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The development of habitable urban skyways: claiming interstitial territories through evolutionary processes

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Abstract

Urban skyways, in which an elevated pedestrian-friendly layer of the city is applied to the existing urban fabric, have evolved from radical conceptual proposals in the mid-twentieth century, such as the continuous monument by SuperStudio, to increasingly realised proposals over the last 30 years, such as the highline project in Manhattan. Developed as either networks that respond to harsh climatic conditions, or solutions that aim to reclaim part of the city for pedestrian use, their use has been additive rather than integrative, in most cases culminating in elevated walkways. This article proposes an alternative approach to the utilisation of urban skyways within existing cities, in which the question of habitation is a primary driver. The research involved the application of sequential evolutionary simulations, to locations in the city of Paris, as an algorithmic approach to achieve multiple conflicting objectives. The results demonstrate the value of urban skyways as habitable spaces that respond to the city as well as being informed by it, in which issues of overpopulation, lack of public space, climatic response and urban farmlands—all of which impact most megacities today—shape the urban decision-making process.

Keywords Habitable skyways, Evolutionary computation, Interstitial territory, Paris, Sequential evolutionary simulations

Introduction

A revolution in city planning occurred in the late 19th and early twentieth centuries, prompted by the development of automobiles, shifting the focus of planning processes to vehicular networks (Flonneau 2006). This influenced the modernist top–down approach to city planning, altering pre-existing cities substantially and having a marked effect on new cities (Weinstock 2013). The top–down approach lacked contextualisation to existing site conditions, instead catering to the automobile and affordances for long-distance travel (Hall 2014). This resulted in Utopian visions of urban centres (such as the 'Radiant City' proposed by Corbusier, or Futurama, proposed by Norman Geddes and funded by General Motors) that created cities that developed in response to the automobile, at times through multiple layers of vehicular networks at a scale so large that the pedestrian's experience of the city became obsolete. As urban populations continued to grow, so did city limits, creating large swathes of urban sprawl. In historic or heritage areas, where the impact of the industrial revolution on urban form is most prevalent (Bayrak 2020), populations continued to grow, but cities could no longer sustain the horizontal growth of the urban fabric due to geographic limitations, driving them to their critical threshold of stability (Weinstock 2010).

Limitations of physical space generated an increase in the integration of skyways within the urban fabric throughout the late twentieth century. Skyways involve the introduction of an elevated pedestrian layer to the

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urban form to reduce the impact of the pre-existing and largely dominating vehicular layer on the city's inhabitants. Their use has been observed at two scales: large-scale repurposing of decaying infrastructure, and smaller-scale bridge morphologies that act as connection paths between buildings (Huang and Levinson 2013). The former usage tends to be a singular system that stretches over multiple blocks in a single urban instance, and is often utilised as public space (Millington 2015), such as the long pedestrianised skywalks located in Hong Kong, Japan and New York. The latter is generally based in specific extreme climates to create greater accessibility within the pedestrian network, such as the ones located in various cities throughout Canada (Corbett et al. 2009).

This article examines the use of skyways as an urban solution to population stresses on existing cities, one that addresses both public space and built form. It investigates current and historical uses of skyways and presents a comparative and critical study of their applications in different locales. Its focus is a case study of a typical superblock in the city of Paris; a multi-objective evolutionary algorithm (MOEA) was utilised as a generative tool to address the urban challenges faced by cities experiencing population growth and lack of physical space. The results are presented in the context of the use of urban skyways as an integral component of urban growth in existing cities.

Skyways: their past and continued use

Skyways—transportation or habitation?

The industrial revolution of the eighteenth and nineteenth centuries, followed by the technological advancements of the twentieth century, triggered a reorganisation of urban form. The introduction of automobiles, and its impact on individual long-distance travel, induced radical modifications to urban tissues' spatial organisation, greatly increasing the significance for variation in the spatial distribution of urban components and their morphological configurations. Academic interest in the manipulation of morphological characteristics of urban tissues and their efficiency in occupying space gained momentum towards the end of the nineteenth century (Batty and Longley 1994). A conflict between two objectives—centralised activity nodes and lateral growth—began to be observed. Whereas the ideal for the former is compactness (centralisation), the latter promotes dispersal (decentralisation) (Batty 2013).

The demands of growing urban populations, especially in cities with geographic limitations, naturally lead to verticality and subsequently increased density. However, this verticality is mostly manifested at the scale of single isolated buildings and has produced dense urban tissues consisting of two-dimensional arrays of tall buildings with minimum regard to the city's flow, which continues to expand laterally at ground level. This propagates architectural programs dependent on the circulatory system of urban tissues at the ground level, while single isolated buildings continue to rise and grow vertically (Makki et al. 2019). The contemporary urge to pursue dense liveable and compact urban environments (Parker and Wood 2013; Sarkisian 2016) can be traced back to Harvey Wiley Corbett's multi-layered cities. His proposal was a response to the isolated growth of high-rise buildings of the industrial revolution by envisioning multi-level streets and mixed-use skyscrapers (Corbett et al. 2009; Goodman 2008). It highlighted the significance of including public and service areas in the vertical growth of urban tissues. Elevated networks of connections could be the critical urban typologies that enable homogeneous growth of urban tissues in a multi-dimensional manner.

There is a trend of change in the patterns of settlements across metropolitan areas from dispersed tissues to centralised nodes of activities (Kern 2007), most of which lack elevated networks of connections and spaces. However, there are instances of successful implementations of such spaces in modern urban tissues across the globe. Cities like Hong Kong, Minneapolis and Calgary have obtained such urban typologies in their contexts for various reasons. Traffic congestion, vehicle and noise pollution in Hong Kong, and extreme climatic conditions in Minneapolis and Calgary, are the reasons why elevated networks of connections have been implemented within their urban tissues. In addition to the environmental and ecological benefits, such connections allow for improved circulatory networks, reduced energy consumption and improved operation of the city as a whole. The term "skyway" refers to the typology of these connections at upper levels of built environments within the urban block; their emergence allows the spaces required for these circulatory systems to evolve at higher levels across the urban fabric, eventually leading to the formation of multi-level networks of connections across the city. As a result, spatial configurations that emerge across connection nodes can be utilised as habitable spaces throughout the elevation of the urban context; the combination of newly emerged urban typologies and the current street-level networks forms a unified three-dimensional network of connections and habitable spaces. Societal changes of the current century pertaining to changes in consumption demands, changes to modes of interaction, and advancements in technological development, necessitate the emergence of such spatial qualities, facilitating urban adaptation to climatic and environmental stresses.

Skyways: influences and existing typologies

The 'inhabited bridge' is an urban typology that has emerged before the evolution of the automobile, where habitation and transportation of people and goods went hand in hand, utilising the bridge (primarily over water) as a dual-purpose typology within a city. Since the adoption of the automobile in the early twentieth century, the cohabitation of bridges has been replaced with the single function of transportation, primarily vehicular (Murray and Stevens 1996). Proposals for bridge cohabitation emerged once more in the mid twentieth century, however rather than the cohabitation of bridges over water, the bridge, or what has become known as the 'urban skyway', was proposed as an urban intervention within the city, primarily one that aimed to respond to the growing demands and changing dynamics of the urban fabric. Although some are more radical than others, it is evident that there has been an increase in the use of urban skyways as an urban typology in the twenty-first century. Examples such as Seoul's Plant Village, Paris's Promenade Plantée, and Minneapolis and Saint Paul's enclosed skyway have successfully responded to climate and refurbishment. More radical approaches to skyway systems, promote the skyway system as an entire city solution, not a singular typology amongst a city's landscape. To explore these alternative facets of skyway development, two contrasting skyway proposals are examined: Superstudio's Continuous Monument and Diller Scofidio + Renfro's High Line. Whereas the former seeks to dominate the landscape through a radical dystopian vision, the latter is a realistic adoption of a skyway that integrates itself within its context, responding to (and limited by) the site's conditions.

Continuous Monument—an historic exemplar

A historic and prominent example of skyway development, due to its radical expression and exaggeration of form, is the mid-twentieth century architectural group Superstudio's Continuous Monument. The project proposed a series of interconnected megastructures that span the globe, replacing the need for multiple cities with one "supercity". The project itself being a series of renders, Superstudio used it as an ironic critique of where they believed the urban fabric to be headed, a large morphology distinctly separate from its surroundings (Budzynski 2011). The drawings themselves—despite often being taken out of context—have inspired many modernist architects, including Rem Koolhaas, who said, "I loved Superstudio because I took the work literally, I thought some of it would be stunning if built" (Chiaponne-Pirou 2021, p. 89). Adolfo Natalini (a Superstudio founder) replied, "Naturally there were those who could not see beyond the metaphors and treated everything as yet another utopian proposition … Too bad for them" (Elfline 2011).

Irrespective of the misinterpretation of Superstudio's work, the form of Continuous Monument is often thought of as a modernist triumph (hence Koolhaas's comments), and thus it has been the inspiration for many elevated elements of existing cities as a radical interpretation and response to the over densification of cities, allowing for a highly theoretical proposal serve as the basis for real-world skyway interventions in densely populated cities. Whilst the skyway is an element that is not uniformly applicable to all cities, it accelerates urban ideologies so that the existing context is on a parallel course to the skyway, not an intersecting one.

The complications of building a system as large as Continuous Monument, regardless of its integration into the surrounding context, are what limits it to the realm of theory. Skyways that have been constructed due to their necessity for a particular environment, often as enclosed spaces (Minneapolis and Saint Paul's skyway systems), occur at very small scale, limiting their impact as a singular unit. A larger-scale single typology, although not on the scale of Continuous Monument, is the New York High Line, which has a wider range of functions and more connections to multiple blocks.

New York High Line—a contemporary exemplar

The High Line is one of the most studied skyway projects of the last decade, and is often depicted as a tool of urban revitalisation through creation of public amenities, tourism, and preservation of nature in the urban environment (Kao 2014). It has two primary functions: as a pedestrian network, and as a public space (with small-scale "parkland") that allows temporary forms of occupancy.

Although starting as a local initiative, the High Line was designed with a top–down approach, and whilst being a public space, the community was not engaged in the design process, with most of the skyway's functions designed by a single studio. This resulted in few access points from street level, lack of physical connection to the surrounding buildings, housing and supporting activities on the same level, and underutilised spaces beneath (Littke et al. 2016). Similar to the Continuous Monument, its modest connection to street level minimises its integration with the urban environment.

Regardless of its shortfalls, the High Line is considered successful in its preservation of culturally significant structures and has generated more interest in the typology of skyways. Since the High Line's introduction, many cities around the world have introduced similar concepts (Littke et al. 2016) on unused elevated infrastructure (often transportation networks, including railways and highways). However, similar connection issues exist, since most transportation infrastructure is quite isolated in order to encourage movement, intersecting with other structures occasionally within a certain radius. Further design and coordination with the surrounding community is needed to create more meaningful connections.

As Superstudio proposed (somewhat vaguely), the skyway typology can provide long-term habitation on or under it, making it efficient in utilising limiting resources and solving many spatial and environmental issues associated with cities. By assessing both exemplar precedents and utilising the positive impacts of them in tandem, we can start to individually assess cities that could build a habitable skyway system, often based around areas that could benefit from a vertical habitable space interlinked to a pedestrian network. Moreover, the Manhattan Highline's successful integration of 'parkland', or green spaces, as a key component to integrate greenery within a densely built urban fabric has been utilised as a driver for the presented case study to utilise a urban skyway for the habitation, transportation, and food cultivation by means of allocating urban farm lands within the proposed bridge typology.

Taking into account the limitations of the High Line and the influence of the Continuous Monument, in this article we focus on the conception of a new type of skyway, one that blends the positive aspects of the two, with a key focus on habitation. The proposed skyway can be introduced into many cities as population density continues to rise, but for the purpose of this experiment, we focus on Paris, France. Paris's low and consistent skyline allow it to adopt a new system such as the skyway while maintaining the core relationships of the city, as detailed below.

Paris

As an urban formation, Paris is like many other European cities. It has high population density (National Institute of Statistics and Economic Studies, 2021), a huge tourism industry based around a large heritage network, and limits on further urban sprawl that challenge population growth. Former Mayor of Paris, Bertrand Delanoë, argued for the city's vertical expansion to house a growing population (Davies 2008). Whilst the concept proposed here involves a rising Paris skyline, it champions the integration of different programs into a skyway system, with habitable space the chief focus.

Champs-Élysées superblock

The superblock examined is located directly south-east of the Arc de Triomphe along the Champs-Élysées. The superblock is bisected by the Champs-Élysées and further bounded by two main roads and five minor roads, consisting of 16 individual blocks and housing 194 buildings. The superblock's building planning remains consistent with the general urban characteristics and building morphologies of Paris as whole (due to Haussmann's planning) and is largely unaffected by the dividing Champs-Élysées. These characteristics include private courtyards, including those located near government-oriented buildings; a mixed-use sector focused on retail and accommodation due to its location along a historic boulevard and near major tourist attractions; narrow streets with one-way traffic; a central connection to the metropolitan train system; and a height limit of six storeys.

The issue of population density is not as pressing in this superblock as elsewhere in Paris because it is located in the 8th arrondissement, which has a heavy concentration of tourism and retail functions due to its proximity to the Louvre and the Arc de Triomphe (Fig. 1). This helped in choosing it as a site of design exploration, due to there being a need for further habitable space around the retail and hospitality infrastructure of the area; the city's population continues to expand, but no further population growth is possible in its most congested arrondissements.

Multiple urban initiatives and conditions were factored into the experiment based on the existing urban characteristics that influence the day-to-day function of the 8th arrondissement. These urban conditions include the height of the buildings, solar access to the courtyards, and a series of urban factors along the skyway system, including public park space, communal garden spaces, habitable spaces and a pedestrian network.

Experiment setup

The experiment was conducted in two stages, evaluating the skyway at two scales. In the first stage we investigated the relationship between the skyway and the superblock at the macro scale, focusing on its integration amongst the ground networks and buildings. In this first stage, the morphology of the selected Parisian superblock was revisited, allowing for critical reflection on the integration of skyways as a core urban typology at the onset of urban development rather than an additive typology to an existing urban tissue. In the second stage we explored the programmatic potential of the network, considering skyway habitation, urban farms (an initiative with some currency in Paris (Lelièvre and Clerino 2018)) and public space, and focusing on integration between these functions as well as with the underlying urban fabric. The experiment was performed using the NSGA-2 MOEA (Deb et al. 2000) in Wallacei software (Makki et al. 2018), a Grasshopper 3D plugin within the Rhino 3D environment. The success of the evolutionary simulation was contingent on the efficiency of the parametric

Fig. 1 Selected Parisian superblock, forming the base phenotype for the experiments

relationship between the genes, the morphology, and the fitness functions, thus the sequential simulation operated within a loop, constantly being updated according to reanalysis of the phenotypic outputs, creating more efficient and optimised solutions. The sequential process built on recent research that aimed to utilise MOEAs as a generative design approach for complex problems without necessitating abstraction or simplification (Randall et al. 2020). The following sections present the fitness functions, alongside the primitive phenotype's construction, for each simulation independently, highlighting the impact of the first simulation's output on the algorithmic setup of the second.

Simulation 1

Primitive phenotype construction

The primitive phenotype has seven chromosomes (in the presented study, chromosome refers to a collection of genes with similar functionality), totalling approximately 60,000 unique values. The algorithm iteratively modifies each of these values, at every iteration evaluating the evolved phenotype's performance with respect to the established fitness functions (presented below). The phenotype's construction was initiated by outlining the two halves of the superblock (to either side of the Champs-Élysées) (Fig. 2.1), generating points along these boundary outlines (Fig. 2.2) and connecting these across each half to generate street networks (Fig. 2.3). Streets originating from the same edge were set a minimum of 50 m apart (with no maximum set). If two streets intersected one another at an angle of less than 20 degrees, resulting in undesirably sharp corners, one was isolated and set to become a path for the skyway network.

Single courtyards were created at the centre of each block of buildings to improve solar access and ventilation, whilst also generating ground plane public space (Fig. 2.4). Buildings were created with various widths, depths and heights (within the constraints of the existing urban fabric) to provide morphological variation and allow for greater integration with the skyway (Fig. 2.5, 6).

The proposed elevated skyway network is a single level, passing over and adjacent to the roofs of buildings across the block. Buildings with roof portions lying under it had their heights limited to the skyway level, and those with portions under it (regardless of size) likewise, with the roofs leveraged as further skyway operable space. These buildings that attached to the skyway were suitable for the retail and hospitality industries prevalent in the arrondissement (Fig. 2.7, 8).

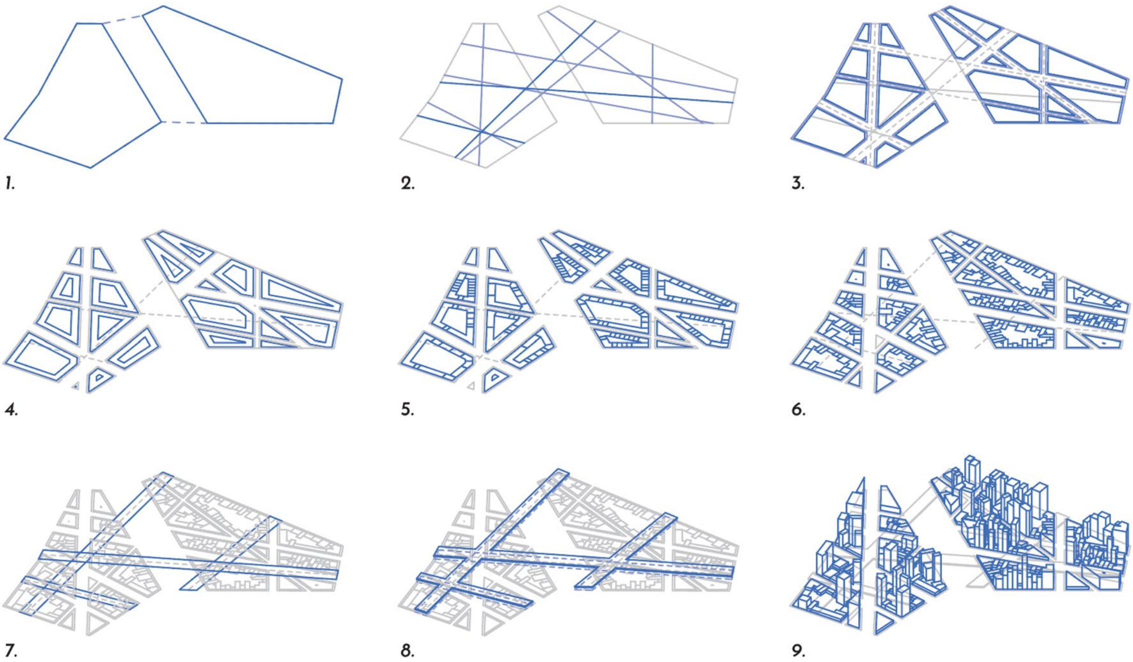


Fig. 2 Primitive phenotype construction of simulation 1

We ensured that individual blocks expanded in size across the superblock, creating blocks with large interior courtyard spaces (above 200 sqm) that could be assigned as extra public space on the ground plane. One or more perimeter buildings were removed to create entrances to these blocks (Fig. 2.9).

Fitness functions

The first simulation employed five fitness functions. Fitness Function 1 generated habitation capacity for future population and tourism growth. This was measured by the total density of all the buildings within the superblock, whilst disregarding buildings with footprint area of less than 70 sqm. Fitness Function 2 ensured adequate quality of solar exposure to buildings. Winter solstice hours (9 am to 3 pm) informed the solar analysis, optimising for building facades with four or more hours of direct sunlight. Fitness Function 3 ensured desirable quality of solar exposure on ground level. Similar to the previous function, winter solstice hours were used, aiming for at least 4 h of solar exposure. Fitness Function 4 ensured desirable quality of solar exposure on skyway level (four or more winter solstice hours). Finally, Fitness Function 5 focused on generating ideal connections between skyways and street level, leveraging the existing buildings within the superblock to do so, and maximising intersection events between buildings and skyways (Fig. 3).

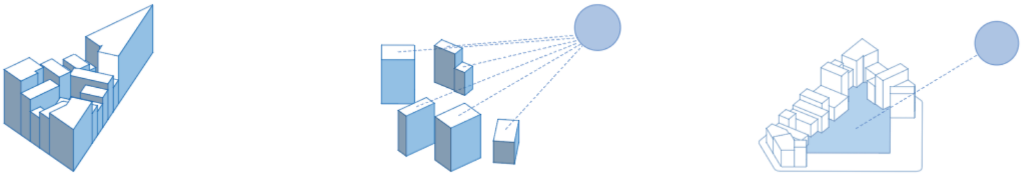
The formulation of the design problem emphasised the relationships between the chromosomes and genes (parameters), and their contribution to the calculation of the fitness functions. The genes, and their extents, defined the morphological characteristics of the phenotype, as well as the potential formal variation in phenotypic output. This variation, although controlled, was the key component of the successful experiment (Fig. 4).

Simulation 1 explored the global relationships of the superblock, recreating them to the point at which a skyway could be introduced, and how the skyway affected these global factors. The skyway promoted pedestrian movement, particularly across the Champs-Élysées, with a potential to expand outside the superblock and across Paris. The simulation evolved 1250 phenotypes, comprising 25 solutions per generation across 50 generations; the algorithmic setup is presented in Table 1. The fittest solution from Simulation 1 served as a fixed phenotype for Simulation 2, which focused on micro-scale factors introduced along the skyway network to improve its functions as both a network and habitable space.

Simulation 2

Primitive phenotype construction

Whereas simulation 1 examined the relationship between urban form and skyway on a macro scale, simulation 2 did so on a micro scale, giving greater attention to the skyway itself (Fig. 5.1, 2) and its



FO 1. Maximise Density Within the Superblock

Increasing the building count and height in order to gain a greater amount of surface are for populating.

Includes: *G1. G2. G3. G4.*

FO 2. Maximise Building Solar Gain

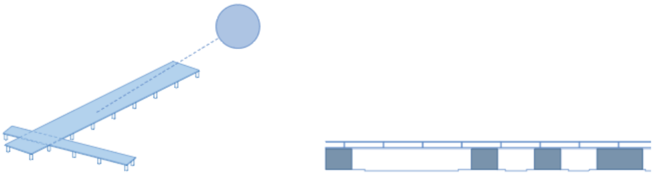
Increasing solar gain for both residential and hotel use, in direct oppositiong to courtyard and sidewalk solar gain.

Includes: *G3. G4.*

FO 3. Maximise Ground Solar Gain

Increasing quality of public space by minimising overshadowing, this encourages use of public areas, with a particular focus on courtyard spaces.

Includes: *G4. G5. G6. G7.*



FO 4. Maximise Bridge Solar Gain

Increasing solar gain increases the area of the bridge system and allows larger spaces for to have varied programs injected.

Includes: *G6. G7.*

FO 5. Maximise Bridge Overlay of Buildings

Creating a higher count of bridge connections over buildings allows building rooftops to be reprogrammed.

Includes: *G3. G6. G7.*

Fig. 3 Fitness objectives and their related genes for use in simulation 1

localised response to the underlying urban fabric, exploring pedestrian networks, habitation, public space and urban farming. The selected phenotype from simulation 1 was selected as the base phenotype for simulation 2, in which it was developed through seven chromosomes, with approximately 145,000 unique values. The skyway was initially divided into a 5 sqm grid of cells (Fig. 5.3), which formed the main unit for all parametric functions in the secondary simulation and was the basic unit of measurement for the various functions distributed throughout.

Single cells were isolated and connected to nearby cells to form hanging habitation units, in which the space below the skyway is included as habitable space (Fig. 5.4). The hanging units consist of 3–7 cells. Each unit was extruded between one and three storeys, with direct access from the skyway. The extruded buildings were grouped into clusters based on their proximity to each other. A public access shaft consisting of a staircase and lift was allocated to each cluster, connecting the skyway level to the street level (Fig. 5.5).

Directly above the habitats, on the skyway, was the integration of spaces for urban farming, placed within the same housing plans, allowing for the added purpose of food cultivation as well as thermal barrier to the suspended habitations beneath (Fig. 5.6). The remaining cells were used as community space (Fig. 5.7), whilst a small amount was deleted to create sky views and light access to the ground plane. A pathway connecting these skylights formed a pedestrian network that liked public park space and created an uninterrupted travel path above street level (Fig. 5.8, 9).

G1. Street Widths

Creating a hierarchy of that allows a range between secondary to quaternary street widths.

n x 3.5 (where n = 1 to 4)

G2. Street Count

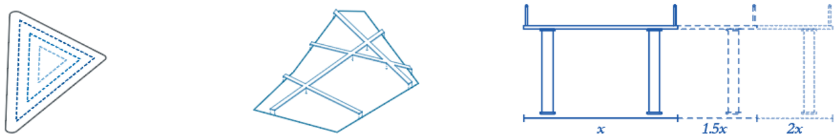
Total count of streets at the secondary to quaternary levels. The Champs-Élysées is the primary road for the superblock.

G3. Building Count

Accounts for the total amount of buildings possible to be built within the superblock.

G4. Building Height

Creating a higher skyline will create an increased floor count and in turn generates a greater amount of total usable floor space.



G5. Internal Courtyard Size

The size of the courtyards helps to inform width of tertiary spaces as well as limit floor outlines for buildings surrounding them.

G6. Bridge Count

Having the skyway span across the superblock allows for a reduction in total bridges, ranging between 1-3 whilst increasing network connectivity.

G7. Bridge Widths

Increasing widths increases the total area of the skyway and allows for increased programs to be dispersed on and around the bridges.

Fig. 4 The chromosomes that define the macro-scale relationships that rebuild the urban fabric of Paris

Table 1 Simulation 1 settings

Simulation size		Algorithm settings	
Generation size	25	Mutation rate	1/(no. of variables)
Generation count	50	Crossover probability	0.9
Population size	1250	Mutation distribution index	20
No. of functions	5	Crossover distribution index	20
No. of variables	60,329	Simulation runtime	3 h

Fitness functions

Sequence 2 was comprised of four fitness functions. Fitness Function 1 ensured desirable quality of solar exposure to urban farm spaces, optimising for five or more hours of winter solstice solar exposure (9 am to 3 pm). Fitness Function 2 preserved and/or improved solar exposure to Stage 1 building facades after the creation of the hanging habitation spaces, similar to the previous criteria, optimising for at least 5 h of winter solstice solar exposure. Fitness Function 3 created habitation spaces that hang beneath the skyway structure, maximising the total habitable density of all the hanging spaces. Finally, Fitness Function 4 optimised public access points between the street level and the skyway network (Figs. 6 and 7).

Due to the complexity of simulation 2, primarily a result of the higher gene count defining the phenotype, the population size was increased to 10,000 solutions, comprising a generation size of 100 and a generation count of 100. The algorithmic setup is presented in Table 2.

Simulation results and analysis

Simulation 1—macro scale

Simulation 1 produced significant morphological and relational variation in the skyway network and superblock. The prominent trends observed were a single branch of skyway; a dense skyway network that was not distributed evenly; a disconnected skyway network; one or more skyway branches isolated from others; a skyway network concentrated on one side of the superblock; and a thin, but moderately distributed, skyway network. These trends, and their urban impacts, are examined below.

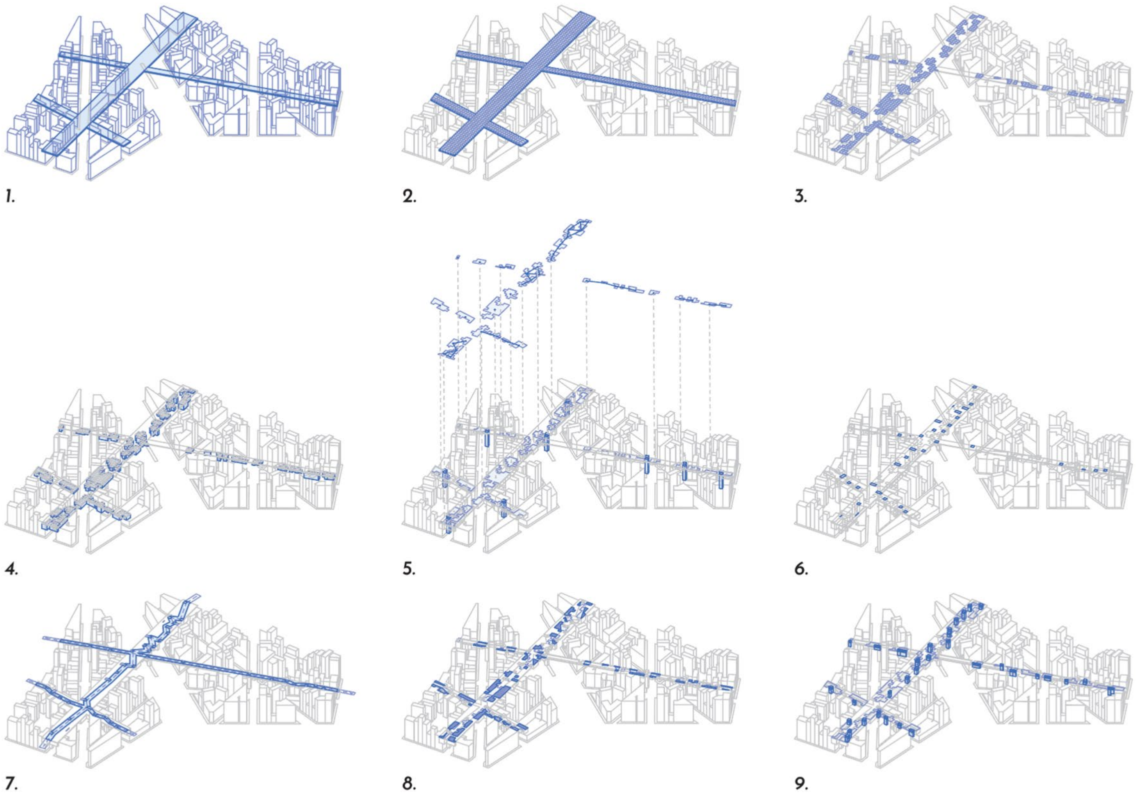
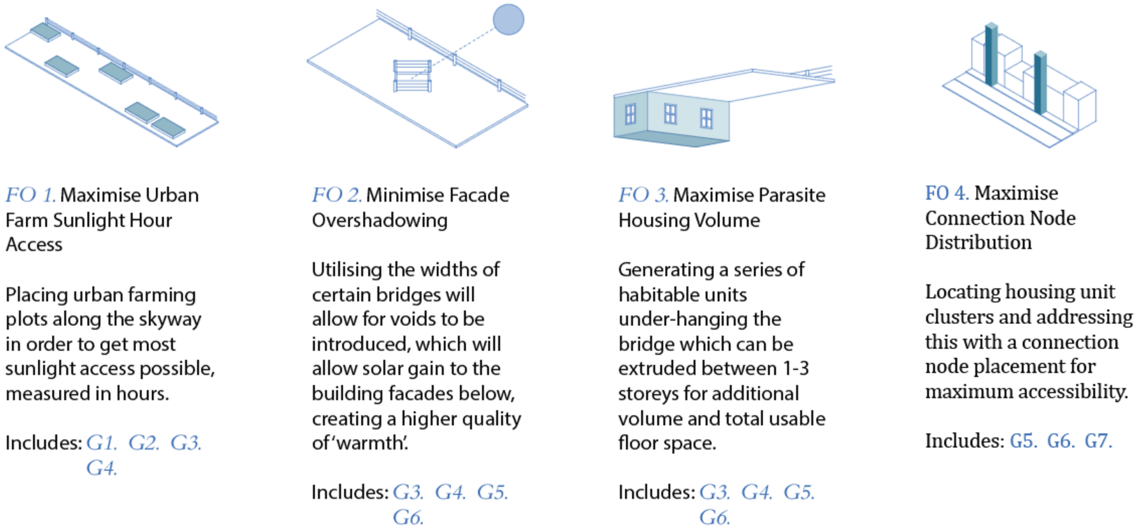


Fig. 5 Illustrated primitive phenotype construction of Simulation 2



FO 1. Maximise Urban Farm Sunlight Hour Access

Placing urban farming plots along the skyway in order to get most sunlight access possible, measured in hours.

Includes: *G1. G2. G3. G4.*

FO 2. Minimise Facade Overshadowing

Utilising the widths of certain bridges will allow for voids to be introduced, which will allow solar gain to the building facades below, creating a higher quality of 'warmth'.

Includes: *G3. G4. G5. G6.*

FO 3. Maximise Parasite Housing Volume

Generating a series of habitable units under-hanging the bridge which can be extruded between 1-3 storeys for additional volume and total usable floor space.

Includes: *G3. G4. G5. G6.*

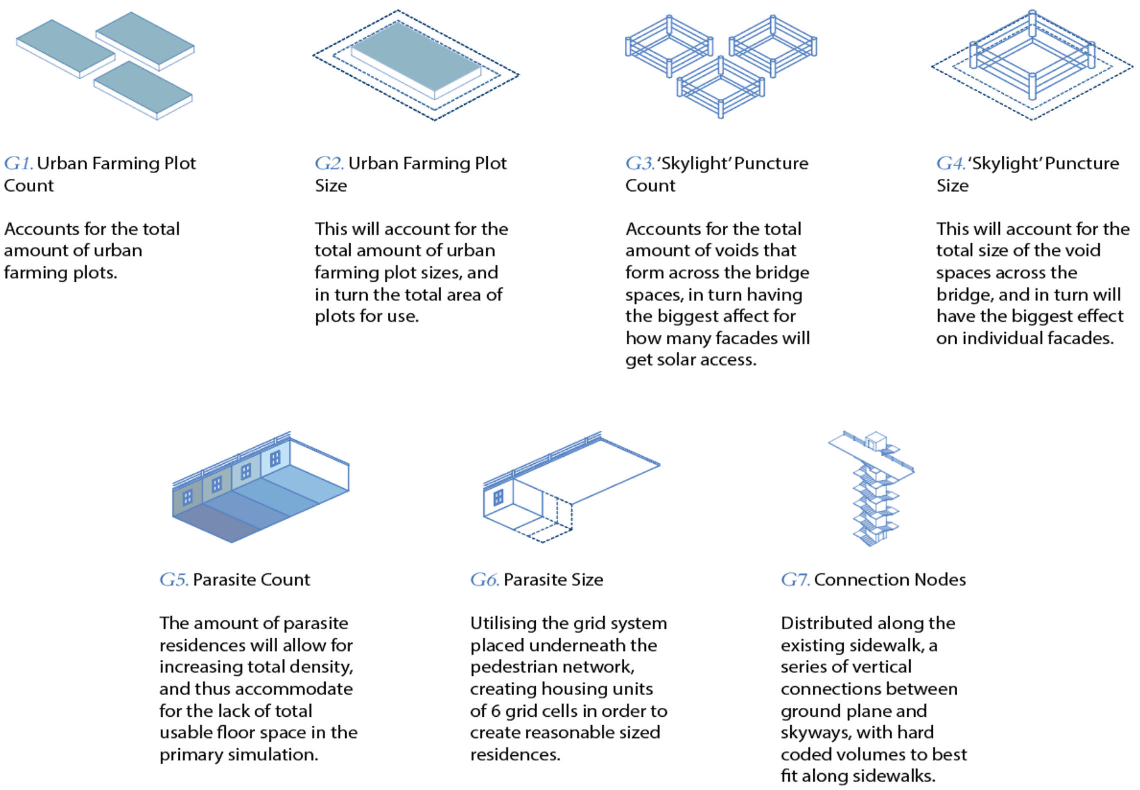
FO 4. Maximise Connection Node Distribution

Locating housing unit clusters and addressing this with a connection node placement for maximum accessibility.

Includes: G5. G6. G7.

Fig. 6 Fitness objectives and their related genes for use in simulation 2

The single-branch skyway can only serve as a bridge crossing the Champs-Élysées, and thus cannot connect different parts of the superblock, because it intersects with few building blocks compared to other skyway networks in other morphological trends (Fig. 8). It also provides a smaller footprint area for habitation. However, its negative impact on the street condition in terms of solar exposure and pedestrian population is minimal. The dense skyway network, on the other hand, allows expansive connections throughout the superblock and



G1. Urban Farming Plot Count

Accounts for the total amount of urban farming plots.

G2. Urban Farming Plot Size

This will account for the total amount of urban farming plot sizes, and in turn the total area of plots for use.

G3. 'Skylight' Puncture Count

Accounts for the total amount of voids that form across the bridge spaces, in turn having the biggest affect for how many facades will get solar access.

G4. 'Skylight' Puncture Size

This will account for the total size of the void spaces across the bridge, and in turn will have the biggest effect on individual facades.

G5. Parasite Count

The amount of parasite residences will allow for increasing total density, and thus accommodate for the lack of total usable floor space in the primary simulation.

G6. Parasite Size

Utilising the grid system placed underneath the pedestrian network, creating housing units of 6 grid cells in order to create reasonable sized residences.

G7. Connection Nodes

Distributed along the existing sidewalk, a series of vertical connections between ground plane and skyways, with hard coded volumes to best fit along sidewalks.

Fig. 7 The genes that define the micro scale programs along the skyway network

larger potentials for habitation (Fig. 9). However, the branches do not exhibit an even distribution throughout the superblock; some are more compact than others. This morphology exhibits greater obstruction of solar gain to street level. The disconnected network has skyway branches that are isolated and unnecessary for the purpose of connection, although have the potential to serve as elevated parks and provide habitation (Fig. 10). If not dense, this type of network preserves street life through solar exposure and pedestrian distribution. The concentrated network creates unbalanced conditions across the Champs-Élysées, creating a disparity between different sides of the superblock (Fig. 11). The thin and moderately distributed skyway network intersects many building blocks with a small number of connected branches (Fig. 12). This type of network commonly exhibits a wide branch crossing the Champs-Élysées, with another branch connected to it on either side of the avenue. This allows for good solar exposure on ground level, adequate area for habitation and good connections between building blocks and across the Champs-Élysées. As such, we designate this typology as the most desirable morphology.

Although the analysis above aided in identifying the general morphological characteristics of the desired solution, there remained significant variation in the outputted solutions. The algorithm produced 1250 solutions, with 273 Pareto Front (the solutions in the population deemed to be the fittest) solutions selected and clustered using K-Means clustering with a K-value of 27. Morphologically, as mentioned above, the most desirable cluster(s) have a moderately dense and distributed skyway system that passes through more building blocks, with an even distribution on both sides of the Champs-Élysées. Once solutions that exhibit these morphological qualities were identified, selection was based on objective prioritisation, attributing weighting respectively to skyway and building intersections, then

Table 2 Simulation 2 settings

Simulation size		**Algorithm settings**	
Generation size	100	Mutation rate	1/(no. of variables)
Generation count	100	Crossover probability	0.9
Population size	10,000	Mutation distribution index	20
No. of functions	4	Crossover distribution index	20
No. of variables	145,200	Simulation runtime	12.1 h

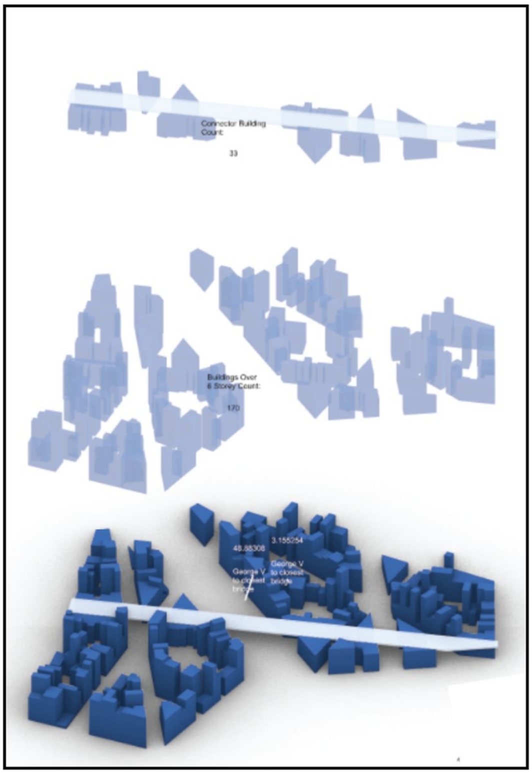


Fig. 8 Single-branch skyway morphology

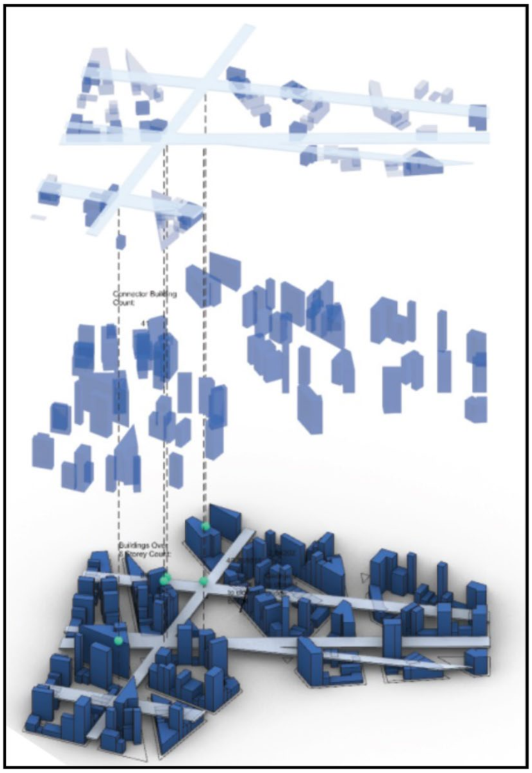


Fig. 9 Dense skyway morphology

building volume, skyway solar exposure, building solar exposure and lastly ground-level solar exposure. This process was applied first with the cluster centres, in order to select the fittest cluster(s). Then the same process was applied within the selected clusters (because there was a wide range of morphological variation within each cluster). The process also considered the distances between the skyway network and the two entrances of George V metro station, with the smallest distances and smallest difference between them being the fittest.

According to the analytic process outlined above, the solution that exhibited the greatest amount of desired urban traits from the population set was solution Gen.46/Ind.21 (Fig. 12). This solution formed the base primitive phenotype for the second simulation.

Simulation 2—micro scale

As a result of the larger population size in simulation 2, significant phenotypic variation was generated, primarily in the location of the hanging buildings, urban farms, public spaces, public access shafts, and skylight punctures. This acknowledged the variety of relationships between these elements with the buildings on street level, the streets and the Arc de Triomphe. The algorithm produced 10,000 solutions, with 212 Pareto Front solutions selected and clustered using K-Means clustering with a K-value of 20.

With regard to public space, the results demonstrated a clear distinction between accessibility of views from public spaces, with some solutions exhibiting greater limitations than others. As monuments play important roles in urban navigation and defining public space (Cudny and Appelblad 2019); solutions with greater views from public spaces were preferred. For the hanging buildings, typical morphologies were those sitting very close to the context buildings (from Simulation 1) and those with a setback that would allow their inhabitants to see the streets below. Preference was afforded to hanging building facades with street views, because this provides basic ventilation and diffused natural lighting to the habitable spaces.

With regard to access shafts, four distribution types emerged. The small, clustered type created a centralised area in pedestrian movements close to public transport, with the implication that hanging buildings are clustered in this area, potentially reducing solar exposure to the streets and context buildings while not necessarily increasing habitation capacity (Fig. 13). The thinly spread-out type commonly has three to four shafts, providing few access points to each skyway branch,

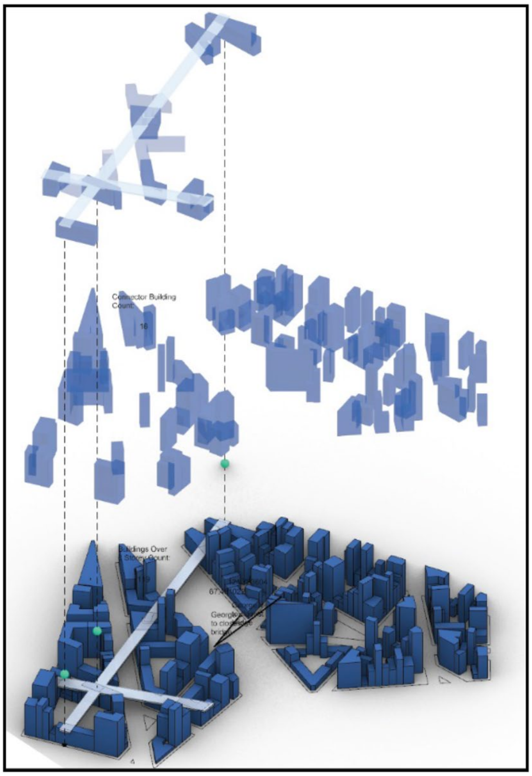


Fig. 10 Disconnected skyway morphology

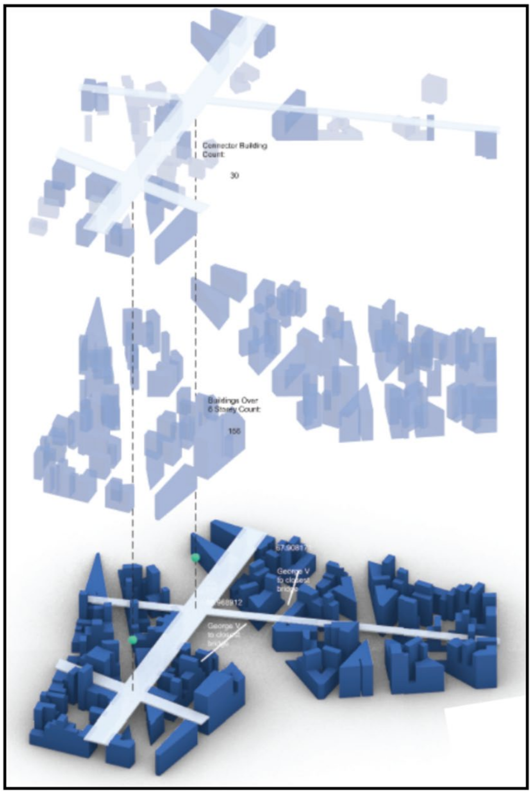


Fig. 11 Concentrated skyway morphology

located relatively far from a metropolitan train station (Fig. 14). The small number of access shafts indicates this morphology does not represent high habitation capacity. The uneven distribution type demonstrates greater density, usually concentrated on one side of the Champs-Élysées (Fig. 15); this leaves parts of the skyways lacking direct connection from the streets. It also implies that hanging buildings are clustered to one side of the superblock, creating unbalanced pedestrian activity. The dispersed type is the most desirable type because it displays a higher and even distribution of direct access points to the network, with some located close to public transport (Fig. 16). It also indicates a higher volume of habitable spaces than the other types.

In addition to the selection process above, the evolved solution set was assessed on added urban characteristics, including the quality of public space on skyway level, view accessibility to urban monuments, the quality of hanging buildings (i.e., number of facades with views to street level within a 50-m radius, views to street level, and views to the Arc de Triomphe), total urban farm area, and view and solar accessibility from skyway level to street level. Based on this analysis, the solution that most optimally met the various analytic and fitness criteria from the evolved solution set was Gen.87/Ind.97 (Fig. 16).

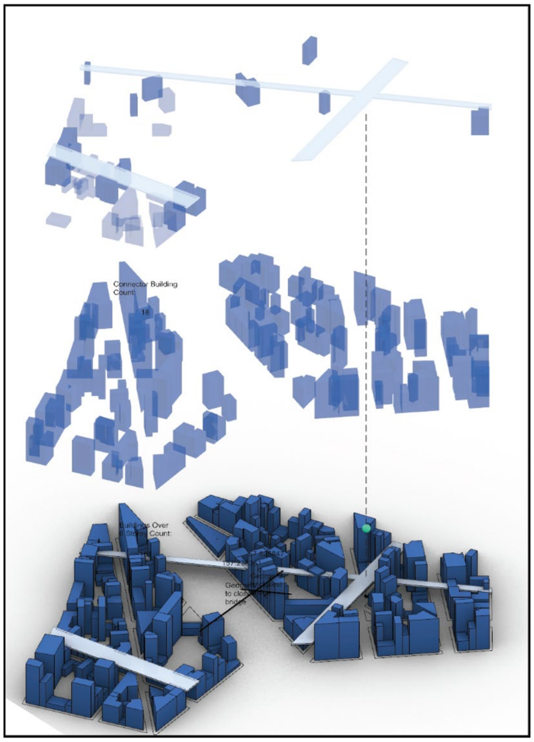


Fig. 12 Thin and moderately distributed skyway morphology—the solution selected for contextual morphology in simulation 2

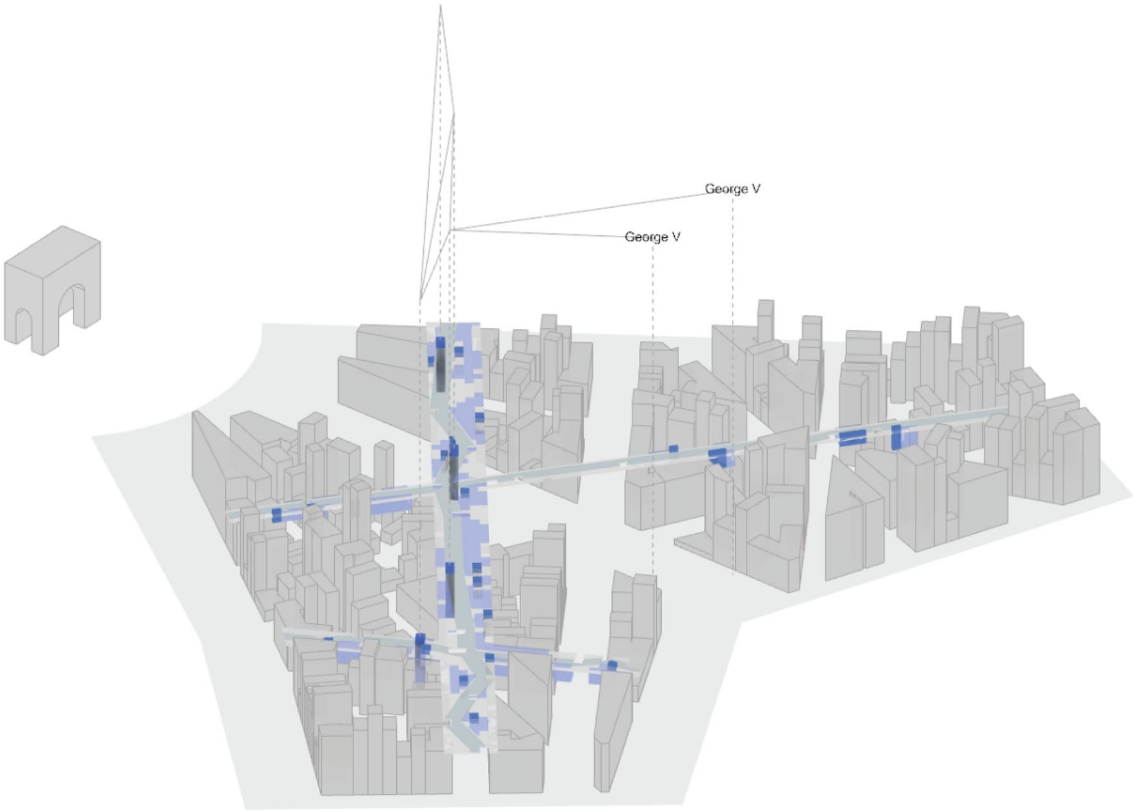


Fig. 13 Small clustered skyway entry point morphology

Fittest solution

The selected solution belongs to the aforementioned dispersed typology of access points for the skyway (Fig. 16). The analytic data representing the phenotypes exhibits a wide range of positive rankings in the fitness objectives of this simulation, showcasing a large amount of total usable floor space for habitable dwellings, whilst maintaining an increased number of facades for ambient light to penetrate into these dwellings. Further, the phenotype exhibits a high number of cluster access points, generating accessibility between ground and elevated planes, focusing on connecting these two levels and creating a strong relationship of usability between them. Public space presents optimal views to the Arc de Triomphe across the entire skyway, demonstrating a strong and successful relationship between views and building height in the urban fabric from simulation 1 (Fig. 17). Finally, provisions for solar and view access points integrated within the design problem's formulation, as well as in the selection criteria of the evolved results, minimise the skyway's impact at street level (Figs. 18 and 19).

As presented in the selected solution (and the algorithmic process leading to it), the morphological characteristics of the superblock demonstrate the opportunity for the integration of habitable skyways within the fabric of a high-density urban tissue (Fig. 20). Numerous cities worldwide have begun to adopt skyways as a solution to stresses that rising population densities impose on their urban environments.

Conclusions

Our research explored the benefits of skyway systems, responding to the needs of growing city populations, whilst maintaining a contextualised urban fabric. Through an analysis of the morphological relationships that shape Paris, localised to the 8th arrondissement, we utilised sequential evolutionary simulations to optimise the morphological output that integrates the skyway within Paris's urban fabric. Shaping the superblock around the Champs-Élysées, with its focus on tourism and retail-centric block formations, allowed for a series of relationships to be identified in the original morphology. These morphological relationships included the varying volumes of the buildings across the superblock (for mixed programmatic use), solar gain to central block courtyards, skyway boundary limits, height placement from the ground plane, connections to the ground

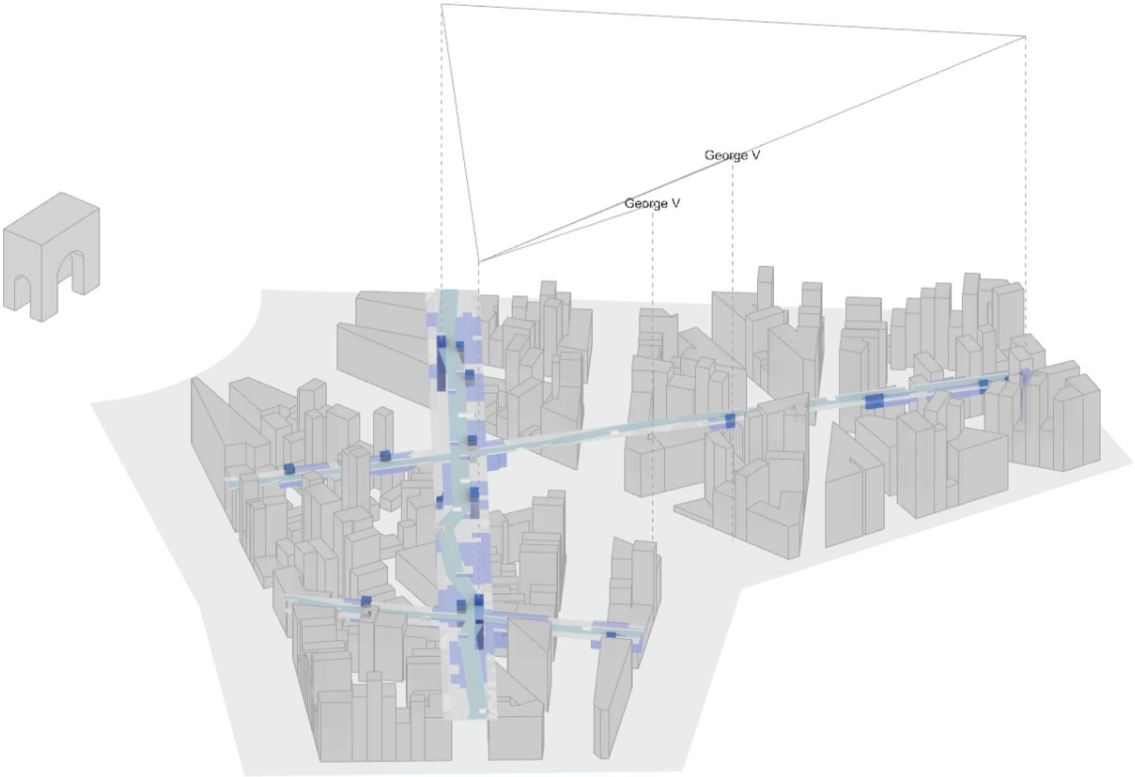


Fig. 14 Thinly spread out skyway entry point morphology

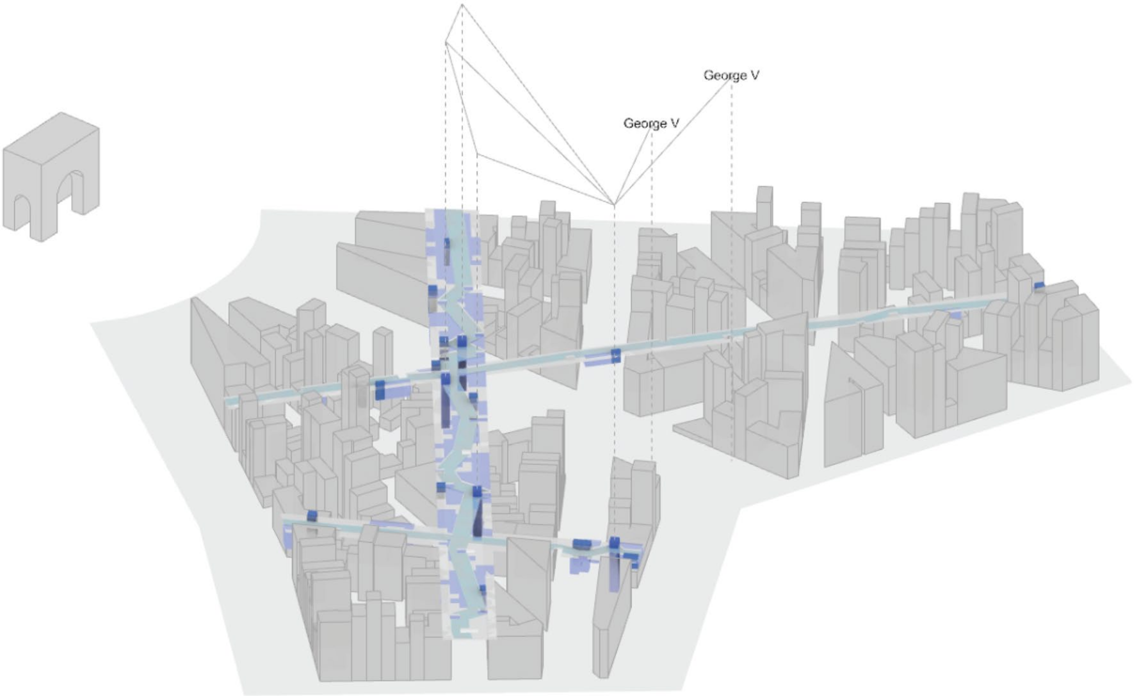


Fig. 15 Uneven distribution skyway entry point morphology

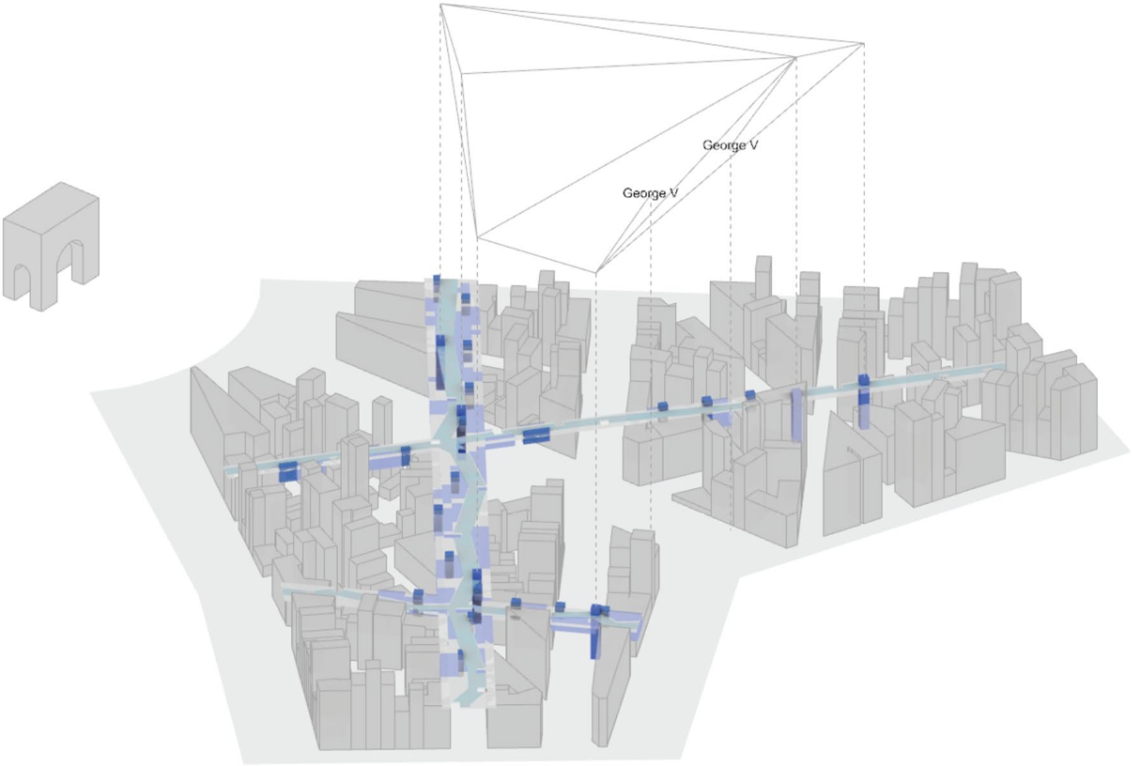


Fig. 16 Dispersed skyway entry point morphology—the fittest solution

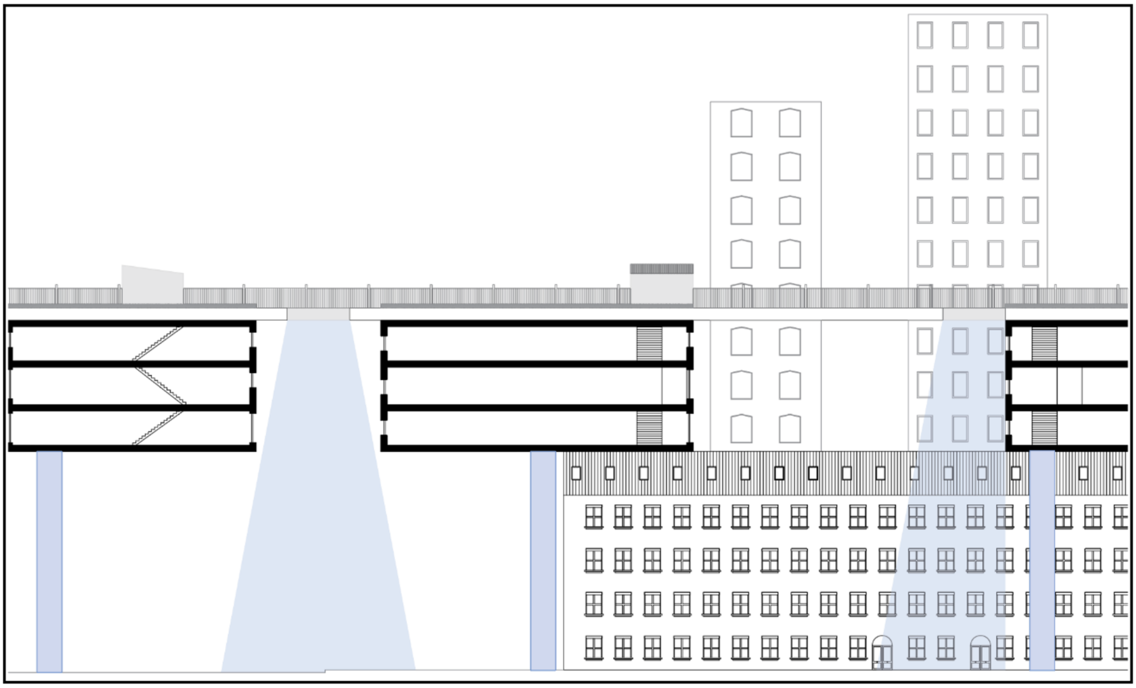


Fig. 17 Section through skyway showcasing skylight punctures

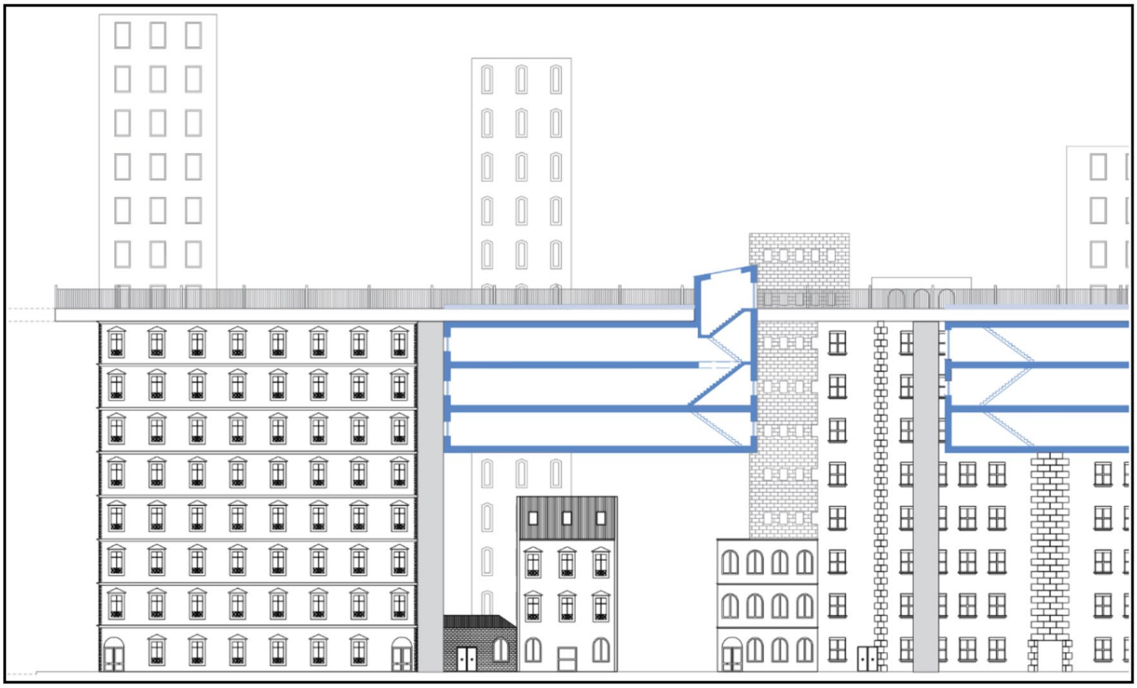


Fig. 18 Section through skyway showcasing hanging buildings

Fig. 19 Section through skyway showcasing ground-to-skyway access points, and hanging buildings at different scales

plane, and skylight openings that allow more solar gain onto the existing roads below. Integrating objectives such as habitation, public space for both movement and short-term occupancy, and urban agriculture shows that creating a specific new typology of skyway that shares similarities with that of a reclaimed infrastructure minimises impact on the existing superblock, whilst increasing habitable space across the entire urban fabric (Fig. 21). Moreover, the integration of spaces for food cultivation within the skyway further emphasises the strive for cohabitation, in this case not only for people and transportation, but also for agriculture; allowing for the potential for emerging ecosystems to evolve within the proposed skyway.

Through the use of sequential simulations, it is possible to expand the size of the experiment and tackle

Fig. 20 Final morphology in plan view, showing the skyway intersecting the superblock, and the individual block morphology being contextualised to the surrounding urban fabric

design objectives at multiple scales, (in the case of the presented, the superblock scale and the skyway scale). In doing so, two multi-objective algorithms are connected to one another where the result of the first is used as the base phenotype for the second, however the design goals, chromosomes and phenotypic characteristics remain independent. An advantage of this is that the second simulation can be slightly modified and applied to an existing urban block (without the need to reconfigure it), highlighting the adaptability of the presented model.

It is evident that the High Line (a large singular network) and the Continuous Monument (which proposed an elevated habitable space) will continue to influence skyway evolution as technologies evolve, allowing us to create rather than to reclaim elevated spaces. Skyways that function as habitable spaces are yet to be widely popularised, yet as the worlds urban population continues to grow, we must look to integrate new living systems into existing urban fabrics. The potential application of our research on urban fabrics with various cultural, environmental and morphological characteristics is driven by a comprehensive understanding of their urban relationships and requires careful adaptation of the presented model to alternative sites. Our experiment focused on localised programs within the skyway system and their integration into an existing urban fabric, and successfully demonstrated how the process of sequential optimisation is utilised to contextualise the relationship between network and built form.

If urban skyways are to be adopted more frequently, it is essential to recognise potential in vertical spaces as an addition to the urban layer, rather than a singular network, in communities and cities that are currently reluctant to change. Further exploration is necessary to examine responses (and inherent changes) to skyway systems in varying urban contexts and with respect to environmental stresses. Whilst habitation is a necessity, the integration of public use—seen as successful in a variety of precedents—must be allowed to continue in order to create varied space for communal engagement. Future work should examine new connections to adjacent buildings, and the impact of programmatic interventions on existing sites. Additionally, the presented study does not highlight the spaces at street level beneath the skyway, although provisions within

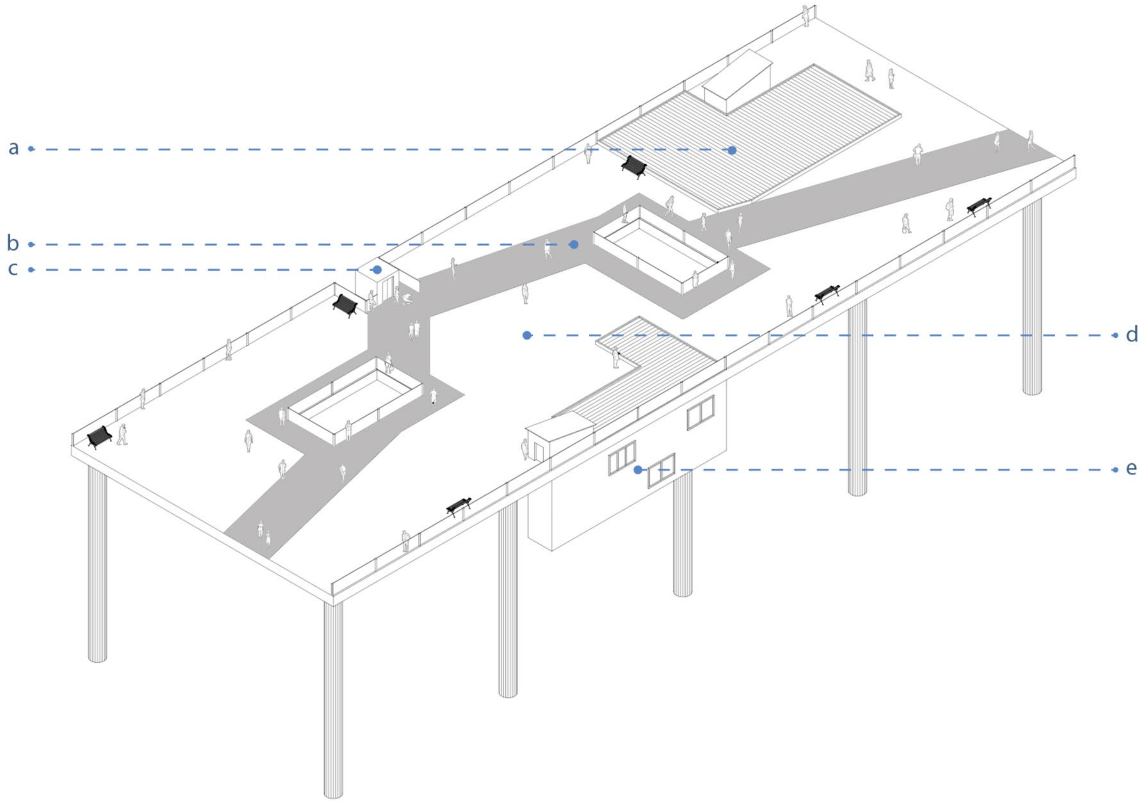


Fig. 21 Showcasing the skyway typology in isolation with a) urban farms; b) elevated network; c) connection nodes; d) public space; e) parasite houses

the experiment have been made to allow for sufficient sunlight to reach the street level (through openings in the skyway); the activities at street level will undoubtedly be shaped by the dominance of the skyway above it, and thus further studies should consider the street level and its activation in response to the intervention above (example projects such as the 'Carrasco Square' and 'Schiphol Airport Park' in Amsterdam by Adrian Gueze and West 8, in which the 'leftover and 'hidden' spaces were addressed through various urban and greening interventions). Finally, a limitation of our research was its lack of temporal acknowledgement of the impact of skyways on the growth and development of the urban fabric; future research on this topic should include such acknowledgement to ensure that the proposed skyway integration is not static but adaptive, allowing for change should the external stresses on the city demand it.

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Author contributions
LB, NXHN, MM and MS developed the literature review and the background and context. LB and NXHN researched and selected the case study. LB, NXHN and MM formulated the design problem. LXHB and NN ran the evolutionary simulation and created the resulting visualisations. MM analysed the simulation results. LB, NXHN and MM wrote the conclusions. All authors read, reviewed, and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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