PPD

Figure 4
Remperature and humidity trends on the respective representative day



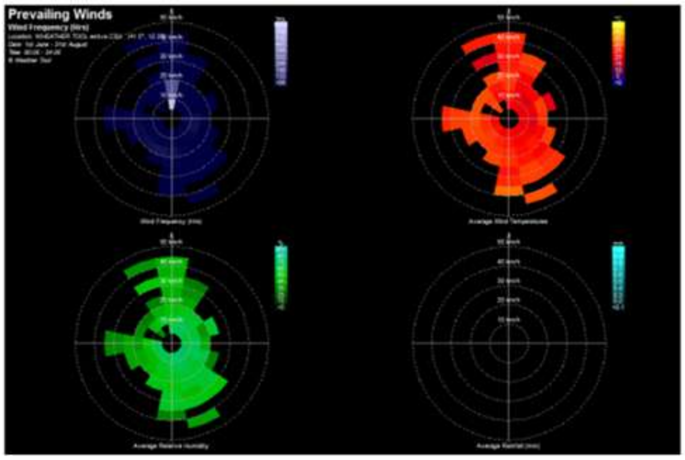


Figure 5
Representative wind rose for the area of study (weather tool software)

suburban areas with lower temperatures. The causes of the phenomenon are mainly due to the effect of the urban geometry on the logarithmic wind profile, the different materials used for urban construction, and the presence or lack of green elements. In particular, the main factor determining urban overheating is tied to the reflection and absorption of solar energy defined as the albedo, that is, the ratio of reflected solar radiation to incident radiation. A major consequence of the increase in city temperature is variations in the urban microclimate and the perception of temperature by city users (Cocci Grifoni, 2013)

Due to local projections of global climate change, an attempt has been made in recent years to consider urban transformations using a weather-climate-environment approach attentive to the complexity of various phenomena, thereby achieving quality in urban open spaces as well as environmental thermal comfort, guaranteeing well-being. In this respect, exterior space acts as an interface between the urban and architectural scales, and can be considered an active, dynamic place between buildings.

It is therefore of fundamental importance to design places of connection among the buildings as ‘thermodynamic mediation’ between the buildings and the environment, between constructions and meteorology. This oscillation between open and built space can represent a scenario for developing architecture that aims for environmentally sustainable living. Spaces are therefore generated thermodynamically that, with their comfort and environmental quality, are identified as pleasant places to live and catalysts and attractors of social activity. The designed space entails a complex set of energy and environmental variables and is not ideal aesthetics a priori; the new forms should grow out of an analysis of the forces of nature and no longer out of an anthropocentric vision of reality.

One of the key aspects of this approach is precisely the goal of designing places based on the meteorological characteristics of the area (Rahm, 2009). The resulting architecture is no longer thought of in a ‘structural’ sense but may even be ‘oriented to the climate’. To this end, careful spatial-temporal analysis of the area is necessary to be able to carefully assess the gradients of the main physical and meteorological variables. In this respect, a method of investigation was developed that, inspired by tomographic image diagnostics, allows capillary information to be obtained to identify ‘nerve points’ with ‘environmental pathologies’ that can be resolved with careful, precise environmental design (Ottone, et al., 2018).

Urban microclimate and its perception

Today, the most effective analytical definition of the conditions of humidity and temperature is the one proposed by P.O. Fanger (Fanger, 1972). This model is based on quantitative considerations tied to the equations of thermal balance and the statistical analysis of a vast sample study made on individuals subjected to controlled environmental

Figure 6
Description of comfort before intervention

conditions in a confined environment. The drive for Fanger's theory is based on the need to correlate physical parameters with the subjective feelings of people exposed to the conditions. The index thus obtained, i.e. the PMV (predicted mean vote, which is tied to PPD, the predicted percentage of dissatisfied) has a range from -3 to 3 (very cold to very hot; see Fig. 3) and is the one mostly used internationally.

From the thermal point of view, the area of study within the City of Rome is classified as a temperate Mediterranean climate, with mild winters and hot summers (Köppen, 1936). Of particular interest for this study is the summer, which on average is hot, humid, and relatively dry. There is notable microclimate variability within the territory, but the significant influence of the UHI tends to cause overheating in the most central areas.

To carefully evaluate the weather/climate conditions of the area, data obtained from the Rome Ciampino weather station were analysed, referring to the representative year (2016) in the decade analysed 2009–2018. The data include temperature (°C), relative humidity (%), wind speed (m/s), and wind direction (expressed in degrees). Through a proprietary algorithm (Pierantozzi, et al., 2012), the representative days were calculated (Tirabassi & Nassetti, 1999) for winter and summer scenarios. The representative day is synthetic weather-climate indicator represented by a real day that describes the summer meteorological conditions for the area of study. In this situation it was identified as 19 August. Figure 4 shows the temperature and humidity trends and Figure 5 shows the wind rose of the wind weather-climate force.

Definition of the functional contour line

In this research, the Aurelian Walls are viewed as a 'contour line' that, even if hidden and little represented in traditional urban itineraries, is deemed capable of embracing the various demands deriving from adjacent places, which are very diverse but pertain to a single unit, i.e the city of Rome and its historical centre.

The main questions emerging from the design analysis promoted by the new GRP derive from recognition of the city walls as a great symbol of the territorial structure and the need to reconfigure this highly irregular and not entirely preserved construction. Its 'new definition' as an environmental device capable of mitigating the effects of the urban heat island occurs by inserting passive strategies (see Fig. 6) appropriately chosen after analysis of the current state (before intervention). The schemes proposed present different configurations using the wall as an urban landscape element that contributes, with its mass, to providing comfort and well-being if accompanied by measured, temporary, and/or reversible interventions characterized functionally based on their location within the ring of the wall ***Fig. 7***. For each mitigation action, the characteristic thermo-physical values of the materials such as albedo, green-ness, and permeability are highlighted.

To numerically simulate the current state (before intervention) and designed state (after intervention), a thermo-fluid dynamics modelling tool was used (ENVIMET, 2019) to represent temperature, humidity, wind strength, and values of the PMV index using coloured contour lines.

The proposed schematizations aim to validate a method to define a complex environmental system based on the idea of 'hooking' the transformations onto a prestigious pre-existing infrastructure. This method may likewise be used in many cases where some characteristic urban elements spread throughout the territory may constitute a 'nervous system' of future transformations.

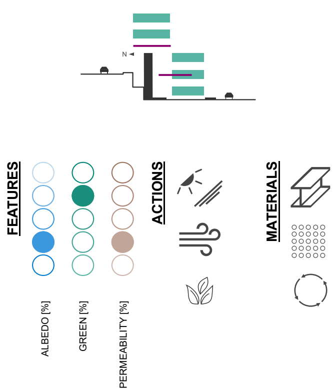
The pictograms represented schematically are clarified further through the key words 'cover', 'green portico', 'offset', etc. This apparent simplification in reality follows analysis that considers both the dimensional quantitative parameters and qualitative parameters such as materials, climate data, separation from pre-existing elements, orientation, etc. The expected interventions regard light or textile coverings, green horizontal and vertical architectural elements, pavilions, and temporary elements. The expected functions are primarily aimed at cultural and collective recreation. The system should be coordinated and made synergic through the identification of complementary functions that are strongly connected not only with the adjacent urban fabric, but also with the entire ring of the walls.

As an open system, the progressive increase in points on the contour line correspond to an analogous increase in the environmental quality of the system as a whole but do not detract from the value of each individual intervention. As can be seen in the general framework, the areas identified as those most suitable for transformation (south-east and south-west sides of the ring marked in red on the GRP) are also those with the most problems since they are abandoned areas that are not very safe. Their reactivation would allow this aspect to turn around dramatically through the use of public spaces, of which there are very few.

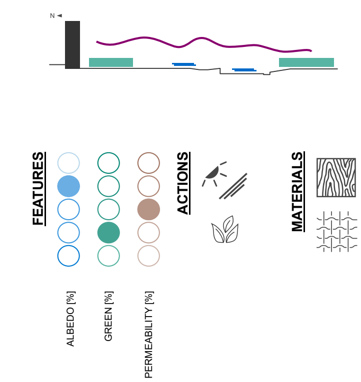
Discussion of the results

Environmental acupuncture allows for the insertion of interventions in 'climate-strategic' positions that have been appropriately identified after carefully studying the history of the area. As shown in Figure 6, some very critical situations are seen in the before-intervention state in the large areas most exposed to solar radiation, those with few trees, and

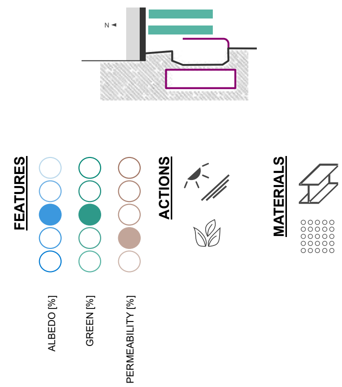
Multi-level (A)



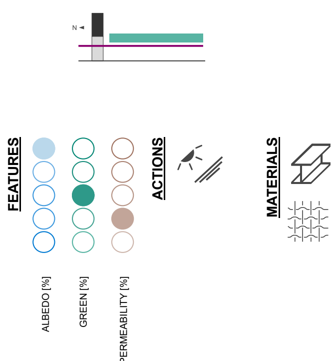
Mantle (B)



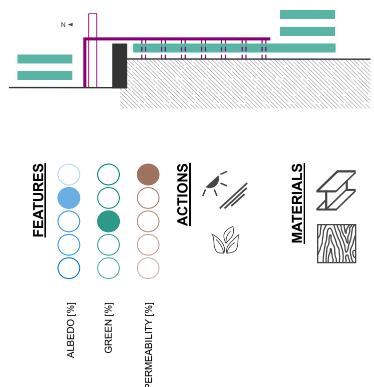
Cavity + Green + Offset (C)



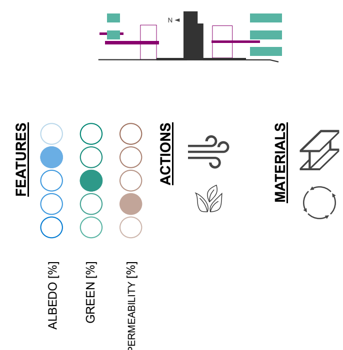
Inside-Out (D)



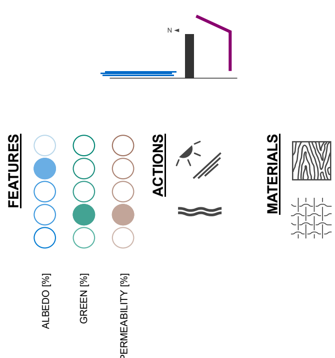
Green "portico" (E)



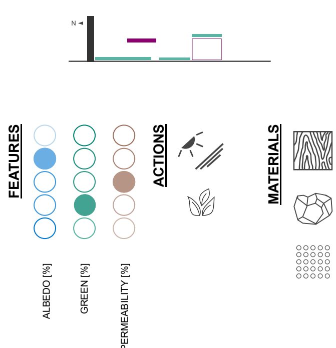
Double face (F)



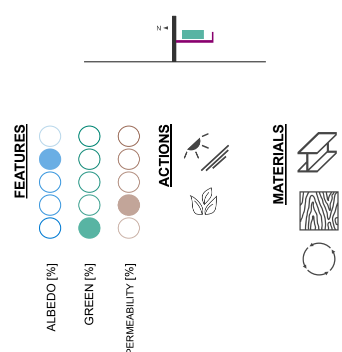
Screen + Water garden (G)

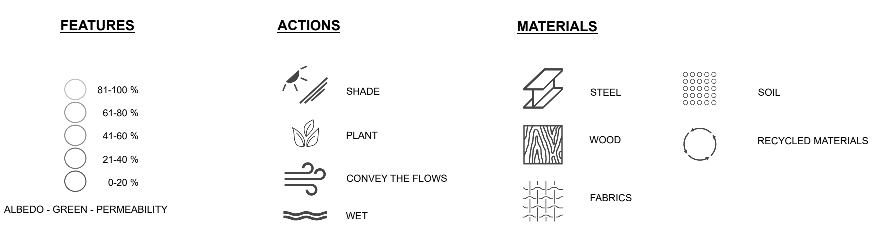


Green "piazza" (H)



Overlooking (I)





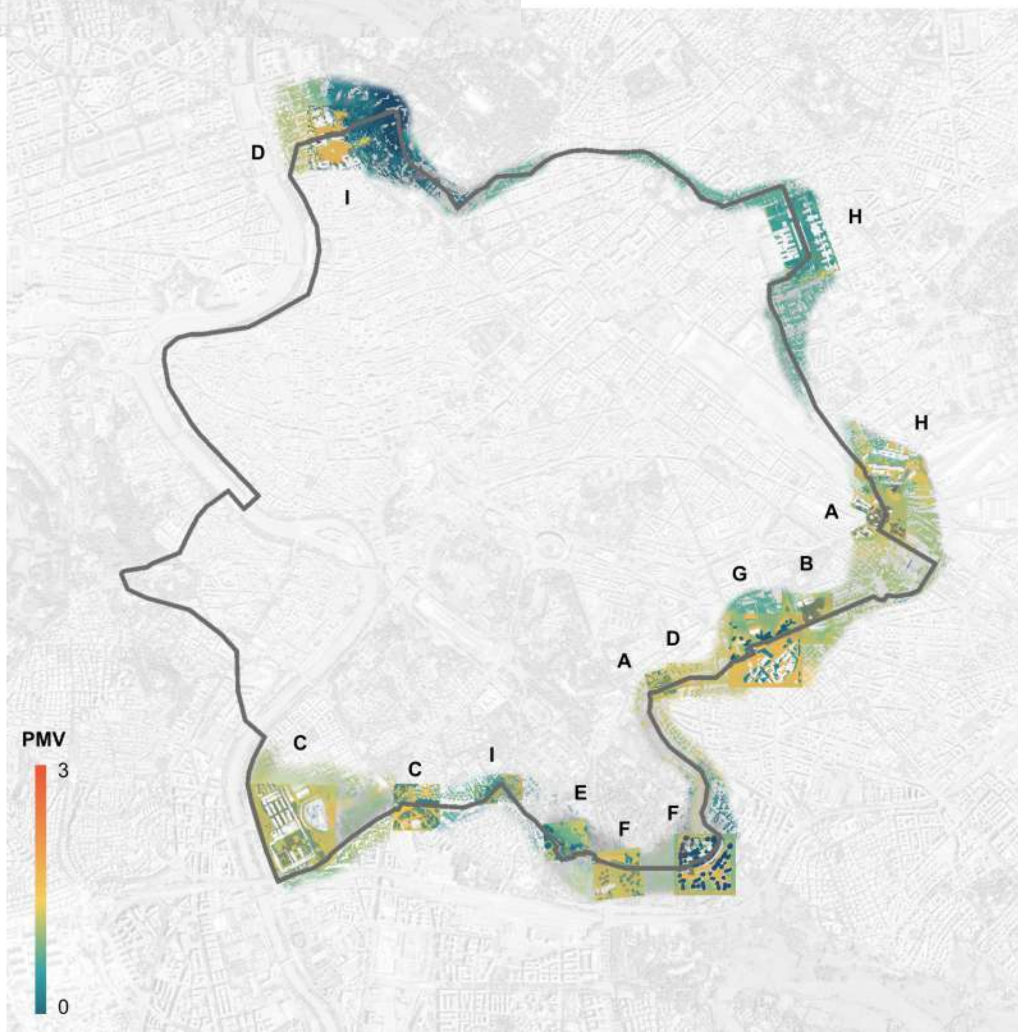


Figure 7
Actions capable of improving comfort conditions

Figure 8
Comfort results after intervention

Figure 9
Example of 'urban contour' in the city of Rome

those characterized by materials with a low albedo.

The distribution of the interventions described in Figure 7 entail the insertion of devices for green or cool covering in the areas with the most solar radiation; permeable devices that act as a diaphragm for areas where, by analysing the horizontal and vertical sections of the wind field, it is possible to channel flows and increase natural ventilation; and devices to decrease the amount of impermeable surface area and its conversion into elements with improved thermo-physical characteristics capable of more effectively managing the albedo and water regulation.

The results in Figure 8 show a PMV index of humidity and temperature comfort close to zero (colours near turquoise), i.e. point-like improvement in the perceived conditions. Figure 9 instead shows the results of climate mitigation also in areas connecting the sites of intervention. These results highlight the potential of environmental acupuncture to act precisely with focused environmental strategies and to obtain positive results on a much wider spatial scale.

Conclusion

Environmental acupuncture allows for point-like interventions in 'nerve' areas of the infrastructure and those that are the most active from an energy standpoint. This concept defines the local character of the interventions, referring to the small scale and to the very simple strategies described in the previous section, in order to improve the perceived thermal comfort in an area much broader than the area of intervention.

Improvement of the environmental characteristics in some problematic areas of the city united by the contour line of the walls appears in this study as a strategy to reactivate places and make them attractive for both inhabitants of adjacent neighbourhoods and those who experience the city and its historical centre, moving from one quarter to another. The historical centre appears to be suffocated by the massive presence of tourists, who suffer from a lack of comfortable, welcoming areas, especially in the summer when there is a greater demand for adequate public spaces to host people and events. The strategy proposed offers technicians and administrators a tool for useful evaluation to consider the relationship between the small scale and comprehensive strategies of city government.

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E - ARCHITECTURE OF COMPLEXITY: (RE)GENERATIVE INTERFACES

Keywords: Parametric design, Numerical simulations, Building skin, Outdoor comfort, Energy efficiency, Quality of life

Abstract

In recent years, global climate change and its local projection have compelled careful analysis regarding the complexity of systems on the small and large scales (architectural and urban), interpreting them as independent yet interacting components that increase the flow of information and design parameters. The (re)generative design of interface devices (vertical or horizontal) leads to the idea of a building as a process of becoming, whose main objective is the ecological, energy, and social improvement of the place where it stands.

Introduction

Today, the study of aspects tied to ecology and sustainability refers to the science of relationships and complexity fed by different interacting skills that have led to a change in paradigm. Starting in the 1970s, the step was made from Descartes's and Newton's mechanistic, deterministic vision to a vision that assumes complexity as a foundation and uses concepts such as unpredictability, nonlinearity, instability, bifurcation, homeostasis, self-study, self-organization, etc. Specified by various scientists as a theory of complexity, nonlinear dynamics, network dynamics, etc. (Morin, 2008), this new paradigm contrasts with the mechanistic idea of nature as a simple, linear machine that can be decomposed into elements reducible to the cause that preceded them in time. The new perspective views nature as an organism, an organized system whose parts interact dynamically and whose behaviour is essentially disordered, irreversible, and connected to the arrow of time but not linearly predictable.

These considerations show that 'complex' models are characterized by their qualitative rather than quantitative character. For example, while traditional mathematics deals with quantities and formulas, the dynamic theory of systems deals with qualities and methods, shifting the attention from the objects to the relationships. In addition, 'complex' models entail nonlinearity and the fundamental role of irreversibility as a source of order and the generator of organization.

The perception of complexity therefore leads to a holistic, ecological vision that tends to attribute phenomena observed in the various scientific fields to their own oikos (home), intended as a system of relationships and also as the root of what we now call ‘ecology’. This new systemic approach is inevitably combined with the use of digital devices (computers, etc.), which are indispensable for conceiving, controlling, and interrelating complex geometries. It represents a tool in much contemporary research for studying and controlling structures that, once realized, reveal themselves to be capable of self-organization and self-growth (Schumacher, 2010) analogous to the capabilities of living organisms (Tucci, 2008). These structures are therefore capable of reacting to information from the external environment, establishing interactions with the outdoors through the continuous modification and adaptation of their state. They can respond to atmospheric forcing and external stress by adapting their shape and spatial and functional configuration to respond to changing environmental requirements.

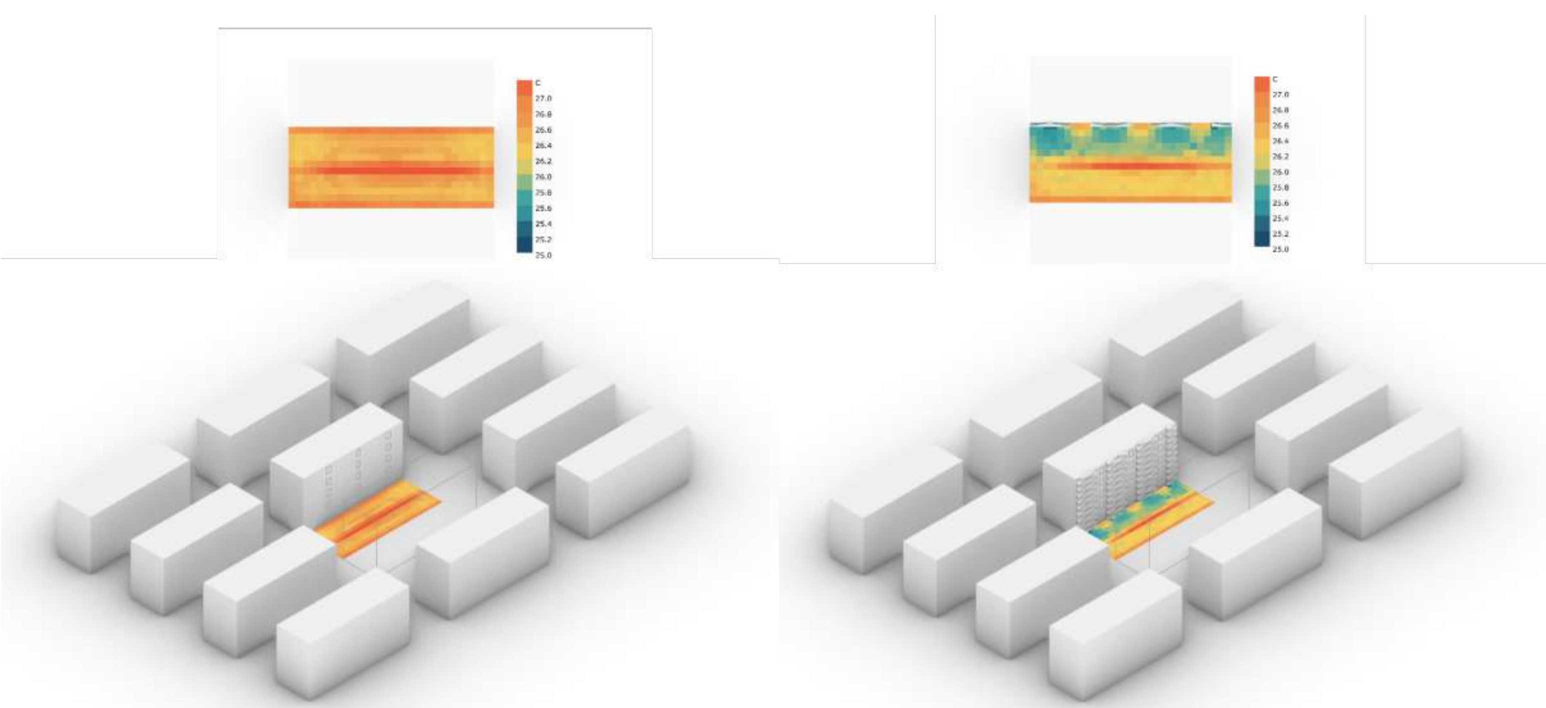
In some examples of architectural complexity, there is instead a tendency to dematerialize, to create ‘vaporized’ buildings (Rahm, 2014), indeterminate forms realized as if the process of formation were perennially progressing. The key aspects of this concept are then attention for the communicational values and sensory and intellectual relationships suggested by the object, an openness to nature, dematerialization of the mass of the walls through membranes and sensors that detect and transmit information, and recourse to the metaphor of fluidity, which represents life itself, in continuous transformation. In contrast to physical masses, the building skin increasingly tends to become a ‘threshold’ rather than a barrier, with the purpose of not only ‘closing’ and ‘containing’ but also ‘opening’ and extending’ in response to stimuli from the exterior. These reactive architectural surfaces can change the way in which we relate to the built environment and the way in which construction of the environment relates to the user.

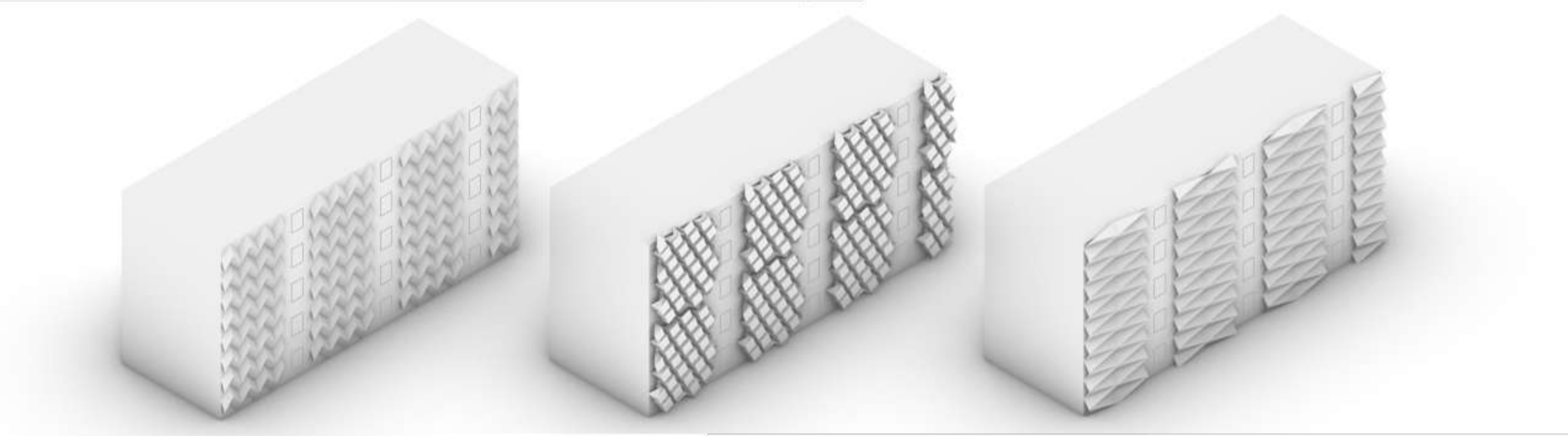
As with many other designers in contemporary architecture, Toyo Ito’s ‘Blurring Architecture’ — fluid synergies between form and matter, appearance, and performance — gives rise to a building with light edges that can react in response to the natural environment (Ito, 2000). The concept of Blurring Architecture does not regard the form of the building as much as the idea of limits, of clear separation between interior and exterior that increasingly begs discussion, making the borders between architecture and environment, between body and space, ephemeral and soft. This ‘new reality’ is capable of testing not only the strength of matter, but also (as always) transmitting the physical and mental sensations, creating sensory experiences through spaces where people can move and live freely.

The objective of this research therefore is to present new environmental parametric strategies in order to improve the technological and environmental project proposals, thereby changing the modus operandi of environmental designers and architects.

(Re)generative Façades

Contemporary research (Peters and Peters, 2018; Rahm, 2018) aims to establish continuous feedback between architecture, the environment, and users using digital tools to





incorporate architecture within the natural or urban context and to integrate the experience of users themselves within the design process and the result.

Matter is not considered an inert substrate on which a form is imposed from the outside, but an active element that participates in generating the form itself. The various materials, with their different characteristics and properties, therefore become an integral part of the design process. Material information may not only be integrated in the computational design but may also act as one of its generating morphogenetic drivers. In this way, the properties and behaviours of the materials and their related characteristics of materialization are not considered limits, but rather the source of an exploratory design process.

Wood is one material that best lends itself to these design processes; with its environmental sustainability (naturally renewable and completely recyclable), thermophysical characteristics, composition, and behaviour, it lends itself to use as a 'living' construction material. In fact, its hygroscopic behaviour allows reactive architecture to be created. Another material interesting for its versatility is cardboard, which, due to its sustainability and resistance, was used by Shigeru Ban (Eekhout et al., 2008) to create environmentally conscious buildings built with innovative, solid systems, even to face natural disasters.

Luigi Moretti (1906–1973) was the first architect to talk about 'parametric architecture' (Pellitteri and Gallo, 2018) with the goal of defining an operational method that allowed the most recent acquisitions in modern scientific thought to be encompassed in architecture. Some design themes (theatres, stadiums, subway stations, etc.) could then be addressed not according to traditional typological references but by pursuing the idea of generating the form through rigorous geometric relationships among the parameters.

The parameters and their interrelation therefore become the expression, the code, of the new architectural language, the 'structure' in the original and rigorous sense of the word and define the forms that those functions satisfy. In determining the parameters and their interrelation, the most advanced techniques and tools of scientific thought should be employed, particularly logic/mathematics, operational research, and computers — especially computers — for their ability to express probable solutions to the values of the parameters and their relationships in recursive series. The development of this setup and the new procedure and theory specified in its methods and verified in the initial results is called "parametric architecture".

Architecture should therefore be proposed as a display of and for finiteness: by probing the limits they may tend towards places of 'possibility' in opaque zones, left in shadow by the design of total technological 'solarization' (Carboni et al., 2015). Even in its current strength and universality, the technique therefore, as a means through which the form is realized, does not subtract space from our creativity. It institutes processes of continuous feedback in which each architect creates an original view of the world, a vision aimed at the future but capable of constantly questioning the limits of one's own work.

Methodology and Methods

Algorithmic and parametric procedures allow complexity to be managed relatively easily: they are versatile and expandable and enable multiple factors that have a reciprocal and simultaneous influence to be addressed. The logical/mathematical capabilities of computer tools thus allow the most correct and efficient solutions to be obtained with respect to all the parameters considered. The computer therefore 'minimizes a parametric functional', wherein 'functional' implies the space of the phases of possible choices based on the input parameters and 'minimize' means obtaining the best choice in terms of efficiency (environmental comfort, energy efficiency, functional requests, environmental impact, structural efficiency, etc.). This is where the designer intervenes; with multiple parameters involved, the designer's task is to choose from among the different possible solutions. It is in this choice that the designer's capacity unfolds, in architectural thought that is not only efficient but also capable of innovating, thrilling, and involving.

In this paper a new methodology to manage and assess the complexity of environmental design is presented. To create the workflow, various tools are used and managed in a single platform called Grasshopper[1]. This platform is a development environment in which programs can be packaged independently according to continuous feedback actions: input commands assigned in the first phase generate output that feeds the input information again in an iterative manner.

Since Grasshopper is a true development environment, it allows for parametric control of each aspect of the process. This means that each aspect of the design should be converted into a numerical variable, translating common 'design' thoughts into new 'parametric' thoughts. With this platform, tools such as ENVI-met[2], EnergyPlus[3], and Urban Weather Generator[4], can be managed by means of the various plugins for Ladybug Tools[5] (libraries configured within Grasshopper as needed).

The workflow can be divided into three phases: the first, pre-analysis; the second, processing and analysis, and the third, optimization.

Once the area of study has been chosen, the first phase entails the insertion of information on the urban scale using data collected from available GIS[6] databases (building volumes, land elevation, and cladding and roofing materials).

For contiguous buildings, where analysis is made on a more detailed scale, BIM[7] (Building Information Modelling) databases may be used, which contain information about the technological details (connection with the ground, windows and doors, roofs, etc.). To best represent the exterior space, the type and position of green elements and the surface materials can be defined, along with permeable and impermeable areas.

Finally, it is necessary to use environmental data represented by the meteorological variables and levels of atmospheric pollution on an hourly basis.

In the second phase, this information is fed into the Grasshopper platform, which automates the acquisition and manipulation of the geometric/metric data, generating three different models and correlating information from very different databases:

The first model is a simplification of the urban context for use in the preliminary analysis with Urban Weather Generator to modulate the environmental data. The result of this initial investigation is a set of meteorological data modified to consider greater adherence of the environmental data in an urban context. It is characterized by typical phenomena tied to climate change as effects of the urban heat island. The output data is used by the other models.

The second model entails exemplification of the urban layout (according to a three-dimensional grid) for use with the ENVI-met tool to generate the thermal fluid-dynamics analysis in the outdoor environment. With this model, variations in temperature, humidity, the wind field, pollution levels, and the state of comfort or discomfort in the representative scenario can be assessed. The output is used in the last model.

The third model represents the 'thermal masses' of the buildings for use with EnergyPlus to generate the non-stationary thermal analysis. EnergyPlus very accurately simulates the energy state of the buildings, which is combined with analysis of the conditions at the edge of the outdoor environment (from the previous phase). The workflow thus developed allows the results of the outdoor analysis made with ENVI-met to be tied to the indoor simulations made with EnergyPlus, returning information that is much more complete. The time to calculate the results of this last phase is short enough to allow for recursion of the simulation to optimize the results.

The last phase is represented by the optimization of the systems in which the values (geometric, material, etc.) of the parameters characterizing the technological devices can be identified using recursion to maximize their efficiency. The generation of the variables is not random, but rather managed through the use of particular genetic algorithms capable of improving the results, which are evaluated with each variation. These tools allow for assessment, for example, by progressively refining the solution to very complex problems entailing one or more objectives.

Case Study and Discussion

The case study is cardboard façades with different patterns inserted in a typical Italian climate context. To highlight the urban heat island phenomenon, Palermo was considered as is often done for its warm urban area.

Under the Köppen Climate Classification, Palermo is defined as Csa, 'hot summer subtropical', a climate often referred to as 'Mediterranean'.

The choice of cardboard originated in the challenge of designing architectural elements capable of controlling the microclimate within the urban space, considering the complexity of the system. The study of cardboard architectural elements grew out of the technological need for a light material that could be formed into complex geometries inspired by the Japanese tradition of origami. Cardboard is a light material traditionally used in architecture for its structural characteristics; here, however, it is used for its physical/technical characteristics (capacity to adequately reflect solar radiation, preventing urban overheating and ensuring impermeability with a surface treatment).

To design these elements, a parametric approach was used to translate complexity into potential, tradition into innovation. With the computerized parametrization of the geometries, it was then possible to easily modify the geometries of the system to find the best energy performance and possibility of realization by means of digital manufacturing.

Figure 1 shows an analysis of the façade to improve the state of outdoor comfort acting as a reflective membrane for solar rays within an urban canyon in Italy. With the optimization algorithms, it was possible to study the correct fold of the façade element to maximize the comfort level. The Figure shows the difference in temperature (bluer colours represent greater comfort) between the bare façade and the façade with the optimized cardboard element. The façade with the cardboard element clearly produces a lower temperature in the immediate area. This shows how it was possible use the recursive parametric analysis to analyse the façade element to reduce the temperature by about 1ºC evaluated for the UTCI (Universal Thermal Climate Index), reaching the thermal comfort zone (between 9 and 26 degrees Celsius).

Figure 3 shows three possible modular variants to be applied on the façade (Miura Ori, Ron Resch, and Yoshimura patterns). Following our analysis, the pattern on the right was found to be the most favourable in terms of improving the thermal comfort in front of the façade. This was the pattern used for the analysis in Figure 1.

Conclusion

In recent years, global climate change and its local projection have compelled careful analysis regarding the complexity of urban systems. These systems are complex and composed of multiple independent yet interacting components that increase the flow of information and design parameters. This complexity is represented by the autopoietic capability of exterior architectural structures, that is, the ability to react to information from the outdoor environment by continuously modifying and adapting their state. It follows that the skin increasingly tends to become more of a 'threshold', a (re)generative and adaptive interface that regulates and minimizes the flows of information that cross it. It is therefore no longer an element of separation but of connection between urban volumes and empty spaces. In this way, the relationship between building and public space becomes the design of spaces for interaction, that is, in-between social interaction. A link is made between the quality of 'between building' spaces, the quality of life within buildings, the possibility for users to establish social activities, and the possibility of designing comfortable places.

Environmental aspects are gaining importance in the design of anthropized ecosystems. The material and morphological characteristics can be associated in complex relationships that generate and influence design solutions on various levels, solutions capable of adapting over time to respond to environmental questions while also activating and supporting social mechanisms for community growth.

(Re)generative design allows computer systems to be used to define architecture whose essence does not lie in techniques per se, but in the awareness of the consequences that the use of techniques may have on the perception and use of open space and architectural structures. In addition, it allows processes for evaluating the design choices to be accelerated due to the association of material, geometric, and environmental characteristics.

Footnotes

1. *Grasshopper is an integrated development environment (IDE) that runs within the Rhinoceros 3D n. The program was created by David Rutten at Robert McNeel & Associates. (http://www.mcneel.com/)*
2. *ENVI-met is a software able to simulate climates in urban environments and to evaluate the effects of atmosphere, vegetation, architecture and materials. (www.envi-met.com)*
3. *EnergyPlus is a complete building energy simulation program that engineers, architects and researchers use to model both the energy consumption for heating, cooling, ventilation, lighting and current and process loads, and the use of water in buildings. Its development is funded by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO)*

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F - A NEW BAROQUE FOR THE ENVIRONMENTAL QUALITY OF THE CITY

Keywords: Baroque façades, Urban comfort, Climate and architecture, Computational urban analysis

Abstracts

In his book about eighteenth-century Rome, Hans Gross (Gross, 1990) writes about the project for St. Peter's Square and Borromini's colonnade, saying that while the plans for Rome were intended to increase the splendour of the city and its sovereign, they were not aimed only at the glory of faith but also at the comfort and satisfaction of tourists. The author highlights a point of view that seemed very current; here it is represented as a research hypothesis that investigates what are the reasons that determine satisfaction (i.e. comfort) in people who frequent certain urban places. The question is: how do some precise, significant examples of Baroque architecture demonstrate, with data in hand, the ability of a monumental building to offer all those quality and well-being advantages for which it was designed? This article develops the idea that the shape and layout of the façade is not only an aspect of formal beauty but also a prelude to a new vision of adaptation to climate change. Some examples of Baroque architecture are investigated with regard to the indoor-outdoor mass/space ratio using a parametric methodology called TENS (Tomographic ENvironmental Section), which is applied in urban and bioclimate studies. The same methodology allows to identify small places diffused in ancient and contemporary urban fabrics as a system potentially able to modify, through targeted interventions, the urban microclimate and to contrast the effects of climate change. In conclusion, what emerges is the modern nature of a project designed to provide urban places dedicated to people (formerly pilgrims) and their full sensory well-being.

Buildings Overlooking Public Squares in Baroque Architecture

This study offers a new perspective regarding Baroque architecture, which is viewed as a depository of urban values that are very important from many points of view. In particular, this article relies on point- like analysis and using innovative computational tools to describe and demonstrate how the architectural device of the Baroque façade, with its 'extroversion', corbels, decorations, and the prominences of doors and windows are capable of best representing with

Figure 1
S. Maria della Pace, Rome

great expressive strength that character of inclusion that was so important for urban design in seventeenth-century Rome.

"La facciata (...) si rende partecipe dello spazio antistante, non è una costruzione isolata ma fa parte dell'ambiente e può essere considerata quasi come una parete della piazza" (LOI, 2006). From this point of view, we can recognize in Rome under Sixtus V the traces of an urban design created to welcome pilgrims and offer extended architecture capable of giving shelter, relief, shadow, and light according to the need and seasonal climate conditions.

Architecture is substituted for nature in its claim to amaze and render service to the open space of the square, opening (Church of Santa Susanna by Carlo Maderno), or street (Church of San Carlino alle Quattro Fontane by Borromini) through the synthesis of urban design, technical device, and architectural/decorative details. All are elements designed to delineate a sensory space never realized before, "capace di rispondere alle rinnovate richieste di una classe dirigente in evoluzione, proponendo moderne soluzioni spaziali opportunatamente dimensionate e coerentemente abbellite in una cornice urbana controllata." (Benincampi, 2017)

In this perspective, the monumental colonnade created by Bernini to delimit the great flood of Saint Peter's Square appears to be a clear response to Mother Church's demand for protection and hospitality for her faithful: an embrace that is not even overly symbolic since pilgrims stop and sleep under its protection and even today Pope Francis allows it to be used for this purpose at certain times. (Benincampi, 2017)

Along with these characteristics referring to the urban culture of the period, one should note the importance of the organization of building production entrusted in the late 1500 and early 1600s to the so-called 'Fontana clan' (F.Q., 2017), a family of powerful builders from northern Italy. They placed a new and efficient mark on the process of transforming the urban face of Rome, promoting the strong integration between design and realization of the works, even with professional contributions that closely integrated creative inspiration — entrusted to famous architects and sculptors — and the technical capacities of worksite management.

It was precisely this construction expertise that served as a background to the great expressive 'fantasies' (Bonaccorso, 2018) of people such as Maderno, Pietro da Cortona, and Borromini, who worked to create façades of great sculptural complexity. Carlo Maderno was called a 'sculptor of architecture', but the same could also be said of Borromini and Pietro da Cortona. All such façades were in fact 'spatial' sculptures (today we could call them 'buffers'), that use air, light, and shadows as environmental devices capable of producing architecture within the building. They act as a mediating element between the open public space and the internal space of the building, protecting from bad weather and preparing the visitor to admire the interior of the church or palace.

In contemporary architecture, we find this idea in Le Corbusier's façades for the administrative buildings in Chandigarh: true environmental filters, climate mitigators designed to soften the effects of heat and humidity at the site. This is also true of F. L. Wright's houses, such as the Herbert and Katherine Jacobs Second House (Middleton, Wisconsin, 1946), where the façade curves to the south and the protrusion of the roof seems to perfectly balance the Sun's path through the sky, preventing light from entering the large wall of windows in summer and letting it through in winter. This attention for the relationship between building interior and exterior today seems to be one of the most efficient strategies for counteracting the overheating of urban spaces and mitigating the effects of climate change.

Case Study: The Church of Santa Maria della Pace in Rome

The chosen case study represents one of the most interesting in Baroque urban intervention within a context that was already densely urbanized. The façade of the church, with its pronaos, was realized by Pietro da Cortona between 1656 and 1667, installed on an existing body built many years before (1482, under the papacy of Sixtus IV). It is impossible

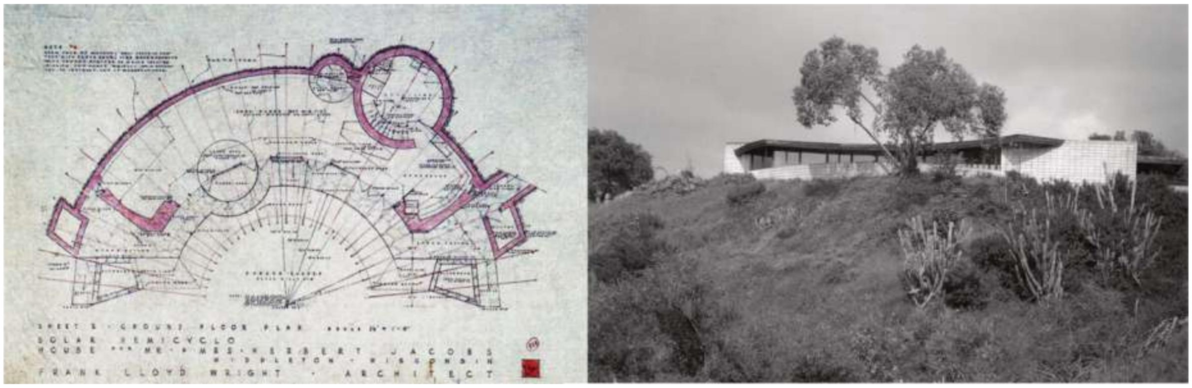

Figure 2
F.L Wright, Jacobs House II, 1944 - 1948

to separate the church from its urban setting, which, in a version more humble than the Church of San Ivo alla Sapienza, was shaped through the insertion of two slightly asymmetric bodies that frame the church on the eastern and western sides, demolishing part of the pre-existing fabric. On the western side, one accesses the cloister adjacent to the church which was designed by Bramante (1500-1504).

Today we could define this project as urban 'environmental acupuncture', recognized as it is as one of the most important and suggestive corners of the city behind Piazza Navona.

An interesting point of view comes from Cesare De Seta (De Seta, 2010), who denies the unitary nature of the Baroque city, stating that the Baroque city 'does not exist'. What exists instead is a sort of urban intervention falling precisely on an already established fabric; so many incisive interventions that they quantitatively and qualitatively changed the entire pre-existing urban layout. De Seta also includes Santa Maria della Pace as something 'unprecedented', capable of modifying a space carved out of the Medieval fabric, offering a view generated by the tension between an indifferent system and a strongly dynamic space resulting from the surprising form of the façade. (De Seta, 2010)

The study presented here therefore concentrates on a place and historical architecture that is situated with maximum effectiveness within its relationship between buildings and open space. Stressing this concept of 'space for interaction', the façade behaves almost like a climate device, created to the advantage of an urban space, relating the form and layout of the elements composing the depth of the façade with the resulting climate benefits. The analysis is not based simply on the effects that the geometry of the façade exerts on the surrounding space; rather, it is carried out by relating all aspects regarding the contextual conditions, such as orientation, climate data, proportions, materials, and the shape of the buildings and adjacent open spaces.

Outdoor Thermal Comfort evaluation for Baroque Architecture

Global climate change represents an emergency being felt increasingly even on the local scale. In particular, various studies have shown how cities are affected by extreme

ASHRAE SCALE		BEDFORD SCALE		SEVEN POINT		NINE POINT	
Hot	3	Much Too Warm	3	Very Cold	1	Very Cold	1
Warm	2	Too Warm	2	Quite Cold	2	Cold	2
Slightly Warm	1	Comfortably Warm	1	Cold	3	Cool	3
Neutral	0	Comfortable	0	Comfort	4	Slightly Cool	4
Slightly Cool	-1	Comfortably Cool	-1	Hot	5	Neutral	5
Cool	-2	Too Cool	-2	Quite Hot	6	Slightly Warm	6
Cold	-3	Much Too Cool	-3	Very Hot	7	Warm	7
						Hot	8
						Very Hot	9

Figure 3

Thermal Comfort scale (Mukherjee and Mahanta, 2014) climate phenomena such as increasing temperatures, heat waves and decreasing precipitations. All these aspects generate uncomfortable conditions and reduce outdoor comfort the quality of life. Outdoor thermal comfort can be defined as a complex issue because the difficulty in understanding the outdoor thermal comfort is represented by the multiplicity of factors involved and the different existing interactions. The evaluation of thermal comfort should be conducted by considering its various physical, physiological and psychological aspects. The physical approach of thermal comfort should consider the human being as a thermodynamic system and determine its interactions with the environment in terms of heat exchange. The physiological aspects are assessed as self-regulatory mechanisms such as sweating or shivering mechanisms of the human body. The psychological approach should evaluate the perception of human towards thermal environment through the relationship between the physiological and physical variables and sensorial results in the individual.

Outdoor thermal comfort parameters

Environmental conditions and microclimate parameters are important factors for outdoor thermal comfort assessment (Olgyay et al., 2015). Urban geometry and urban canyon that related to height-to-width ratio, or aspect ratio, are affecting local climate through their effect on radiation and wind flows. The outdoor thermal environment is significantly influenced by the built environment (i.e. land use or ground surface cover such as natural grass and artificial paving, pervious and impervious materials, anthropogenic heat, shading by trees, man-made objects, and soon) and by its architectural form.

“Architectural form is the point of contact between mass and space … Architectural forms, textures, materials, modulation of light and shade, color, all combine to inject a quality or spirit that articulates space.” (Bacon, 1977). Achieving conditions of environmental thermal comfort in design is very challenging: it is necessary to create environmental thermo-hygrometric conditions that can satisfy the perception of physical/psychological well-being, determining a mental state of thermal satisfaction within the generated microclimate. This is strongly linked to subjective conditions and individual expectations *Fig. 3*. The thermal comfort places represent “thermodynamic mediation” between a building and the environment, construction and meteorology.

According to theories and studies made by Fanger (Fanger, 1970), thermo-hygrometric well-being is reached according to relationships found among the subjective and environmental variables. When evaluating the thermal environment, it is important to understand human responses to various thermal conditions as well as the diversity of human responses. Therefore, to determine thermal comfort, the predicted mean vote (PMV; (Fanger, 1970)) was used. This widely used index predicts the mean value of the subjective ratings of a large group of people on a seven-point thermal-sensation scale (+3 hot, +2 warm, +1 slightly warm, 0 neutral, − 1 slightly cool, −2 cool, −3 cold). The predicted percent dissatisfied (PPD) is a related index that predicts the percentage of a large group of people likely to feel thermally uncomfortable. To calculate PMV and PPD, the indications provided in technical standard ISO 7730 (ISO 7730, 1994).

Outdoor comfort simulations and Results

The research method uses 3D parametric tools, Grasshopper which is a graphical algorithm editor integrated with Rhinoceros, a 3D modelling program. Grasshopper is developed to be connected to multiple plugins in order to facilitate the relation between different disciplines, using the same simulation platform.
More specifically, the research uses a variety of plug-ins in Grasshopper, such as Ladybug *Fig. 4*, Honeybee *Fig. 5*. Honeybee is an open source plug-in that connects Grasshopper to EnergyPlus, Radiance, Daysim, and OpenStudio to simulate energy transfer and daylight in buildings. Ladybug is an open-source environmental plug-in

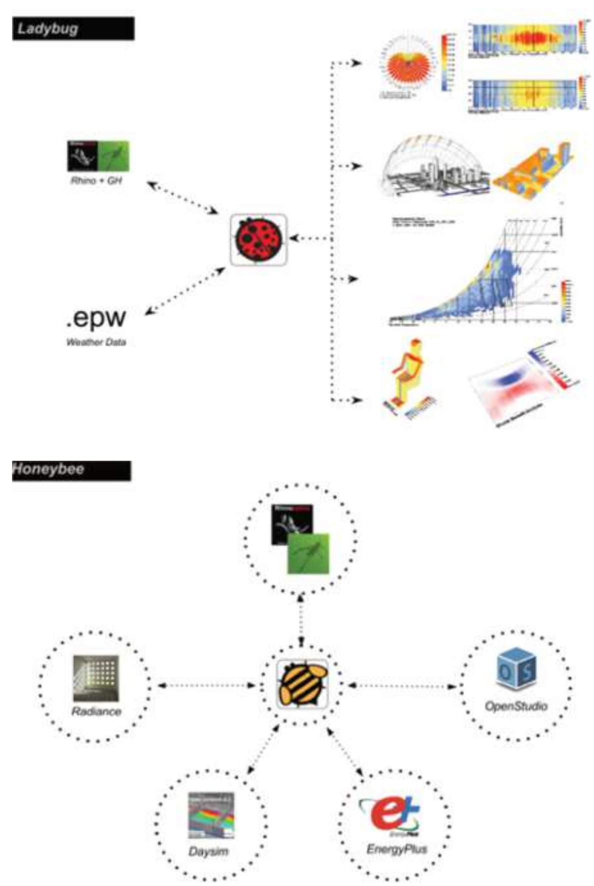

Figure 4
Honeybee plug in and Ladybug plug in

for Grasshopper. It imports Energy Plus weather files (EPW) into Grasshopper and helps to create 2D and 3D graphics for weather data analysis.

In order to assess the solar radiation reaching the façade, Radiance software has been used. It is a suite of programmes for the analysis of lighting phenomena and can solve a wide range of lighting phenomena such as object modelling, rendering, intensity calculation, image processing and display. The interesting capability is to simulate complicated light behaviour accurately by using backward raytracing, following view rays from the virtual focus of the eye or camera through pixels in an imaginary image plane into the environment (Ward Larson Shakespeare and Shakespeare, 2004).

"interpenetration" of elements that belong to the square and to the attic. The design of the architectural elements in the Baroque façade produces self-shadowing and consequently less energy has been gained *Fig. 5*. There is certainly a relationship between the architectural form and thermal comfort as depicted in figure 6. The figure shows how the PMV values, in case B, are higher than in case A, increasing thermal outdoor comfort given by the "complexity" of the geometries.

Conclusion

The materials and technologies that are currently being studied in the urban and architectural fields, used with the aim of obtaining consistent and measurable effects of climate mitigation, belong to two categories: air, sun, water and green, on the one hand; form and consistency of the building on the other. While for the former it is easier to acquire data for the definition of the simulation model, for the latter the literature provides for an excessive simplification of the shape of buildings and façades. This simplification de facto reduces the potential climate support of buildings towards the open space. The results shed light on new interpretations of urban phenomena, starting from the ability of a complex

and articulated façade device to modify the environmental conditions of the adjacent spaces. The goal was to measure and make even more evident what was probably (and intuitively) one of the important requisites in the design of urban spaces in the Baroque period: the physical integration of architecture and open space to obtain and strengthen the effect of well-being and hospitality destined for visitors through climate/environmental control.

This aspect consequently participates in the thermodynamic generation of spaces that, characterized by comfort and environmental quality, are identified as places that are pleasant to live in, and are catalysts and attractors of social activities.

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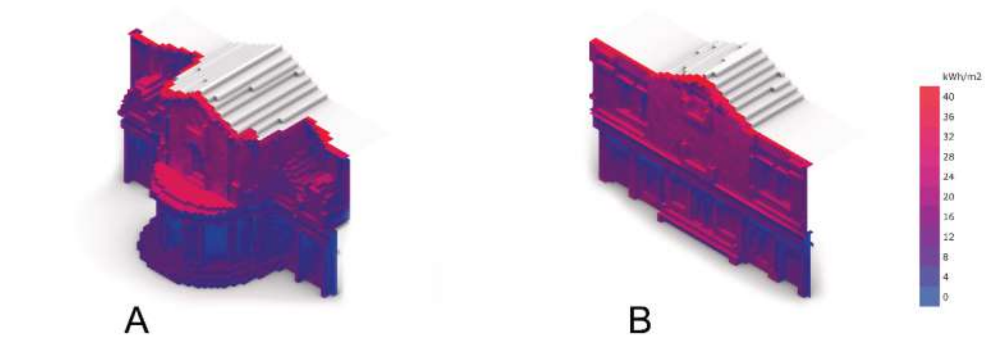

Figure 5
Radiation analysis comparison

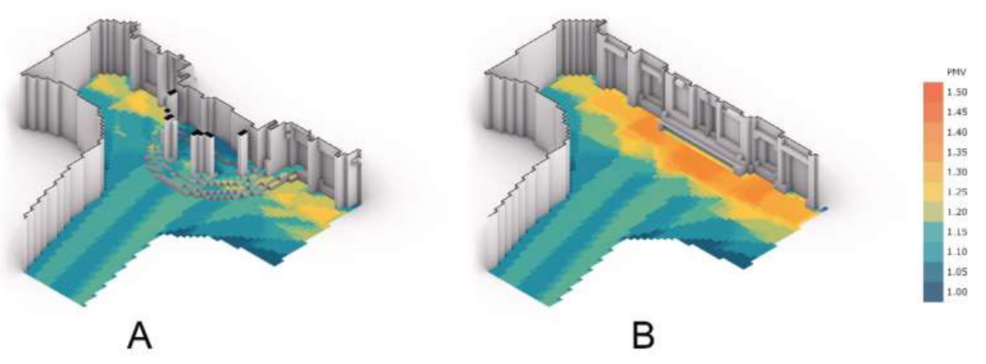

Figure 6
comfort analysis comparison (PMV)

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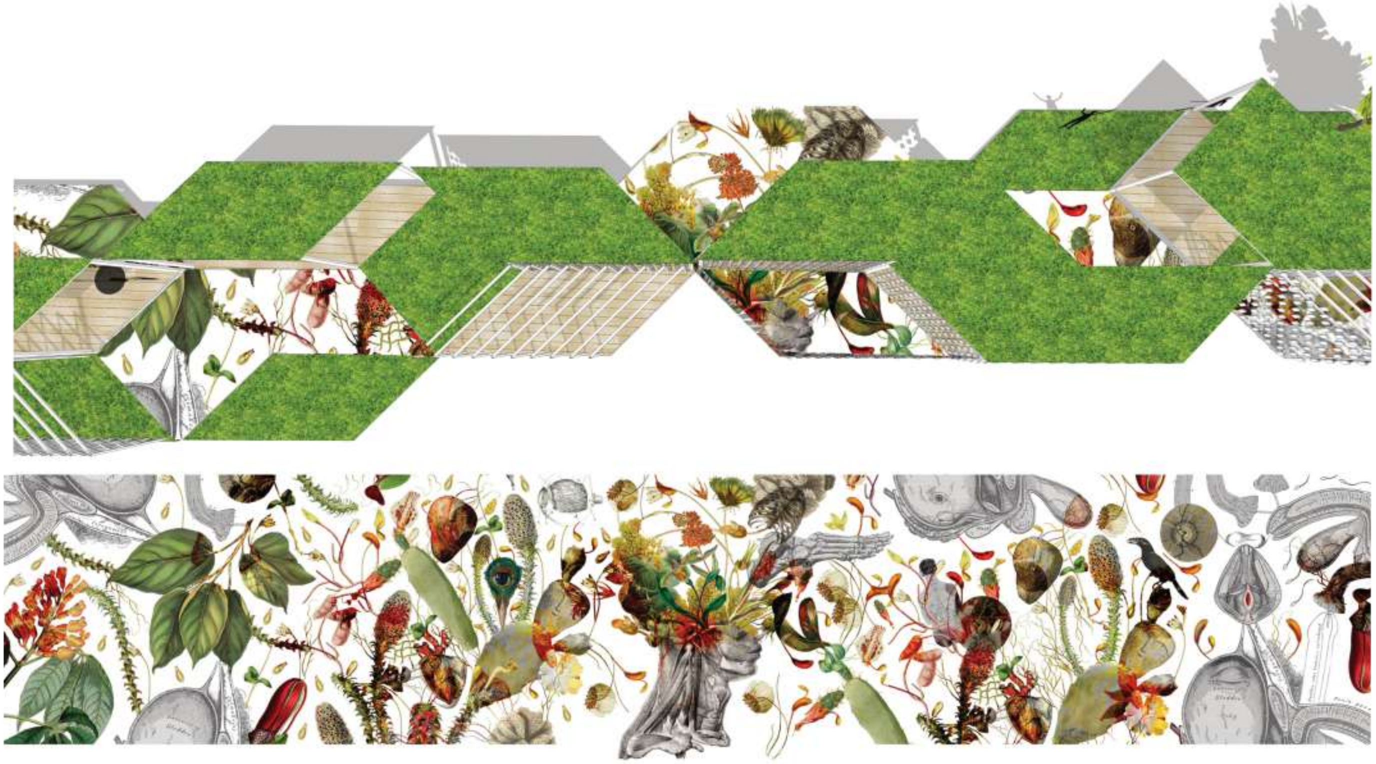
G - NEW RENAISSANCE

Keywords: Green façades, Parametric optimization, Energy-efficient design

'To re-establish a relationship centred on the dynamics of primary elements: substance, conviviality, nature, and their cosmological correspondences. Outdoor devices appear as new systems to reinterpret the landscape and collective spatiality, in which nature worked by man reveals its meaning, expressive textures, constructive rhythms, and new paths — elements that communicate with each other to become forms, within the expressive core which forms their pattern. The secret to their relationship with man is the new spatiality to which we are adapting. Showing the sense of "inhabiting": I am because I inhabit our inhabitation of the world, this is the task that art and architecture propose in our present. If new canons of distancing reign in daily life and our usual habits conflict, it is only through art and grace that we are allowed to free ourselves and formulate new perspectives and new depths of vision.' (Paola Tassetti)

Will the global crisis tied to COVID-19 one day be read in the form of our cities? Will it leave an imprint on paths, the width of pavements, or the number of cycle lanes? Will it change the way we move around the city day after day? This is the question posed by Le Monde[1] in an article published on 19 June 2020 at the dawn of a desired restart. In order to encourage residents to respect the principle of physical distancing without missing the opportunity to meet and interact, many mayors have outlined new urban frameworks. According to its needs and size, each city is addressing new paradigms to organize work, transport, public health, and social life. The geometry of streets and squares will change, more outdoor areas and neighbourhood services will be needed, the major commercial and service sector hubs will have to be transformed, and widespread services will be needed throughout the territory.

The pandemic has not only enhanced existing processes, but has also shifted the focus to others that deserve to be explored. The cities we have today were largely created to 'cure' the great epidemics of the nineteenth century, which were caused by overcrowding. The need for distancing and the disposal of waste harmful to human health generated new standards and forms that we have more than metabolized by now. Never before, however, has space between people been synonymous with safety, and never before has the human body, or rather the 'metre' between



ANATOMIA VEGETALE Renascentia flōs aequĭnoctĭum{XX} - addo me in florem = passare allo stato di fiore
STUDI del NUOVO RINASCIMENTO 2020 Paola Tassetti

bodies, been the unit used to measure space. Albert Lévy[2], a researcher at the Laboratoire Architecture Ville Urbanisme Environnement and the CNRS in Paris, states that 'health has been a determining factor in the birth of urban planning'. By the fifth century BC, Hippocrates was already exploring the links between disease and the environment. 'To delve into medicine, you must first consider the seasons, know the quality of the water, the winds, the seasons of the year, the influences that each of them can exert …; and also the winds and hot and cold, First of all, those that are common to all places, but also those that are typical of each region.'

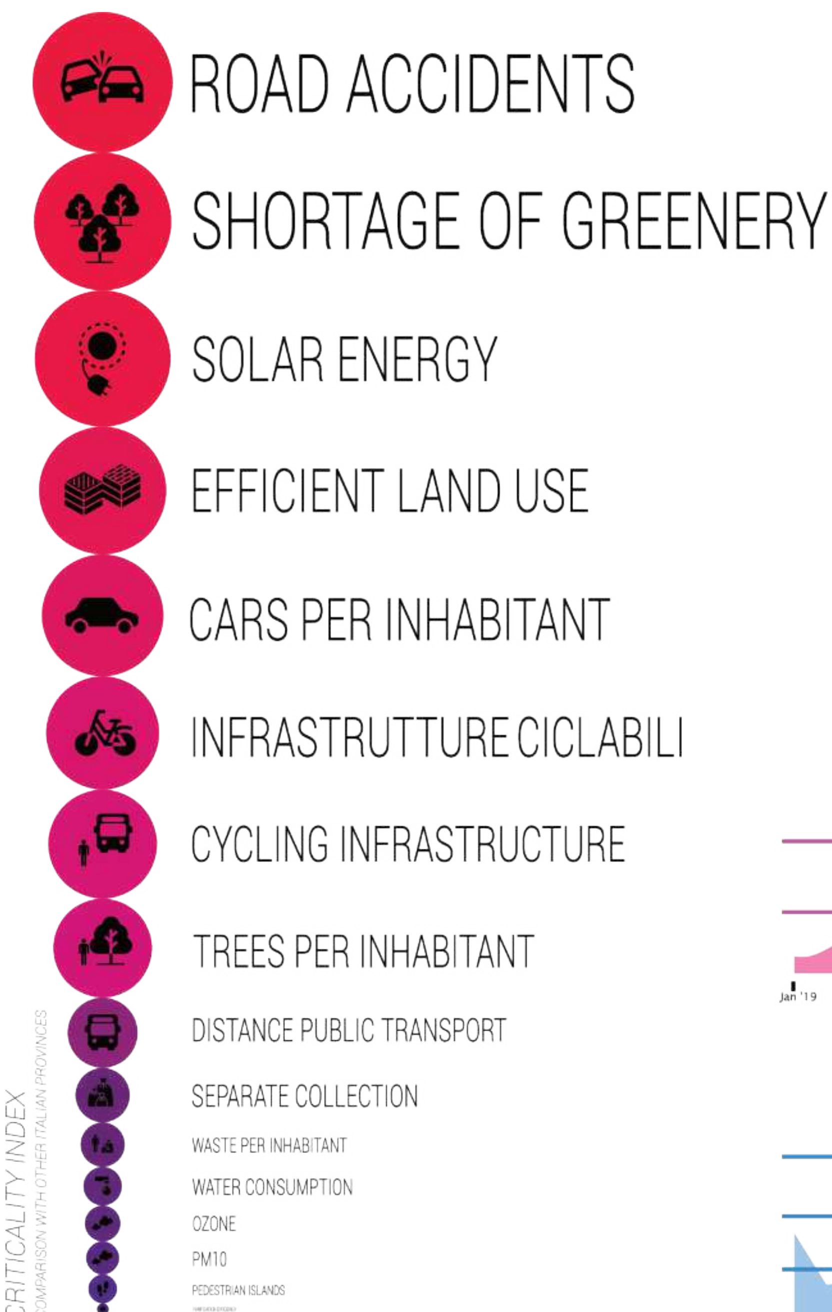
The quality of the urban environment acquires further, fundamental importance. During the days of the strictest lockdown, the residents of Ascoli Piceno lived in their homes with an average of 46.68 m^2 per inhabitant (the national average is 63 m^2 per inhabitant)[3], rediscovered services close to their neighbourhoods, and were able to appreciate better air quality and the absence of noise pollution. As soon as the bans were lifted, they began to use open spaces, particularly the public green areas available, which, according to the data, allow for only 8.9 m^2 per inhabitant. The same applies to pedestrian areas, which amount to 0.55[4] m^2/inhabitant.

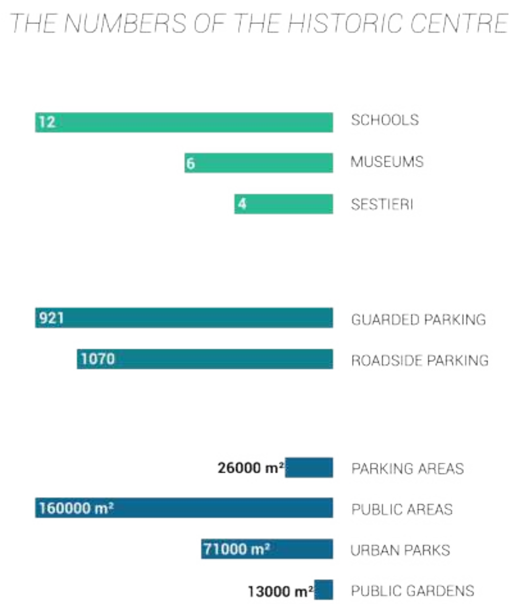
The need to invest in quality public space to cope with the emergency phase, but even more so for future scenarios when public spaces will once again have to accommodate thousands of people, is clear and can no longer be overlooked. Spaces are required that can contribute to improving air quality, comfort, and health and guarantees the safety needed in the post-emergency phase. The increase in green surface area can modulate thermodynamic variables to generate comfortable environments with a lower risk of viral infection by controlling the microphysical stability of the droplets (L. Liu et al., R. Mittal et al.). In addition, the use of green spaces makes it possible to counteract some of the city's structural deficiencies and provide activities with an engine for restarting. This is not just a question of redesigning space, however. It is about rethinking behaviour, social relations, and the measurement of bodies in space. As Sennett5 argues, it seems clear that there will be a renewed focus in the future on finding design solutions for individual buildings and larger neighbourhoods that allow people to socialize safely. The implications for large cities are immense. We don't know the answer yet, but in the new and unpredictable connections being rapidly forged within our cities as a result of the pandemic, there is some cause for optimism. Sennett believes we are potentially witnessing a fundamental shift in urban social relations. 'City residents are becoming aware of desires they never realized they had before' such as 'more human contact, a more liveable city.' And in the historic and consolidated city, it is possible and necessary to intervene through projects that combine all these instances.

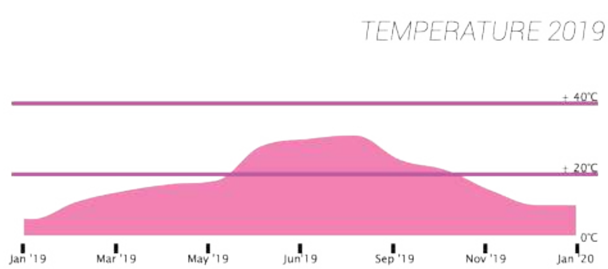
Public space remains the place where these changes can be tested and where the social distance required must not create dispersion. The City Administration of Ascoli Piceno immediately grasped the need to equip public spaces to serve activities and citizens, and in the document with the Guidelines for the 'Use of Public Areas in the Management Period of the COVID-19 Health Emergency' valid points of attention emerge: new forms of commerce and producerconsumer relationships through temporary elements to be dismantled when necessary; spaces for several activities to share, allowing the transfer of non-adjacent areas if necessary.

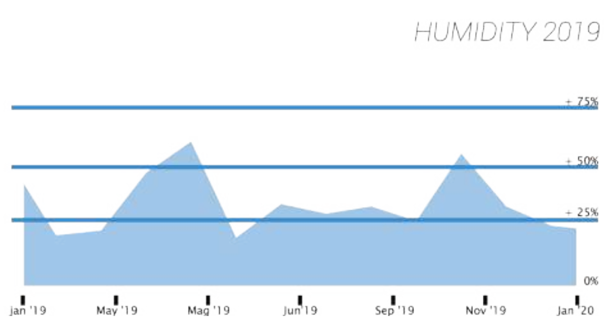
How can this be done? By dotting cities with temporary devices capable of supporting the activities and citizens' social lives, guaranteeing an improvement in comfort conditions and contributing to urban environmental quality: green living systems. These are reversible, temporary but 'contagious' installations capable of feeding on urban energy and improving the conditions where they are inserted. The environmental analyses carried out highlight critical issues that potentially prevent open space from being usable. Summer temperatures are increasing, highlighting the growing trend of urban heat waves, while there are fewer cold snaps in winter with a rather moderate average seasonal temperature. The success of outdoor spaces derives from their ability to provide a pleasant experience in terms of temperature, humidity, and visual comfort. The urban morphology has a significant influence on these characteristics and its design is able to maximize the environmental comfort conditions, contributing to the improvement of urban parameters.

All commercial activities can benefit, enhancing synergies and fruitful spread for a sustainable restart. In addition to the large squares where such interventions would be more









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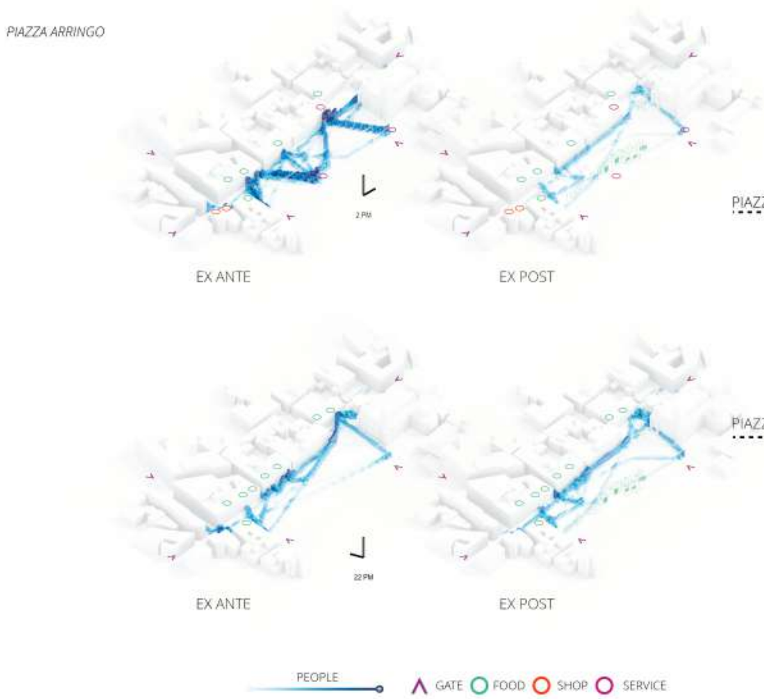
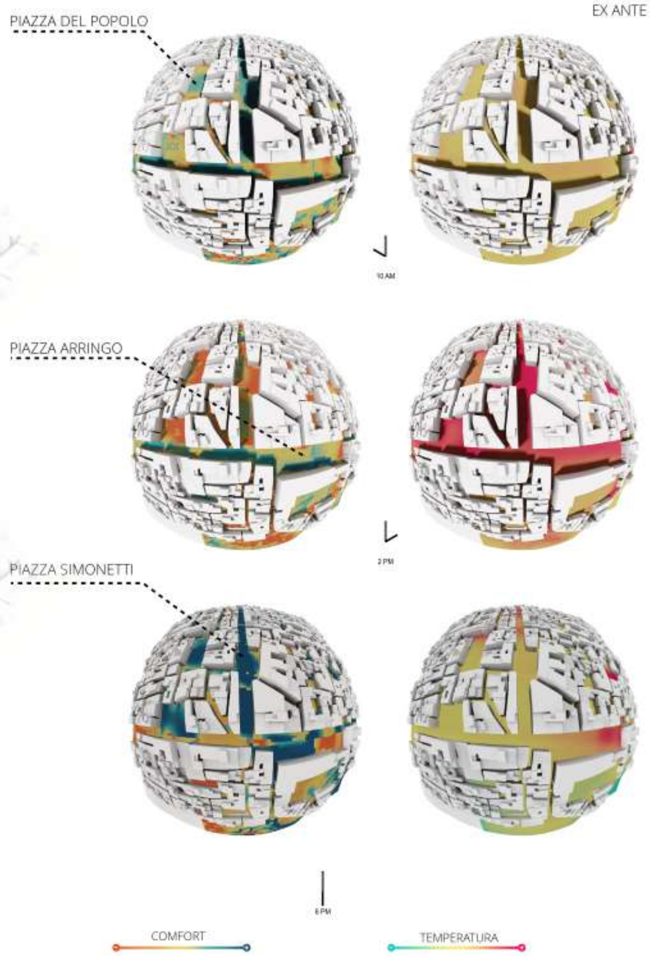
PATH ANALYS



ENVIRONMENTAL ANALYS

EX ANTE



HEAT ISLAND ANALYSIS

EX ANTE

natural, we could think about removing space for cars, primarily car parking along the streets, and providing areas for shops to spread greenery along the city's roads. The city could create a support system by creating warehouses in areas close to the centre (the city's river belt) to store and maintain structures and nurseries for greenery.

City, architecture, technology, and art combine to create new scenarios. And indeed, important synergies can arise from collaboration with artists. The artistic works that will cross the squares will have their own material thickness that will blend with nature and botanical textures, developing imaginary connections and new correlations, chasing sensations in which the inner feeling of change faces a new spatiality. Lively thought — art, that is — enters this vortex of symbolic correspondence and crosses the frontier. It is the time for a 'New Renaissance' that includes any form of creative genesis and reconnection with nature through the arts that can be strengthened through the architectural process capable of dressing the views and perspectives of our squares with new spatiality.

Footnotes

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3. *http://dati-censimentopopolazione.istat.it/Index.aspx#, floor area data per housing occupant*
4. *Source and indicators available in "Ecosistema Urbano 2019", edited by Legambiente, Ambiente Italia and Il Sole 24Ore, https://www.legambiente.it/ ecosistema-urbano-2019, https://ecosistemi.legambiente.it/risultati*
5. *https://www.theguardian.com/world/2020/mar/26/l ife-aftercoronavirus-pandemic-change-world?fbclid=IwAR09jN2fsSpekRwKlHjQKHfrXMcO0Xyhl50zpuFBMS9t5T6p3l5lrfDtKo*
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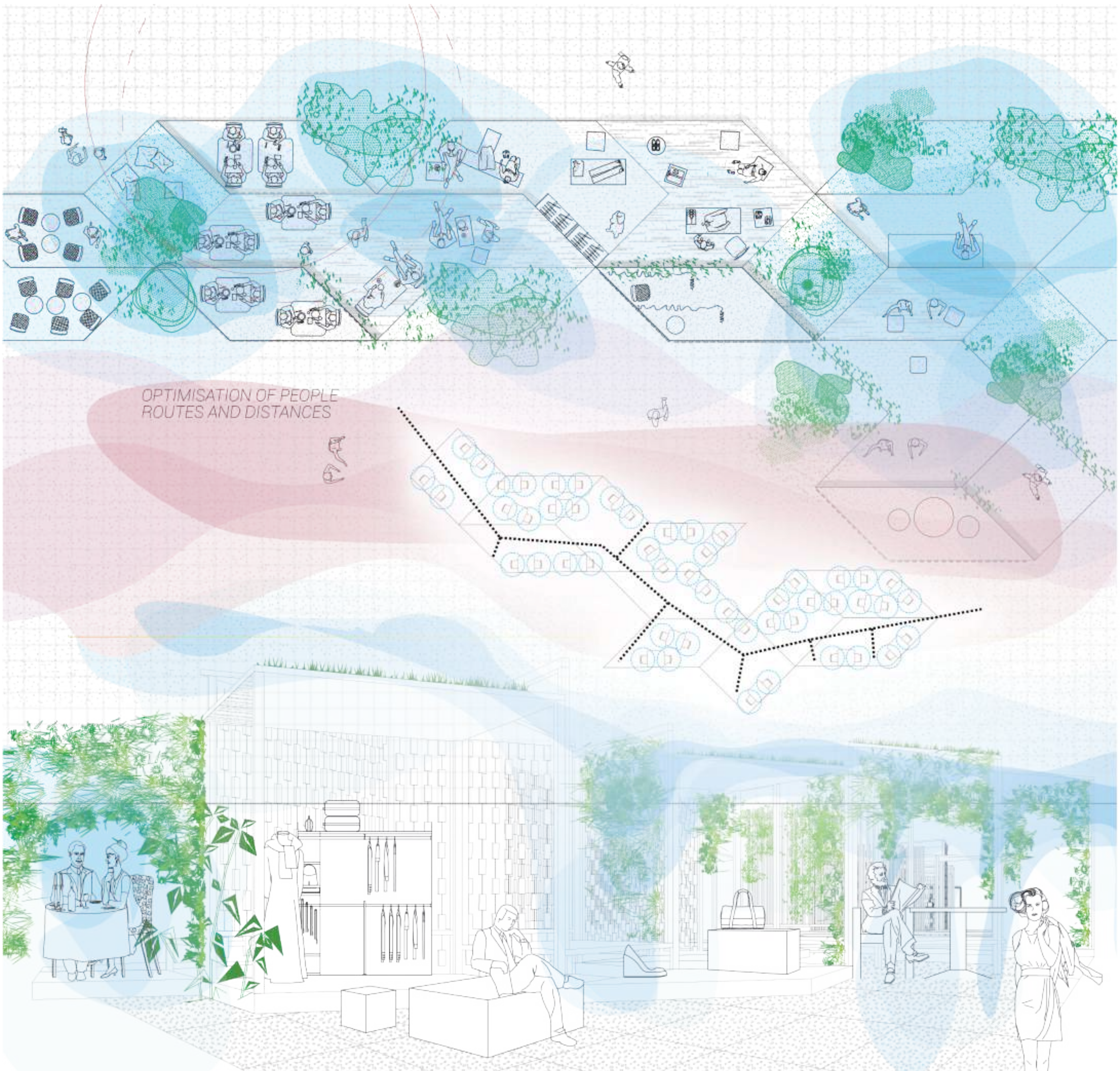
11.

AGGREGATION SYSTEM

ENVIRONMENTAL CONDITIONING

GREEN SUGGESTIONS

DETAIL



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H - ON THE CLIMATE CHANGE RESILIENCE OF FAÇADE 3D GEOMETRY

Key words: Building façade, 3d Geometry, Microclimate, Climate Change, Ladybug Tools

Abstract

Within the bounds of climate change, most of the urban surfaces need to be designed to cope with the changes. The design of building façades as a feature that balances the thermal effect of climate change is today an unstudied field. A few studies focus on façade material thermal properties influence of the localized microclimate, however, there are no publications dealing with the influence of façade 3D geometries on the local microclimate.

Considering the rapid expansion of 3D custom façade systems, that article created "by design" a number of geometric configurations based on architectural languages types and the observation of their thermal behaviour via the use of physical scaled models. The models are used to inform the creation of a full Ladybug Tools' simulation model, that is used for the assessment of outdoor comfort conditions in an urban canyon situated in Nicosia within today and 2080 climatic projections.

The paper assesses the climate mitigation potential of façade geometry. Furthermore, it discusses the specific resilience potential of each of the 3D geometrical patterns via comparative charts.

By creating a hierarchy of importance of geometrical interventions, the work offers information useful to foster the design of façades that curate localized climate control. The results, which focus on summer conditions, show that small variations of 3d façade geometry strongly affect the local indoor and outdoor comfort.

Introduction

Rapid industrialisation and population growth have contributed to the development of buildings and cities that generate climate change, globally and locally. Climate change affects average patterns, as well as the manifestation of extreme and more frequent weather events, such as localized heatwaves. This condition is exacerbated in urban areas where spaces are warmer than surrounding rural areas (Naboni and Havinga, 2019). Considering climate change, controlling microclimates is an increasingly pressing concern. Microclimates have a significant effect on both outdoor and indoor comfort, and on the energy efficiency of buildings.

This concern is particularly important as current climate conditions reveal that warmer summers are threatening the quality of microclimates.

Such heatwaves deteriorate the Outdoor comfort in cities especially those where buildings are significantly exposed to solar radiation which is absorbed and re reflected. In this context, a series of urban climatic surfaces, aimed at creating a proper microclimate were studied in the past. Most of these studies have focused on horizontal surfaces properties (streets and roofs). Scarce attention has been given to how vertical surfaces and façades and how they affect outdoor temperature ranges. Façades' materials are conceived to reduce energy demand and increase indoor thermal and visual comfort (Naboni et al., 2020), with no care of their thermal impact on the front-facing spaces (De Luca et al., 2020).

Since modernism, 3D façades the applied geometries are primarily based on visual criteria, and little attention is given on the relation between 3D macro geometries and environmental performance as means of inspiration since there is no clear indication or sufficient exploration on how complex geometries help to control and improve conditions outside the buildings. It is now relevant to discover the design of façades that act as outdoorclimatic mitigators. There have been a few pieces of research that focus on the influence of buildings envelopes on the outdoor.

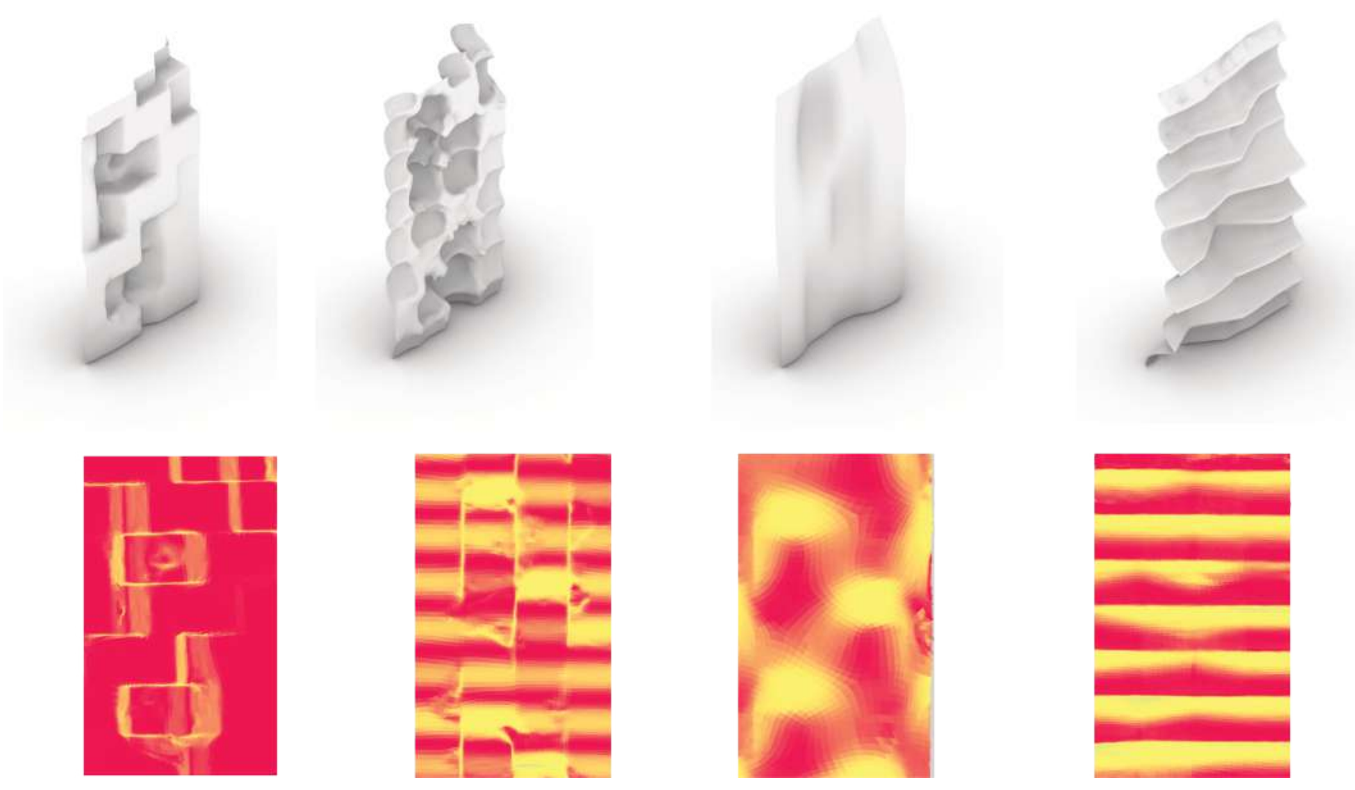
A few undertaken simulation studies showed that canyons temperatures and the related thermo-physiologically significant assessment indices are impacted among other factors, by the façade type. Lee and Mayer argue that the transferability of the findings of these studies from one to another urban site is nearly impossible due to their hyper-specificity, and the disparate different.

site characteristics. Such studies analyse the façade role in more complex settings where other variables are involved, hence conclusion on the role of façade as an outdoor climate giver is hard to extrapolate. Other façade research is oriented toward the development of retroreflective envelopes characterised by a surface conformation that reflects the solar radiation back in the same direction of the incident radiation. These solutions, which are proven to control local temperatures.

With these above-mentioned gaps in mind, an obvious research question arises: how can the design of buildings façade be rationalized in relation to the climatic and urban context they are built? In other words, is it possible to configure geometrically correct façades so that local climatic resilience is achieved?

The study presented here addresses this question by using a novel digital design process based on Ladybug Tools that couples indoor and outdoor thermal models (Sadeghipour Roudsari and Pak, 2013). After defining the framework and scope of the research, the paper outlines an approach that investigates the mutual relations between façade geometries and local microclimate in today and 2080 climatic scenarios. Analyses are performed on a number of architectural configurations derived by the discretization of 3d concrete models. The scope is to provide insight into the relation

Figure 1



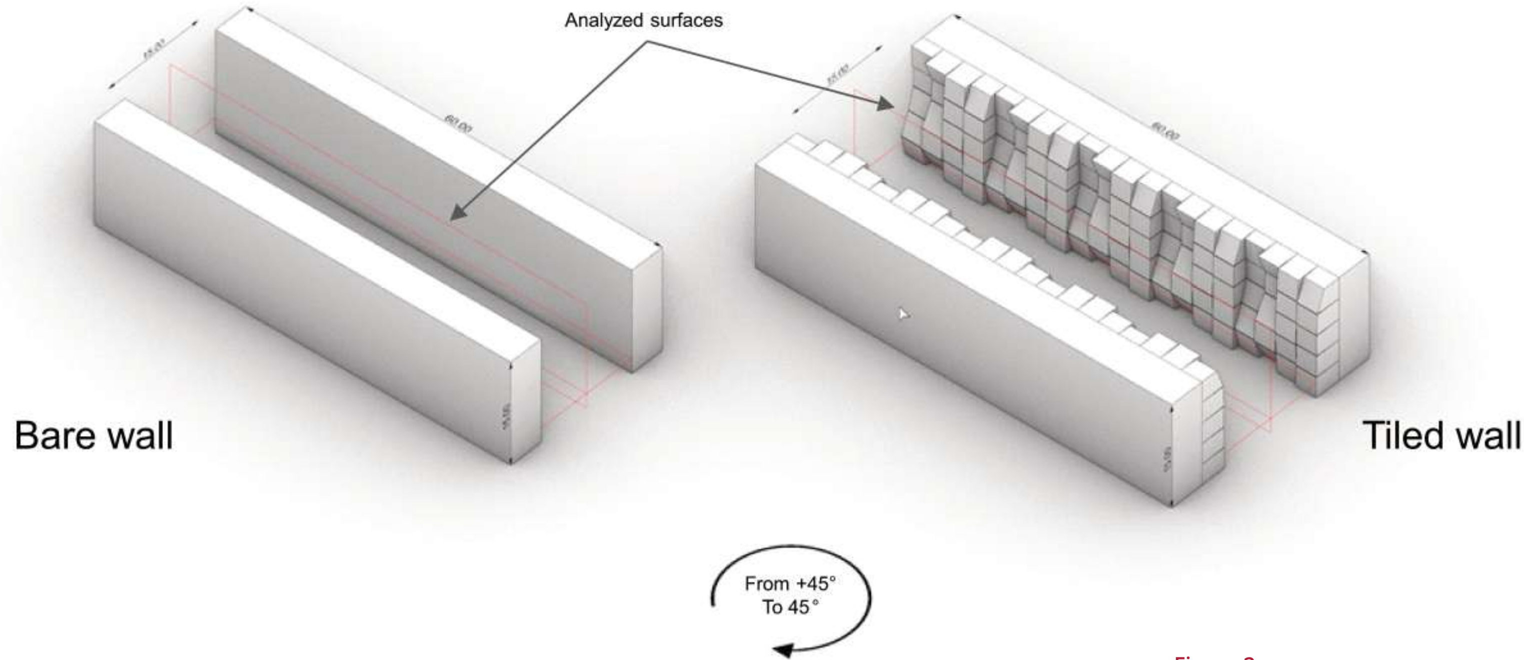


Figure 2

between façade geometry and microclimate and the need for designers to analyze and control this aspect during the early design phases when the most influential design choices are made. In addition, this study provides recommendations for optimal solutions for achieving resilience within the context of Nicosia, In Cyprus.

Aim

The aim is to test to what extents Digital fabrication allows us to generate non-ordinary shapes whose thermal behaviour can be customized to

Objective

Test basic geometry parameters influence of high and low sun angles performances.

Background

3D façades

Traditionally, façades were perceived to cope with aesthetic features, or in order to create a thermal barrier between the indoor and the outdoor, thus paying less attention to how their surface thermo-physical performances could affect the outdoor microclimate. Common sense and tacit knowledge have led to building surface finishes and 3d forms that were based on local technology. Each material was assembled and treated in a way that thermodynamically positively created tempered indoors.

Nowadays, non-conventional and complex 3D façades in macro-level are of increasing interest, with many examples referring to different types of geometries, which are represented, among others, as wave-like, bio-inspired and origami ones (Schultz and Katz, 2018). To some extent, their application serves environmental needs, for instance, daylight control, in buildings where façades are implemented through static and dynamic systems.Towards this direction, different materials were applied, ranging from a shape memory alloy to clay and cement-based ones, to name a few.

More specifically, examples of investigation on how building façade geometrical variations impact the local urban climate are little or non-existent. Thus, despite the rapid increase in the capabilities of technology and the advent of 3D modular units and building components' shape customization, the architectural scene have shown several 3D façades populating cities, there is no clear explanation on how such geometries relate to outdoor comfort.

Design of the Facade

3D façades in macro scale are based on their geometric control both locally, i.e. at the macro scale unit and in particular at the level of transformation, enabling their protrusion from a certain flat surface, and globally at the level of their overall control, as single or double-curved surfaces. The classification of the geometries of the 3D façades based on the above observation, allows a range of types of façades to come to the fore, although in a practical and feasible level, which is representative of many buildings today, these are distinguished in tho main architectural languages.

Wave - like. The second architectural language of 3D façades again follows single or double surface curvature in global level but with the more distinguished transformation of their unit elements, which at the local level have more intense projections than the flat state, but maintaining a rhythm of recesses and protrusions in a way that bears the characteristics of origami structures, for instance in the example of Argo Building in Colombia or the Beijing Greenland Centre in Beijing. This category of 3D façades shall be called “wave-like” façade.

Pixelated geometries. The third category refers to 3D façades, which in the global level are presented as a curve or flat ones with strong differences in the protrusion of the units that constitute them. Examples of such buildings are The Street in India and the Unicato Residential building in Poland. Due to the strong differences in regard to the protrusion of their façade elements shall be called ‘pixelated’ façade.

The curve-like, the wave-like and pixelated geometries, despite their complexity, are today accessible via the rapid diffusion of computational design and digital fabrication, which are opening the possibility of their design development and then their construction in actual and macro scale. Although such techniques have not been applied to the examples demonstrated herein, the construction and control of custom 3D façade units using emerging technologies, provide the opportunity for more direct control of their performance in order to respond to the local environmental conditions and users’ needs. In particular, the construction of 3D façade units in macro scale, due to their increased complexity compared to conventional designs, requires the introduction of new techniques and materials, opening the opportunity for overcoming the difficulties arising during the construction of one-of-solutions. Also, it allows affordable and economically effective production techniques of complex shapes to come to the fore compared to conventional construction approaches applied in the case of mass customization of 3D façade components.

Towards this direction, a number of computer numerical control (CNC) and robotic fabrication techniques have been applied in the physical production of 3D façade systems, debating at the same time the effectiveness of this application. In the early example by Bock (2008), the digital design and prefabrication of pre-cast 3D façade elements were demonstrated, debating the advantages of robotic technology in the construction of highly customized façades at affordable construction costs, constant quality and ergonomic working conditions (Bock, 2008). Nowadays, several examples of 3D façade construction in macro scale can be found in practical and research direction, using automation and robotic techniques that include techniques for 3D printing, moulding but also forming 3D components in large scale. In parallel, methods for façade installation and assembly, but also off-site automated prefabrication and on-site application of such systems are discussed in several studies.

Their potential to provide solutions that minimize time-consuming and costly approaches (Chen et al, 2019), in particular using widely used materials like concrete, with the aim of overcoming difficulties arising in construction industry towards digitization of processes and products have been also discussed. Leveraging the potential of mass customization for the production of concrete building components, modular units and digitally fabricated 3D façades in macro scale can thus be made for given locations and the specificity of the site in order to contribute to control the microclimatic conditions of outdoor spaces.

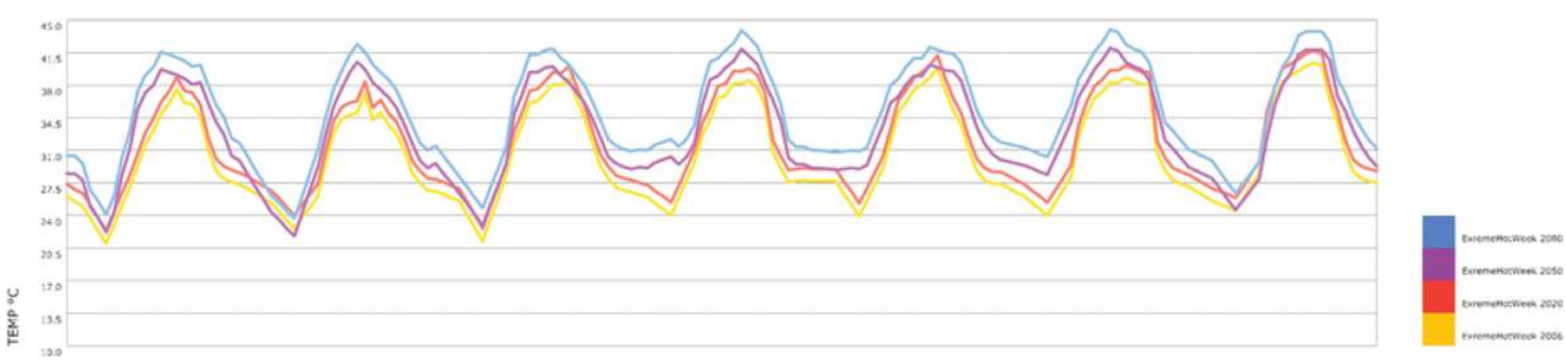
What seems to be an topic with high currency is to link todays capabilities in the making of 3d façades to outdoor microclimatic control.

Previous Studies of Facade Geometry and Climate

In summer, solar absorption by urban surfaces is the dominant cause of the UHI effect. The efforts to mitigate the formation of heat in urban canyons should be from one side based on controlling the absorption and emissivity of solar radiation. On the other side, it should be based on thermal reflection. Until now research has been discussing heat mitigation solely focusing on “cool” materials—those with high solar reflectance and high infrared emittance applied to building envelopes (roofs and walls) and urban structures (roads, squares and footpaths).

Highly reflective materials are usually used to decrease solar radiation absorbed by horizontal urban. However, the use of cool materials on building façades is shown to be less

Figure 3



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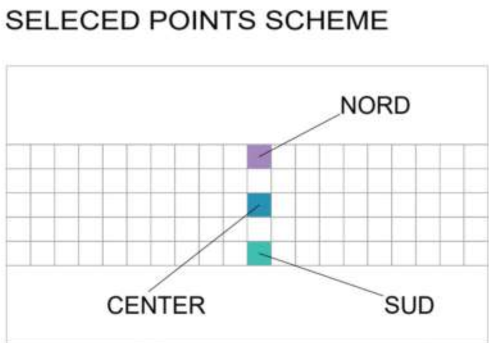


Figure 4

effective

than in roofs because of the multiple reflections between the walls, and the ground implies a

consequent entrapment of the solar radiation in urban canyons.

However, the 3D geometry of buildings' façades should affect the amount of shortwave radiation absorbed by the buildings. Furthermore, shortwave radiation is reflected or even multi-reflected when buildings face each others like in canyon. Longwave solar radiation is also a primary type of local thermal exchange in such urban contexts. Here, façade emissivity becomes a significant parameter influencing the local microclimate (Doya et al., 2012; Han et al., 2015) These causes assign a primary role to tall building façades, and their influence varies according to solar angles and the geometry of façade. Therefore, it is logical to conclude that small design variations of façade can substantially impact the local thermodynamic exchanges. Clarifying the link between emissivity, reflectivity and the impact on radiant temperature as a function of building façade geometry is therefore considered of primary importance to grant a favourable outdoor microclimate.

The hypothesis to be verified is that the geometrical variation of tiles' surfaces could lead to self shade, which is one means of controlling their temperatures. Furthermore, by orienting surface directions a second interesting hypothesis to be verified is that these surfaces can selectively exchange short and longwave radiations withe the body of pedestrians as well as with the sky. Overall, such characteristics, if varied can lead to the main hypothesis to be verified that assume that façades' surfaces can be efficient in controlling summer heatwaves and can overall contribute to temperate winters by geometrical means of their tile surfaces. In short, façade can become a resilience factor.

Background on simulation

Due to the complexity of outdoor environments, in terms of both geometry and materials, the

calculation of Tmrt needs to rely on simulation tools that simulate the 3-dimensional radiation field.

Some modelling tools try to solve such complexity: CitySim-Pro, ENVI-met, RayMan, Ladybug

Tools, but, when the thermal effect of façade details, and precise building operations are

involved, Ladybug Tools is found to be more suitable. Ladybug Tools workflows allow the

thermal coupling of outdoor and buildings. The workflow supports the understanding of the

thermal influence of the outdoor space toward the interior, and vice-versa, via the combination of

engines invoked by Ladybug Tools.

The digital workflow proposed in this paper is designed to leverage the synergies and interdependencies between the different evaluations. The modelling approach brings together many disciplines and works on multiple spatial and temporal scales. It is implemented in the Grasshopper environment in Rhino. The individual pieces discussed are: generation of future and urban weather files, calculation of MRT, calculation of building and streets thermal behaviours and sky view factors.

In the workflow for the simulation of Tmrt, the first step is the computation of long-wave radiation

based on surface temperatures through the EnergyPlus simulation engine. Then, view factors of every

surface are calculated with the ray-tracing capabilities of the Rhino 3D modelling engine . The

workflow tracks all of the thermal flows involved [44] and preliminary validation of the workflow

were performed with measurements conducted infield; however, these studies cover only three hours

of validation and one specific. Further validation of the workflow that covers a full day in

two seasons is thus necessary and therefore, is performed within the boundaries of this study.

A recent set of studies compare on-site measurements to simulations conducted using Ladybug Tools, showing a good agreement between the real and simulated measurements

(Evola et al., 2020; Naboni et al., 2020). These studies represent methodological development as comfort and building energy modelling tools are generally disconnected. Such studies also highlight large applicability of the workflow with a minor issue for the accounting of the shortwave radiation reflected off vertical surfaces (Naboni et al., 2019a). This was accounted for in the used scripts by adjusting the input of diffuse solar radiation to the Solar-Adjusted temperature component.

Methodology

Research by design

The verification of the hypothesis implies the development of concrete 3D façade finishes samples and the observation of their thermal behaviours in laboratory settings under different angles of emitting thermal radiation so as to reproduce summer and winter sun position. This research will thus offer an understanding of the magnitude of the climate mitigation potential offered by a set of surfaces with particular 3D façade geometries based on the architectural languages presented.

Climate analysis and climate forecast

Before proceeding to the simulations have been assessed starting weather data such as dry bulb temperature, relative humidity, dew point and, finally, have been calculated the values of comfort UTCI considering the combinations sunny-shaded and windy-sheltered. Based on these data will be made forecasts to 2080, where it is expected to be changed the values of temperature, humidity and solar radiation. Based on this prognosis, simulations will be done subsequently.

Simulative apsproach

Tests are made in urban canyons where complex surfaces will be compared to a perfectly smooth surface. "Virtual sensors" will be placed inside the canyon (closed to ground) to calculate MRT values. It will also be evaluated the surface temperature of the ground and walls.

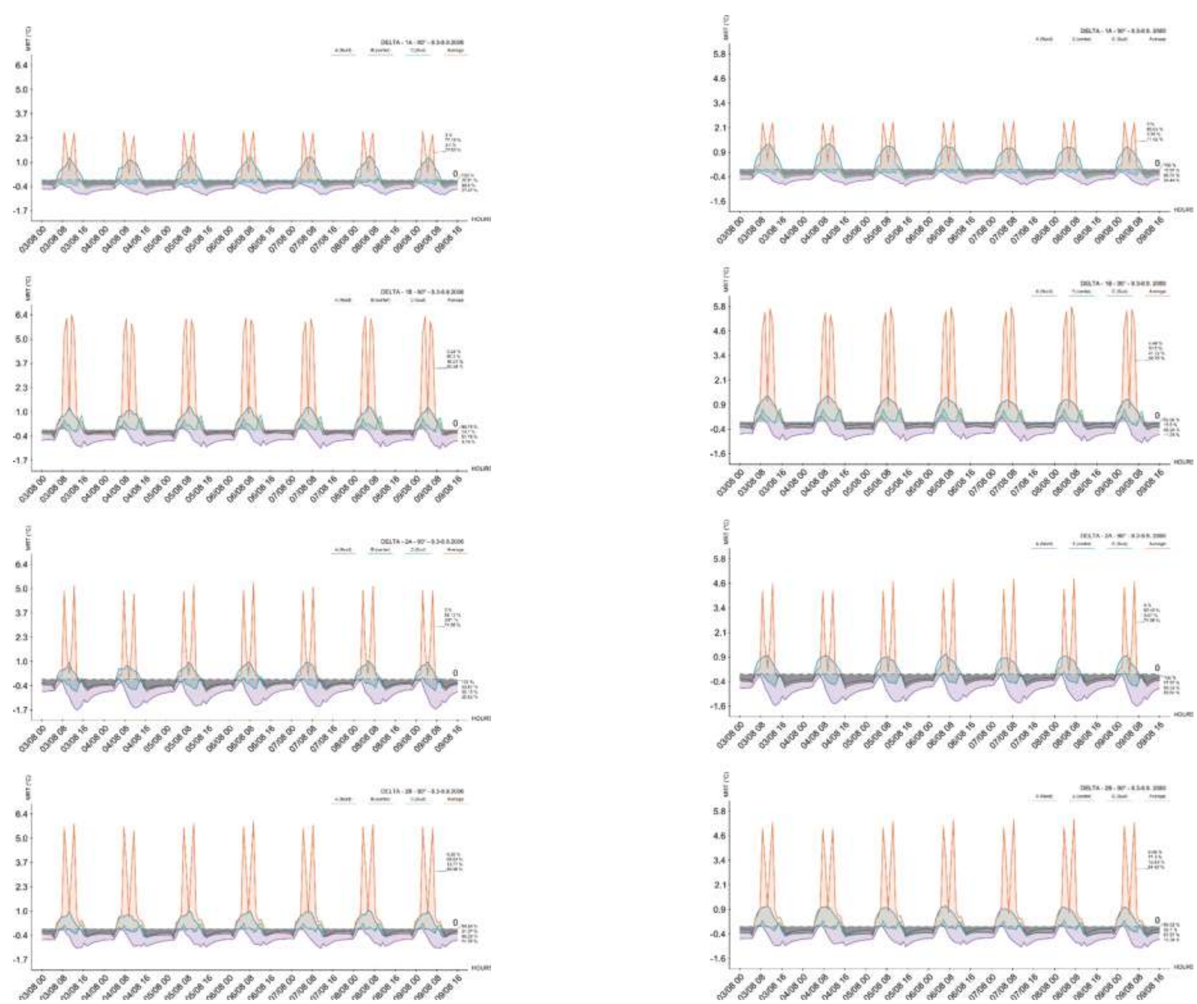


Figure 5

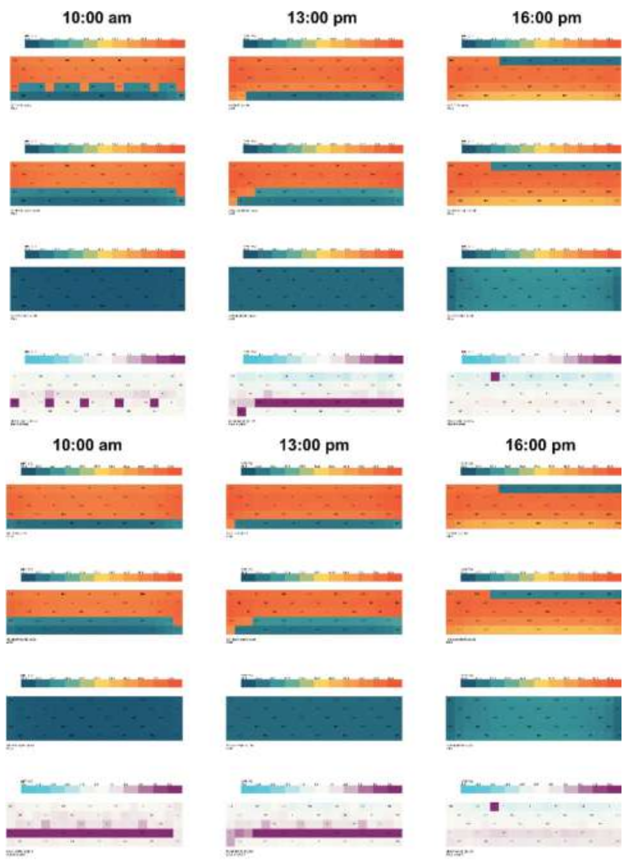


Figure 6

Methods

Study the behaviour of typically fabricated surfaces.
A fundamental process to make the complexity of geometries interpretable to the computer requires applying a strategy to rationalize the shapes. Each surface was subdivided into a uniform grid from which tapered extrusions were generated. The amount of tapering was varied to describe each type of surface. The algorithm was set up to generate only planar quadrangular surfaces. Flatness and volume closure are essential to ensure a successful simulation with the EnergyPlus software. Each of these volumes is a thermal zone that is next to the rear adiabatic space.

3d Canyon simulation
The geometric model that served as a base for the full set of algorithms was created in Rhinoceros 7, a commercial NURBS 3D software. The Ladybug script referenced in the background is compiled by running the EnergyPlus simulations of the building facing the canyon via the Honeybee components. The outputs of the simulations include the surface temperatures, and account for the value of reflectance and emissivity that are assigned to the façade model. The ground of the canyon is modelled as a “"ground thermal zone '' consisting of a volume with null internal gains and delimited by soil. The upper surface facing the sky is defined according to the ground reflectance and emittance. Each of the surface belonging to the canyon’s canyon's temperatures can be calculated for each of the simulation time steps and as a function of building operations, the shadows cast and the heat storage of the ground surface ***Fig. 2***.

Following a point in the centre of the canyon is placed at 1.5 m above the ground ***Fig. 4***. Here, the component calculates the view factors with every surface of the canyon through a ray-tracing approach. The output of this component is used by the Outdoor- ComfRecipe component, which also receives information about the outdoor surface temperatures previously calculated by EnergyPlus in order to generate an output called comfRecipe. The latter is a matrix containing all the essential variables for defining Tmrt, such as air temperature, wind speed, relative humidity, view factors, scattered solar radiation, direct solar radiation and horizontal global radiation.

Climate Change Scenario

Climate will significantly change in the city of Nicosia (Cyprus) with significantly hotter summer. The chart shows variations of dry bulb temperature in 2080 (modelled according to the IPCC scenario A2), which are compared to recorded data in a locally built weather station. The first chart displays a monthly analysis of the second focus on temperature recorded along a typical summer week ***Fig. 3***.

To project the data into the future, it was used the CCWorldWeatherGen which takes into account the IPCC projection data.The tool reconstructs the EPW dataset according to the scenario A2 from IPCC projection data.

The following microclimatic simulations, by comparing today and future climatic scenarios physical variables analysis allow for understanding what type of 3D measures are effective to achieve a local resilience to climate change, granting a correct local microclimate, outdoor comfort and reducing buildings cooling loads.

The analysis is not taking into account anthropogenic heat that may come from dense traffic, as well as it does not take into account for summer cooling systems heat that is released to the site.

USE OF MEAN RADIANT TEMPERATURE AS A COMPARISON METRIC

Radiant heat can play a significant role in achieving thermal comfort, promoting a healthier home environment and lowering economic heating costs. This value indicates how much energy is directed to evaluated points. It follows that the higher the value of MRT more likely there will be a discomfort zone. It was preferred to assess the mean radiant temperature instead of comfort indexes because the experiment does not consider a real canyon but only a test case. The mean radiant temperature is also helpful to exclude random components of comfort assessment such as wind and person-related factors that add bias to the result.

Results

The diagrams ***Fig. 5 and 6*** show the deltas comparison between the mean radiant temperature produced by the complex façades and the planar one. It is shown that the surfaces do not all have the same performance. The results are shown in the north (A), centre (B), south(C) ***Fig. 4***, and the average value calculated over the whole area. MRT gain and loss alternates between the hottest and coldest hours. The best performance is usually achieved at north point (A), where, in case 2A, MRT reaches 1.7 °C in 2006 and 1.6 °C in 2080. Calculating the average of the MRT over the entire surface, it is possible to see spikes of gains of more than 5° C in the hottest hours because the outer parts of the canyon (never shaded) are considered. Calculating MRT in three single points, this phenomenon is attenuated, and the result's reading is understandable.

The top-down view of the canyon shows how, as the geometry at the façade changes, the distribution of MRT varies ***Fig. 6***. The shape of the façades can attenuate or accentuate the ground-directed energy. The top-down view of the canyon shows how, as the geometry at the façade changes, the distribution of MRT varies. The shape of the façades can attenuate or accentuate the ground-directed energy. In some concentrated zones, there can be an MRT gain of about 30° C and distributed losses of about 1° C for the studied configurations.

In addition to the ability to project solar energy onto the ground, as the façade's geometry varies, the ability to store energy also varies. The study of surface temperatures shows that a complex façade is cooler than a planar one losing about 1° C.

Geometry as a medium for climate control

Here is how at tile level, geometry can affect thermal exchanges in a canyon

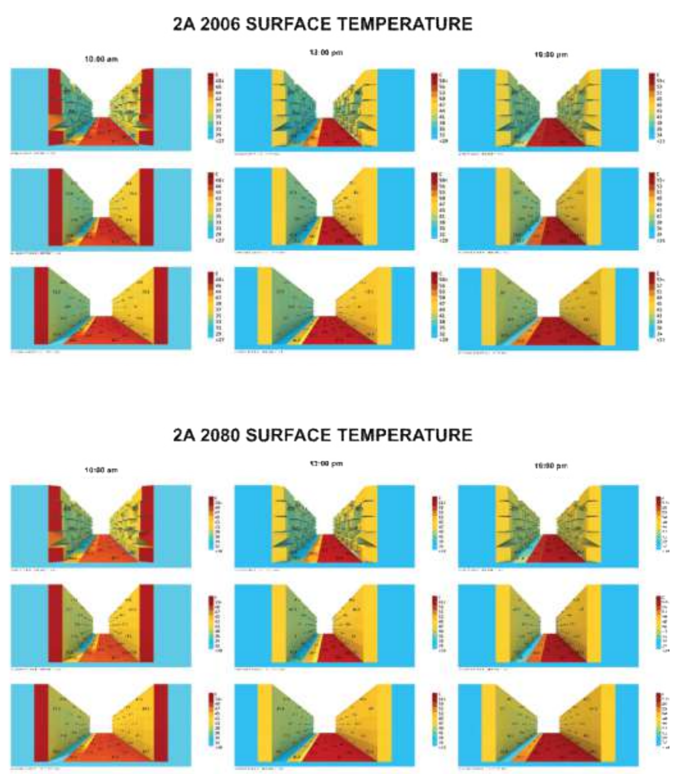
• Avoid short radiation. The primary summer daytime energy input into the urban canopy layer (UCL) is solar radiation, which is reflected or absorbed by vertical surfaces such as building façades. A reduction in the surface's surface temperature, which can thus be achieved by surfaces' self shade, this is per se a topic that should be investigated.

• Reflect short Radiation toward the sky. The second characteristic of surfaces is their reflectance. Reflectance is based on the geometry of the tiles, that if well study according to solar angles of incidence allows to reflect the radiation back to the sky avoiding that is reflected toward other surfaces or people standing in canyons

• Avoid reflecting solar radiation on new surfaces and people.

• Limit the view factors of tiles surfaces, specifically limit the view factor of the warmer surfaces within a tile. Via long-wave radiative transfer, hotter surfaces emit infrared radiation to cooler objects within view. And this can be geometrically avoided.

Figure 7



Conclusions

As discussed in the background, the most pursued line of investigation for mitigating UHI and climate

change focus on the optimisation of horizontal surfaces thermal properties. In

in contrast, limited attention is given to the study of the mitigation potential of façades, and no attention is given to the climatic resilience of façade geometry. The work thus fills a gap in knowledge by comparing the relative importance of façade geometry, on the localised mean radiant temperature in the climatic zone of Nicosa, Cyprus.

The study was conducted according to a novel Ladybug Tools workflow which was validated under

Previous works. The thermal model is based on a parametric urban canyon, which fully

couples indoor and outdoor thermal environments. A first outcome is that depending on the façade 3d geometry the localized Mean Radiant Temperature varies significantly.

The shape of the façade can control the amount of radiation hitting the ground. There can be an MRT gain of about 30° C (in small areas) and distributed losses of about 1° C for the cases studied. At the same time, the energy storage capacity of the façade varies. The study of surface temperatures shows that a complex façade is cooler than a planar one and loses about 1° C.

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