Precedent Based Design Foundations for Parametric Design

The Case of Navigation and Wayfinding

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ABSTRACT

Parametric design systems serve as powerful assistive tools in the design process by providing a flexible approach for the generation of a vast number of design alternatives. However, contemporary parametric design systems focus primarily on low-level engineering and structural forms, without an explicit means to also take into account high-level, cognitively motivated people-centred design goals.

We present a precedent-based parametric design method that integrates people-centred design "precedents" rooted in empirical evidence directly within state of the art parametric design systems. As a use-case, we illustrate the general method in the context of an empirical study focussing on the multi-modal analysis of wayfinding behaviour in two large-scale healthcare environments. With this use-case, we demonstrate the manner in which: (1). a range of empirically established design precedents —e.g., pertaining to visibility and navigation— may be articulated as design constraints to be embedded directly within state of the art parametric design tools (e.g. Grasshopper); and (2). embedded design precedents lead to the (parametric) generation of a number of morphologies that satisfy people-centred design criteria (in this case, pertaining to wayfinding).

Our research presents an exemplar for the integration of cognitively motivated design goals with parametric "design space" exploration methods. We posit that this opens-up a range of technological challenges for the engineering and development of next-generation computer aided architecture design systems.

Keywords.

human behaviour studies, navigation, wayfinding, architecture design, spatial cognition, visual perception, parametric design, architectural computing, design computing, architectural design cognition

1. Introduction

Parametric design is a well-established method in several engineering and manufacturing design domains such as architecture, product design, and construction (Gun et al. 2010). Decoupling *form* from physical *structure*, parametric and generative approaches offer the ability to rigorously explore many design alternatives and reveal new solutions during the design process (Rybczynski 2013, Boucherie et al. 2012). They have been used to replace traditional shapes with more eccentric morphologies and provide adaptability and flexibility in the design procedure (Boucherie et al. 2012). The Trade Fair ceiling project (Figure 1(a)) is an example of optimisation of the construction, while the Al Bahr Towers project dynamically incorporates environmental attributes into the design procedure (Figure 1(b)).

A People-Centred Parametric Design Approach. Parametric design lends itself well to the manipulation of numerical, geometric features and relationships between object parameters (e.g. width, height, positions). However, parametric design fails to integrate the dimension of human behaviour, i.e., contemporary parametric technologies are unable to incorporate high-level cognitive design requirements (e.g., pertaining to visuo-locomotive perception (Bhatt and Schultz 2017)), and parameters of morphological formulation emanating therefrom.

Consider the case of the the geometric form of the London Aquatics Centre; according to public reports, the design failed to take into consideration the dynamic performance of users and anticipate a perception-related problem concerning visibility. As per reports (Archinect 2012, Buchanan 2012, Rosenfield 2012, Laylin 2012), the curve of the roof obscures the view for a vast number of the audience (Figure 1(c)). This observation, for example, concerning user's experience can be translated and used to create a number of morphologies for the ceiling that ensures an uninterrupted view from all seats in the stadium. Here, one approach is to formally interpret the topological contact and overlap relations between the respective geometries of the ceiling and the visual *range space* (Bhatt et al. 2012b) during a parametric optimisation stage within advanced design systems.

Our goal to promote the primary role of users during the design procedure requires a wide range of behavioural precedents obtained by empirically driven behavioural experiments for the particular functional building cases (Bhatt and Schultz 2017). Towards this direction, a better understanding of people-environment interaction, aspects of spatial perception and cognition about user's spatio-temporal experience is required (Bhatt et al. 2014, Bhatt and Schultz 2017).

1.1 People - environment interaction during navigation

People interact daily with their surrounding built environment and they formulate their visuo-locomotive experience. One common daily type of interaction between users and the built environment is formulated during navigation. Users-navigators of built-up spaces depend most of their locomotive actions on external information of the environment. Designing these built-up spaces and specifically large-scale public buildings requires consideration of multiple user-related aspects such as functionality or comfort. For instance, healthcare design gives priority to unhindered circulation and effective navigation for different user-groups (e.g.

(a) New Trade Fair of Milan (Fuksas Studio). (b) Al Bahr Towers (Aedas Architects). (c) London Aquatics Centre (Zaha Hadid Architects).

Fig. 1 Examples of implemented projects used parametric design systems.

patients, families, physicians, and nurses). In this framework, behavioural evidence about user's experience, and cognitive aspects of navigation performance, derived from evidence-based design knowledge and post-occupancy evaluation studies, are crucial for the design procedure.

People's experience in space is based on interactions between individuals and the environment (Weiss 1999). It is an embodied experience constantly intangible and bodily related to other cues in space (Csordas 2008). These interactions between built-up space and humans, occur at discernible levels: that of the space of the body, that of the space in reach or in sight of the body, that of the space of navigation (too large to be apprehended at once), that of the space of external representations, or graphics (constructed to augment human cognition) (Tversky 2005). The interactions are also depicted on users' movement patterns. For instance, navigation according to the classification by Montello (2005) includes two components: locomotion, and wayfinding. Locomotion is associated with human perception; and wayfinding to human spatial cognition (Kaplan and Kaplan 1982, Carpman and Grant 2002). Additionally, human-environment relationship can be described in more spatial and semantic terms, on a perceptual level through the notion of *affordances* (environmental cues that provide behavioural options for immediate action without reasoning (Gibson 1979)), or at a spatial cognition level through *image schemata* (the cognitive concepts which structure a meaning of our perception and action).

1.2 Cognitive Aspects of Design Composition

Design for navigation, as a cognitive task, and for different user groups is a challenging process. For instance, complex building facilities such as hospitals usually present wayfinding problems of users as a result of complicated layouts that lead to stress (Arthur and Passini 1992, Kondyli and Bhatt 2018). Numerous studies have demonstrated that many navigation problems are caused by the problematic arrangement of complex decision points, their linking paths, the vertical incongruence of floors (Weisman 1981, Arthur and Passini 1992), or other environmental aspects such as location, size, distance, direction, separation and connection, shape, pattern, and form (O' Neill 1991). Consequently, navigation performance varies according to user-groups, and regarding affordances [plan configuration, geometry of the environment, geometry of the scenes (formulated during user's locomotion), available visual range, architectural differentiation] as well as manifest cues [signage, landmarks] (Devlin 2014, Evans 1980).

New-generation design assistive tools, take into consideration these cognitive people-centred aspects in order to expand the abilities of digital computer-aided architecture design (CAAD) systems (Bhatt et al. 2014) and feature-based parametric modelling systems (Schultz et al. 2017). Particularly, the aim is to develop artificial intelligence and analytical design computing using design semantics, common-sense spatial reasoning, and human cognition as the foundations of the systems (Bhatt et al. 2012b). In this way, the design systems will be equipped with analytical capabilities in order to anticipate architectural building design performance (Bhatt and Schultz 2017).

1.3 Parametric modeling

The term parametric modelling denotes the use of parameters to control the dimensions and shape of CAD models. The objective of parametric modelling is to represent, manipulate and reason in a CAD model about the three-dimensional shape of parameterised objects. Instead of rules imposed when shapes are generated, in parametric systems shapes are initially generated based on operations and constraints, and the constraints are also maintained as an integral part of the model's geometry during editing. Parametric design focuses on the steps creating a shape and parametrises them. Consequently, defining features of a parametric model is not the outputs but rather the need to construct and maintain relationships associated with the model, and to manipulate geometrical concepts through a program (visual or textual). To construct a parametrisation scheme the aspects to consider are: the identification of top-level variables (which dimensions are the design variable and which are the subordinates), how the model should change when one of these top-level dimensions is changed, and how those dimensions, datums, and constraints allow your CAD model to change accordingly (Woodbury 2010).

Parametric modelling as a depiction of a design intent, allow modellers to generate computer representations of physical objects and define the relationships between them (Aish and Woodbury 2005). The relationships define necessary topological relations among objects making up a system, define a graph of relations expressing how the different parts should be. In this way, parametric modelling software applications dedicated to specific design domains define relations and constraints to express the logic of design conditions. Parametric modelling utilises different types of primitive elements such as dimensions, datums, and constraints. Constraints can be geometric or algebraic relations that designers want to impose on the geometry of CAD models. For example, typical geometric constraints are parallel, perpendicular, offset, tangent, and alignments. These constraints can be applied to many different types of geometric entities, such as lines, planes, and surfaces. Alignments are used to constrain parts relative to one another when constructing assembly models. Algebraic constraints on the other hand, are equations that the designer adds to ensure that features sizes meet design requirements (Bettig and Hoffmann 2011).

1.4 Parametric modelling beyond the form. The contribution of behavioural studies

In the context of architecture and building design, parametric modelling has been used primarily for three purposes: exploration of formal design ideas, refinement, and integration through building information modelling. The fundamental premise of parametric modelling concerning the initial phase of morphological exploration, is that it can help the designer create a multitude of candidates for design solutions, evaluate them, and allow flexibility in management of geometrical components, while at the same time it can include fixed values or constraints. We suggest that designers will benefit from the integration of people-centred behavioural aspects into parametric modelling from the first steps of the design procedure, as the system can reassure that people-centred requirements will remain stable during morphological experimentation. Towards this direction extracting data from empirical studies about people-environment interaction and re-apply this knowledge to the design of new built-up spaces can lead to better people-friendly performing models.

1.5 Organisation of the paper

The paper presents a methodology for bridging the gap between behavioural studies in large-scale buildings and contemporary parametric design systems. The steps of the methodology are examined based on an empirical study of occupants navigation in two large-scale health-care buildings and a re-design task of an atrium lobby, focusing on people-centred design principles. The paper is organised as follows:

- Section 2 presents an overview of the proposed methodology, highlighting the principal components of our approach: (1). behavioural experimentation; (2). establishing design precedents; (3). translation of precedents into design constraints; and (4). parametric design space exploration.
- Section 3 presents a model case-study involving multi-modal behavioural analysis of user's visuo-locomotive experience in space during a navigation task in two large-scale hospitals
- Section 4 presents the manner in which observations from the empirical studies can be the basis of design precedents. We illustrate design precedents established based on a hospital (Section 3) domain case study.
- Section 5 focusses on the translation of design precedents into design constraints, and their embedding within parametric design systems. We demonstrate this process with Rhino 3D-Grasshopper.
- Section 6 describes the morphological experimentation stage involving design space exploration (using a parametric tool) under the constraints of the design precedents established in Section 4) and formalised in Section 5.
- Section 7 summarises and concludes the paper with a discussion of the broader implications of the proposed line of research, and a call for a confluence of research in

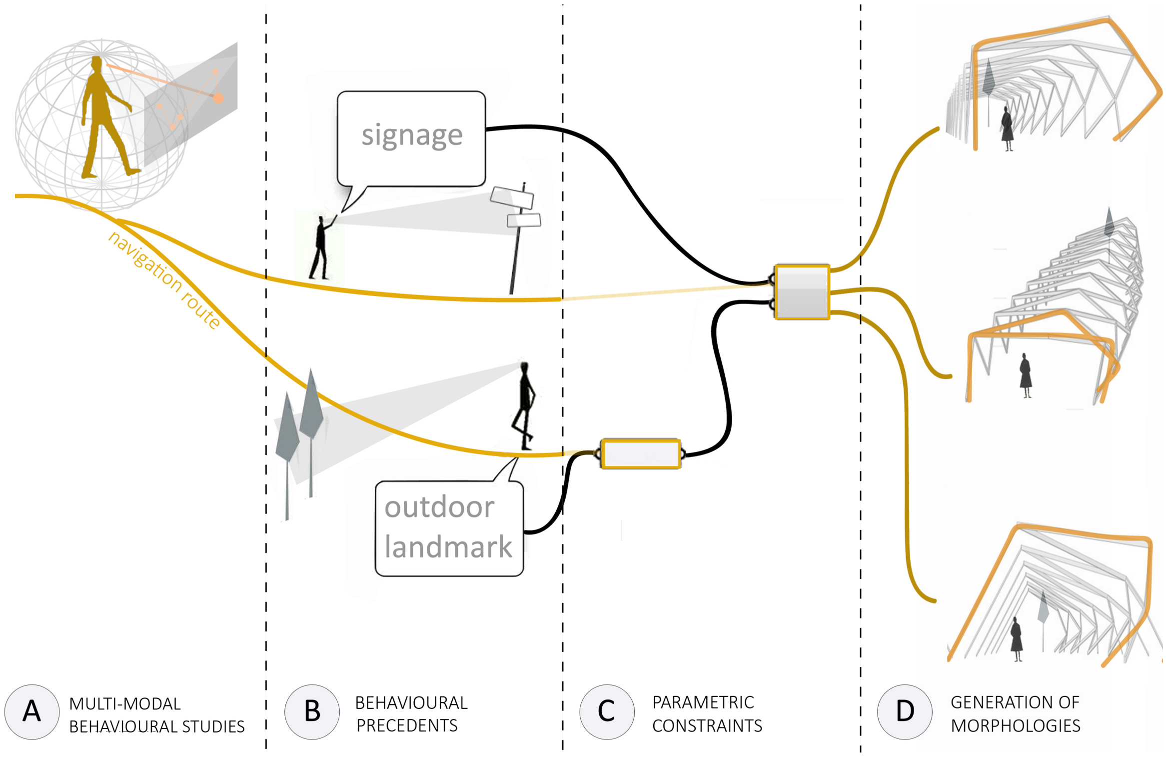


Fig. 2 The proposed precedent-based parametric design methodology includes four steps: (a) analysis of the embodied visuo-locomotive experience (here is based on a navigation study), (b) definition of design precedents, (c) translation of precedents to parametric design constraints, and (d) generation of a range of morphologies that satisfy the precedents.

cognition, artificial intelligence, interaction, and design towards the development of next-generation design technologies.

2. Methodology: From behavioural studies to parametric design morphologies

Design for facilitating and best formulating people's daily experience is overtaken during the design process, or it is considered at a late stage of design. In our approach, we seek to influence designer's work at all stages of the design procedure, by formulating a method to bridge the gap between user's spatial behaviour analysis and contemporary design tools, such as parametric design systems. Consequently, we suggest that new design-assistive-tools can provide flexibility, as parametric systems support, and also give the opportunity to designers for morphological experimentation while reassuring that people-centred design principles are fulfilled. The proposed methodology includes four distinctive steps (Figure 2):

2.1 Analysis of the embodied visuo-locomotive navigation experience

To approach the interaction of people with space, we employ a range of sensors for measuring the embodied visuo-locomotive experience of users in a built environment: eye-tracking, egocentric gaze analysis (from video), external camera-based visual analysis to interpret fine-grained behaviour (e.g., stopping, looking around, interacting with other people), aa well as manual observations made by human experimenters (Bhatt et al. 2016a). New cognitive-assistive technologies aim at generating declarative narratives of visuo-locomotive user experience from digital computer-aided architecture design (CAAD) based on this collected behavioural knowledge (Bhatt and Schultz 2017, Bhatt et al. 2014, 2016b). The combination of multi-modal behavioural data analysis with morphological analysis of space and computational geometric structure analysis; contribute to the systematic study of user-environment interaction (e.g. during navigation, wayfinding, exploration), and in drawing conclusions about the impact of (peculiar) morphological features on users' experience (Kondyli and Bhatt 2018).

2.2 Definition of design precedents

In architectural design the involvement of precedents in the design procedure is a common practice and it refers to the reuse of previous examples or rules from the design domain to authorise or justify a subsequent act of the same or an analogous kind. Precedents are widely used for assisting the design procedure from the stage of the concept until the final design decision-making (Clark and Pause 1985). From our perspective, a precedent-based people-centred design approach needs to ground design decisions on credible empirical research and so the definition of precedents is the following of the observations and the evidence from empirical behavioural studies and the state-of-the-art about people locomotive performance or people "pleasant experience" in space (Ulrich et al. 2010). The behavioural-based design precedents can be formulated as design suggestions or indications for the effects of the spatial morphologies on people and they can be used in multiple cases, various buildings types of different scales and functions accordingly. As our work focuses on navigation studies the precedents we formulate aim at assisting navigation performance, comfort, and reduce stress rate during wayfinding.

2.3 Translate precedents into parametric design constraints

To ingrain human perceptual and cognitive aspects into the procedure of morphological creation we choose to embed people-centred design precedents into parametric design systems. Concerning the implementation of these constraints, we extend the industry-standard parametric systems to support a range of qualitative high-level spatial constraints using incidences (positions or regions in interior or exterior space), topological relations, size (smaller, larger), visibility and movement, etc (Bhatt et al. 2012b). The implementation can be made by using a range of parametric design systems; in our case we are using Rhino 3D-Grasshopper[1] and FreeCAD[2] (Kondyli et al. 2017b, Schultz et al. 2017). The defined precedents have to be translated from natural language rules to qualitative spatial relations, and to be expressed within a parametric design system. To do so we translate precedent-based qualitative constraints to geometric constraints, and we represent high-level spatial objects in terms of the low-level parametric system spatial entities such as points, lines, circles, etc (Schultz et al. 2017). Consequently, the geometric constraints enforce consistency between the higher qualitative and conceptual layers of the design, giving the designer the opportunity to propagate changes throughout the design process by manipulating parametric values, and to ensure that the significant for him constraints are maintained.

2.4 Alternate studies: Generate a range of morphologies that satisfy behavioural precedents

Using parametric design systems for the implementation of people-centred precedents has the advantage of the quick generation and evaluation of a large number of different morphologies. The parametric assistive design technologies do not only allow a flexible design procedure but they also promote the integration of multiple aspects in a design task or a combination of them; the evaluation and experimentation of alternative morphologies, by reassuring that particular people-centred principles will be fulfilled. This approach supports creativity while it can assist in avoiding design omissions that may affect negatively users' spatial experience.

3. Case study: Precedent-based parametric design of the atrium lobby at the Parkland hospital(s)

3.1 A wayfinding behavioural study in Parkland hospital

To illustrate the proposed method we created a design scenario to re-design an atrium lobby of an existing hospital based on the results of an empirical wayfinding study. The study was conducted in two large-scale complex healthcare facilities, the Old Parkland Hospital (OPH), and the New Parkland Hospital (NPH) in Dallas (Texas), with 25 participants from the local community, who were not familiar with the two buildings. Their age ranged from 26 to 83 years old (average 48 years old). Our main goal was to investigate the interaction between users and the environment during indoor navigation to confirm precedents related to cognitive aspects of design composition and use them to generate a number of morphologies for the atrium lobby.

[1] Grasshopper is a graphical algorithm editor tightly integrated with Rhino 3D modeling tools. http://www.grasshopper3d.com

[2] FreeCAD is a parametric 3D modeler. http://freecadweb.org

3.2 Procedure

The participants were taken to the same spot at the emergency hall of the hospital, they were fitted with mobile eye-tracking glasses and introduced to the wayfinding task with the destination of the pharmacy area, with oral route and landmark-based instructions by the experimenter. The task lasted approximately fifteen minutes, the route included five turns, one transition between floors and the same destination (the pharmacy area). An orientation task after the fifth turn was also included. Two experimenters were following the participants throughout the task and made notes about participants' behaviour. The trace and the timing of participant's performance were recorded together with the egocentric videos of the eye-tracking. External video recordings add supplementary information for events and trajectories of the participant during the task. A questionnaire before and after the navigation task was included, with questions related to visual abilities, distance estimation, and memory retrieval about landmarks and signage.

3.3 The outcome of the behavioural analysis

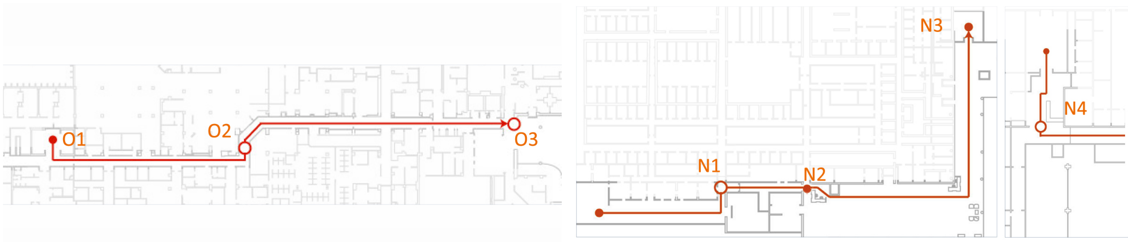
The analysis focused on the cognitive aspects of design composition, and it included a number of behavioural observations many of which confirmed previous behavioural studies in the field of wayfinding performance. The combination of eye-tracking analysis with the Visibility Graph Analysis (VGA) of layout revealed problematic decision points of the route, where participants stopped or to expressed confusion. Many of these decision points combined low navigation performance results for the majority of the participants (e.g. time delays, behavioural events related to confusion etc.) with low visibility (e.g. decision points, landmarks and signage not visible ahead in the route) that provoked delay on visual detection and as a consequent, they impair the navigation performance. The multi-modal behavioural analysis also confirmed previous studies suggesting that people tend to proceed towards the direction that provides the longer line of sight at a decision point, or that people fixate more on functional landmarks (sitting area, information desk, doors, stairs, elevators) than architectural (pillars) or information cues (posters, signs) (Ohm et al. 2014). We also collected a range of observations to evaluate participants' confusion behaviour events, and how environmental features are related to these events, as well as what precede and what follow these events in terms of embodied visuo-locomotive experience. We discuss in detail three main behavioural observations derived from the multi-modal analysis of the wayfinding task at the Parkland hospitals, to demonstrate the influential environmental aspects that can be used to define design precedents. The first is related to visual accessibility at the entrance hall/atrium lobby, the second is about the advantages of available outdoor view during indoor navigation, and the third is about spaciousness and enclosure and its effects on user's visuo-locomotive experience.

(a) Decision point O2 (OPH) - 51 sec spend by participants on average, while 36 required.

(b) Decision point N1 (NPH) - 9 sec spend by participants on average, while 4 sec required.

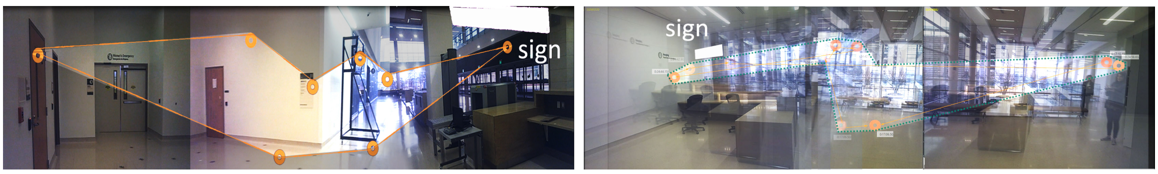
(c) Decision point O3 (OPH) - 34 sec spend by participants on average, while 12 sec are required.

(d) Decision point N4 (NPH) - 24 sec spend by participants on average, while 15 sec are required.



(e) Navigation route and decision points at the Old Parkland Hospital (OPH).

(f) Navigation route and decision points at the New Parkland Hospital (NPH).



(g) Visual attention frame in decision point N2 (NPH).

(h) Visual attention frame in decision point N4 (NPH).

Fig. 3 Transition/decision points in both hospitals with low (3(a), 3(b)) and high (3(d), 3(c)) visibility are analysed, where low navigation performance has been recorded in combination with indicative events of behavioural confusion. The first line includes screen captures from the eye-tracking egocentric camera in key positions of the route pointed in diagrams 3(e) and 3(f); the second line presents the Visibility Graph Analysis (VGA) of the layouts with colour coded indications in the range from blue (low) through green and yellow to red (high visible locations); the third line summaries the qualitative analysis of the behavioural mapping for the group of participants crossing the transition/decision points (the dashed lines are indicative for backtracking). Figures 3(g) and 3(h) present two examples of the visual attention frame constructed by one participant at two decision points in the New Parkland Hospital (NPH). The resulting image is the product of stitching of successive egocentric images (as many as the fixation points) from the eye-tracker, involving the head movement during the visual search. The fact that significant signage (noted in white) for each of these transition/decision points are not included in the visual attention frame is considered crucial for the decrease in navigation performance recorded in these positions.

■ Observation 1: Visibility in key positions

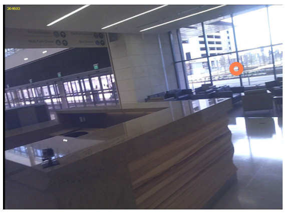
> The degree of visual access to important landmarks and signage in transition points, entrances or decision points, has a significant role in navigation performance.

Specifically by analysing seven decision points of the routes at the Old and the New Parkland Hospital (Figure 3(e), 3(f)), we notice that four of them, which provide low visibility conditions (based on the Visibility Graph Analysis (VGA)), record low navigation performance and many confusion behavioural events by the participants (stop, looking around, asking for help, etc.). In the two decision points with low visibility, participants spent more than double the average time (5.5 sec) recorded at all the decision points (Figure 3(a), 3(b)). Additionally, the analysis of two more decision points in combination with the visual attention pattern analysis from the eye-tracking recordings, suggest that even transition points with high visibility can provoke low navigation performance if the manifest cues (landmarks, signage, maps) are not positioned according to the average frame of visual attention (the frame formulated at the egocentric visual scene and includes the fixation points from the group of participants in an aggregate level) (Figure 3(d), 3(c)). The frame of visual attention is formulated by the participants at the transition point, and it is related to the geometry of the space, the distance and the size of the visual cues, as well as human visual abilities. Specifically, human's binocular vision covers 114°-120° of the visual field, creating a cone of view with a concentric cone of 5° that represents the normal line of sight and involves the fixations each moment (Howard and Rogers 1995, Grosvenor and Grosvenor 2014). This cone of view is the area from where humans are able to receive visual information of the surrounding space. For instance, in two decision points at the New Parkland Hospital, 30% of the participants did not detect the appropriate sign as it was not included in the frame of visual attention (Figure 3(g), 3(h)). As a result we recorded 20% delay in relation to the average time spent in all the decision points (calculated for the group of participants at New Parkland Hospital experiment), as well as the behavioural patterns that indicate confusion (80% of the participants stopped, 30% of the participant looked all around several times, etc.).

■ Observation 2: Outdoor views during navigation

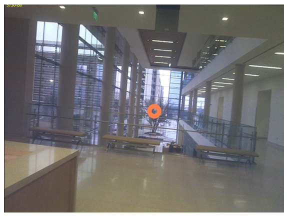
> People tend to look outdoors during indoor navigation.

Along the navigation route at the New Parkland Hospital, the participants had the opportunity for an outdoor view in three parts of the route as a result of the glass wall at the atrium lobby and the dining area. However, the instructions did not mention the outdoor space and the participants were also not familiar with the area. Consequently, it was not anticipated from the participants to use outdoor landmarks or other visual cues for orientation purposes. Nevertheless the analysis of the visual attention throughout the whole path reveal that 85% of the participants fixated shortly on the outdoor space, mostly on trees and the



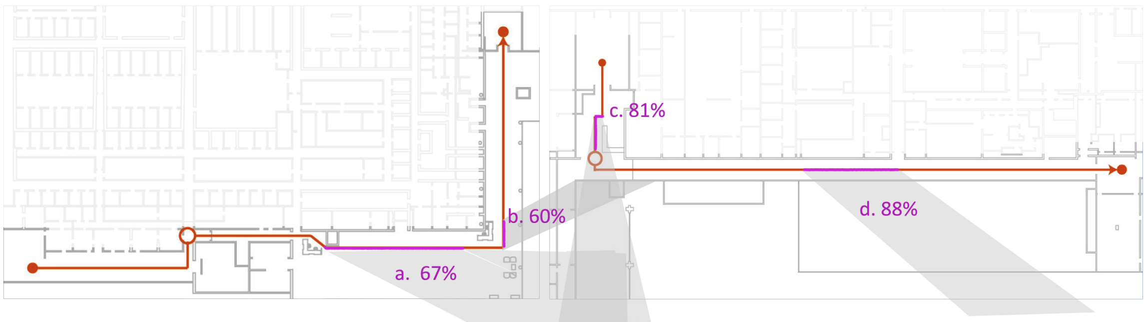
(a) Outdoor fixation from point (a).

(b) Outdoor fixation from point (b).



(c) Outdoor fixation from point (c).

(d) Outdoor fixation from point (d).



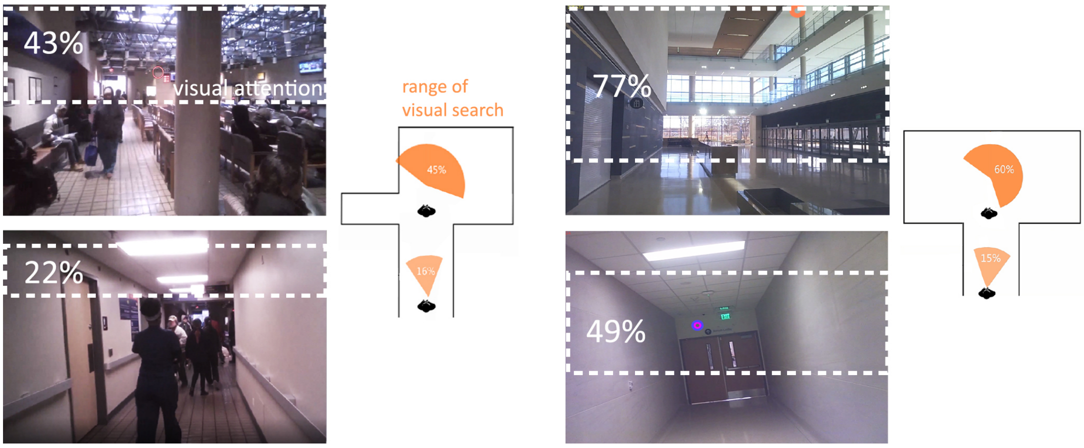
(e) The navigation route at the New Parkland Hospital and the percentage of participants (recorded by the eye-tracking) fixated outdoors.

Fig. 4 We observed that the majority of participants fixated (at least shortly) outdoors in four parts of the route (4(a) - 4(c)) during their navigation task at the New Parkland Hospital.

exterior facade of the hospital, for at least two times in at least one of the four parts of the route with visual outdoor access (Figure 4). These findings confirm results from previous studies concerning the visual range and the depth of view, suggesting that people tend to use the available visual range and expand their field of view, as this is formulated by the structure of the built environment, while they also tend to move towards the direction that provides visual depth (Peponis et al. 1990, Golledge 1995). Moreover, many studies suggest that views to the external environment can enhance the legibility of interiors (Gärling et al. 1986), or even affect positively people's healing conditions or the stress rate (Ulrich 1984).

Despite the number of fixations we collected towards the outdoor space, these fixations are not directly related to any decision making procedure because the points of the route with an outdoor view are situated in between the decision points.

However, these observations come to support previous studies suggesting that people use outdoor salient objects as landmarks as they are useful for global orientation mostly at non decision points (Anacta et al. 2016). These landmarks known as global landmarks, are located off the route and are therefore not necessarily immediately visible. They mostly have secondary usage (after the primary use of the local indoor landmarks) for indoor navigation, to assist the maintenance of orientation during a complex navigation task (Kondyli and Bhatt 2018). Consequently, the exposure of users to the outdoor environment during indoor navigation seems to help in orientation as it gives an overview of the wayfinding area but



(a) Transition/decision point O3 (OPH). (b) Transition/decision point N2 (NPH).

Fig. 5 The comparison between the frames of visual attention (that accumulate fixations from the eye-tracking data) during the transition from a narrow corridor with low-ceiling space, to a wide, high-ceiling space, from four transition/decision points, indicates that the frame of visual attention is getting wider in the horizontal as well as the vertical axis as the space that participants move is getting wider. For instance, in the transition/decision point O3 (3(a)), the frame of attention is changing on average from 22% of the overall screen coverage to 43% (5(a)) after the transition, and from 16% to 45% concerning the scanning angle in a horizontal axis. Similarly, on the point N2 (5(b)) the frame of the screen scan changes from from 49% to 77%, and the angular from 15% to 60%.

they have to be well-known to the user and ideally highly visible (Bauer et al. 2017).

■ Observation 3: The geometry of the decision points

> Narrow and enclosed decision points contribute to a negative embodied visuo-locomotive experience.

Decision points have a crucial role in navigation performance and an obvious effect on user's experience concerning delays, confusion events or changes of the stress rate. In our study at the Parkland hospital, we listed a range of events during participants' transition from the decision points, many of them can be related to discomfort and stress. The analysis of the external and the egocentric videos and the behavioural mapping of participants' experience, shows that 41% of participants experienced events related to confusion. Particularly, 35% of participants stopped in a decision point, 30% looked around, 20% asked for help, 10% looked around and 5% moved backward to the route for several meters. These events were recorded mostly at four of the seven decision points (two decision points from each hospital). Two of these points are characterised by a significant transition from a narrow, enclosed, low-ceiling space to a wide, high-ceiling, atrium lobby; and the other two are decision points in narrow corridors with low-ceiling (Figure 5).

These observations are related to previous studies indicating connections between spatial morphology with navigation performance, embodied experience, or even stress rate. Firstly, Hartley et al. (2004) suggested that the boundaries of the environment play an important role in determining the place cell representation of the location, which is weakly affected by the global geometry of the environment. Gallistel (1990) notices that disoriented people reorient themselves by matching geometric properties of the directly perceived and the recalled environment. Moreover, the legibility of the layout - which depends on the arrangement of settings and a reasonable amount of geometrical complexity (Baskaya et al. 2004, Tversky 2005) - is a significant variable for an effective navigation task. Additionally, from a neurological point of view, a recent study by Vartanian et al. (2015) suggests that spaces with higher ceilings as well as wide/open spaces are more likely to be judged as beautiful, and to activate structures involved in visuospatial exploration and attention in the dorsal stream. The study also shows that enclosed spaces are more likely to elicit exit decisions, because of a reduction in perceived visual and locomotive permeability that characterises enclosed spaces. In support of this interpretation, Fich et al. (2014) recently demonstrated that participants exhibit greater reactivity to stress when placed in an enclosed rather than an open room. In conclusion, compared to open spaces, enclosed, narrow spaces can increase one's vulnerability to stress.

4. Formulate design precedents for navigation in large-scale building

The behavioural observations from the case study in Parkland hospital confirm previous knowledge about navigation performance and its relationship with environmental-cognitive aspects as well as morphological aspects of the surrounding space. We are focusing on spatial characteristics related to users navigation performance and sense of comfort, such as geometrical features of the scene and the layout, visibility at particular points on the route, visual connectivity between points of the route or towards important manifest cues. Based on the state-of-the-art on behavioural and cognitive studies in navigation, together with our observations from the empirical case study at the Parkland hospital, we provide a list of design precedents for large-scale public buildings (Figure 6). However, we focus on three of them (Figure 6 (P1-P3)) for the re-design task of the atrium lobby at the New Parkland Hospital, which correspond to the three observations analysed in detail in Section 3:

Precedent P1: Visual access to landmarks and signage from the entrance or a transition point can promote the navigation performance.

Precedent P2: Transparent materials and voids extend the visual range, give access to outdoor landmarks and contribute to global spatial orientation.

Precedent P3: High ceiling and wide places expand visual search and can be related to a sense of comfort and a positive spatial experience.

The analysis of each of the precedents reveals the involved environmental-cognitive and morphological aspects, in respect to navigation performance. The environmental aspects

	Environmental-cognitive aspects	Morphological aspects for navigation	Design Precedents
P1	Visibility, Manifest cues	Entrance, Transitional point	Visual access to landmarks and signage from the entrance or a transitional point can promote the navigation performance.
P2	Visual range, Manifest cues	Transparency, Voids	Transparent materials and voids extend the visual range, give access to outdoor landmarks and contribute to global spatial orientation.
P3	Visual range	High ceiling, Wide space	High ceiling and wide places expand visual search and can be related to a sense of comfort and a positive spatial experience.
P4	Spatial Configuration	Layout Symmetry	Symmetry of the layout is helpful for spatial configuration.
P5	Visibility Manifest cues	Manifest cues detection Navigation path	Manifest cues are detected when they are positioned in accordance with the zone of visual attention in a particular point in space.
P6	Geometry	Decision point	A decision point positioned in a narrow space is more likely to provoke confusion events to the users than a wide high-ceiling space.
P7	Visibility, Visual range	Navigation path	Visual connectivity provided at the atrium between several parts of the route assists orientation and spatial configuration.
P8	Visibility, Layout configuration	Decision point	Paths with long line of sight are more attractive to users than short ones in a decision point.
P9	Layout configuration	Decision point	Decision points are more effective when they provide less than three options.
P10	Geometry	Visual distraction	People navigating in crowed narrow public spaces are very likely to get visually distracted by (in order): other people, multiple paths and open doors, as well as obstacles and objects positioned on the route.
P11	Geometry Layout configuration	Navigation path	Non anticipated changes in the geometry of the path can provoke confusion events.

Fig. 6 Design precedents. The design precedents derived from our case study in Parkland hospital. The precedents are characterised by the environmental-cognitive and morphological aspects involved in navigation performance. Three of the precedents have been chosen from the list (P1-P3) for the design implementation that follows in Section 5.

related to user's cognitive navigation procedure, include visibility and visual range, manifest cues, spatial or layout configuration, as well as the spatial geometry. The morphological aspects related to navigation are the entrance, the transition points, the transparent elements of the voids, the symmetrical or scale features, as well as the paths and the decision points.

Combining the results from the behavioural observations from our empirical studies together with knowledge from the state-of-the-art, we conclude that significant navigation landmarks and signage should be visible from positions during a navigation path, such are the entrance, transition or decision points (Figure 6 [P1, P5, P7]), as well as other key positions during the route. Outdoor landmarks are also considered useful for user's orientation performance and so the design of the boundaries between the indoor and the outdoor space should consider visual connectivity between significant points (Figure 6 [P2]). The geometrical features of the scene as well as the geometry of the layout play a significant role in spatial configuration and consequently in navigation performance (Figure 6 [P3, P4, P8, P9]). Moreover, the geometrical features of the scene and the layout may also contribute to a less stressful environment and an enjoyable experience (Figure 6 [P6, P10, P11]).

5. Precedents integration to parametric design systems - Design Constraints

To explain how precedents extracted by the empirical studies can be integrated into parametric models, we use the atrium lobby of the New Parkland Hospital as a morphological design study. We translate three precedents from the list presented in Figure 6 (P1-P3), to parametric design constraints using the graphical algorithmic editor integrated in Rhino 3D modeling tool, named Grasshopper.

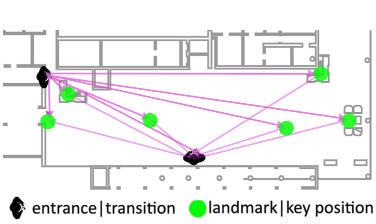
This three-floors-high volume of the atrium lobby, originally designed and constructed as the main entrance hall of the building, is a rectangular parallelepiped that includes a series of entrance doors in one of the boundaries, and two main connections on the ground-floor (transition points) with the emergency section and the dining area, while it also provides visual connectivity between the pedestrian routes in the two upper levels with a number of key positions and salient objects that can be used as indoor landmarks. These are the information desk, the elevators, the sitting area and the elevated pedestrian routes above.

■ Translation of the Precedent P1: Atrium lobby volume manipulation algorithm based on the cones of view

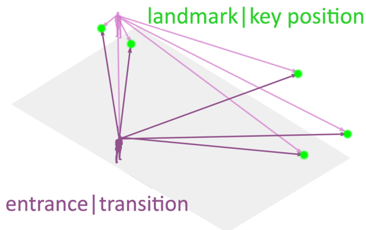
> Explore the geometry of an empty volume based on the cones of view, as they are formulated by key positions of the navigation route (entrance, decision point, transition point) and the available manifest cues (landmark, signage).

We use the first precedent (P1) from the list in Figure 6, to modify the geometry of the volume of the atrium lobby (Figure 7). We define in Rhino 3D the points of interest and we group them in two categories: the entrance or transition positions and the key positions or landmarks (Figure 7(a)). Then we introduce these two groups of points as two categories in Grasshopper. We draw visual connectivity lines with the <Vector 2Pt> component between these two groups (Figure 7(b)), and we represent the cones of view using the entrance/transition points as the tip of the cone and the landmarks/key positions as the endpoint of the vector using the <Weaverbird's Mesh Pyramid> component (Figure 7(c)). The width of the cones is fixed at an opening angle 60° according to human visual abilities dimensioning by DIN[3], and the number of sides of the pyramid is adjustable but high enough (around 50) so that it can simulate a cone (Figure 7(c)). Using the vertices of the polygons from the bases of the cones we create a <Delaunay Mesh> and we introduce it as a new <Geometry> to the *Object-manipulated mesh* algorithm (Appendix B: Figure 12(a), 12(b)). In this case the *object* is the geometry produced by the cones (Figure 7(d)), and the

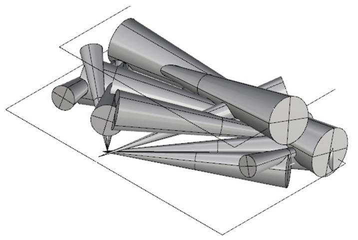
[3]Deutsches Institut für Normung is the German standards body, and specifically DIN 1450 refers to legibility of texts.



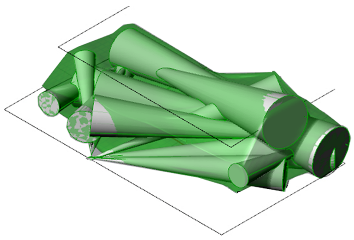
(a) Key positions for inter-visibility at the atrium



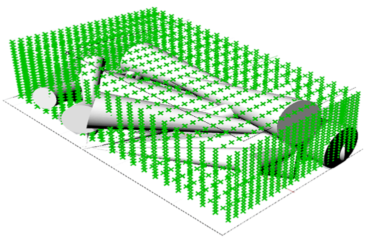
(b) Visual connectivity vectors from the entrance



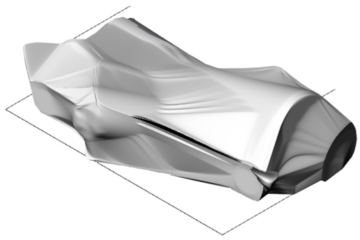
(c) Cones of vision based on the inter-connectivity diagram



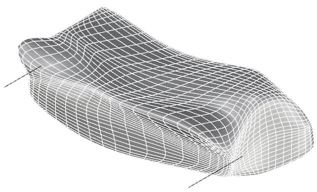
(d) Minimum volume that incorporate the cones of view



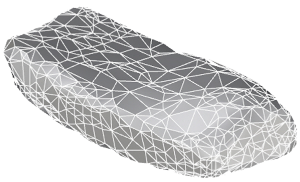
(e) Boundary box of the combined cones of view



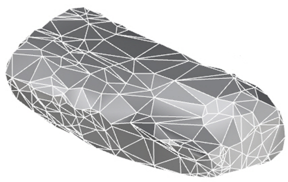
(f) Adjusted surfaces of the volumes based manipulated by the boundary box



(g) The mesh of the volume with reduced vertices (30%)

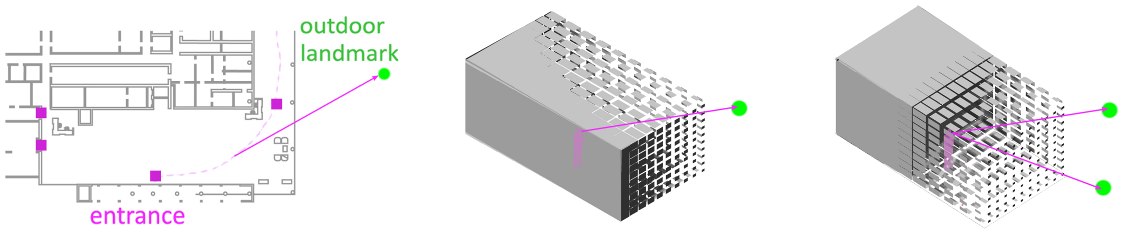


(h) The mesh of the volume with reduced vertices (20%)



(i) The mesh of the volume with reduced vertices (5%)

Fig. 7 The steps for the implementation of precedent P1 includes: (a) define entrance, the transition points, as well as the positions of key objects and landmarks displayed at the existing layout of the atrium lobby of the New Parkland Hospital, (b) define visual connectivity vectors between the points, (c) draw cones of vision, (d) connect the volumes of the cones with the boundary box, (e) adjust the volume from the minimum that includes only the cones until the existing boundary box, (f) suggest a surface that covers the minimum suggesting volume, (g) - (i) adjust vertices from the mesh and create triangulated or curved geometries.



(a) Define a vector of visibility from the indoor route starting from the entrance towards the outdoor landmark.

(b) Perforate boundaries of the atrium based on one vector of visibility.

(c) Perforate boundaries of the atrium based on two vectors of visibility.

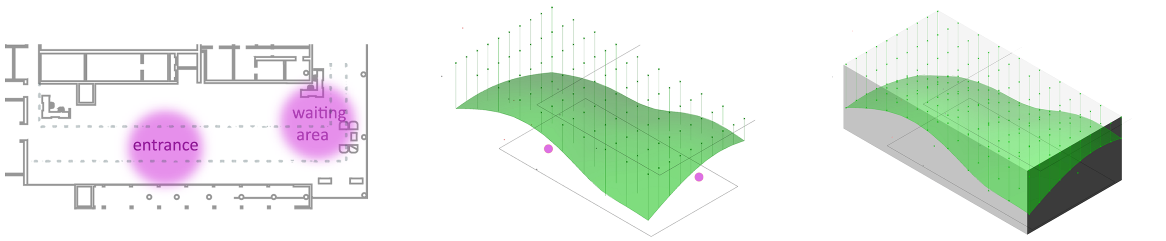
Fig. 8 (a)Initially we define a main route from the entrance to the atrium lobby, an outdoor landmark and the like of view that indicates the area of the surface that should turn into a perforate boundary, (b) we use the point on the path as an attractor that adjust the openings on the surface, (c) the perforate surface can be adjusted based on multiple points on the route or multiple outdoor landmarks.

Manipulated mesh is the boundary box (Figure 7(e)). The boundary box of the geometry defined as a <Mesh Box> is based on the existing rectangular parallelepiped of the atrium lobby. The mesh that defines the volume of the atrium lobby can be further manipulated in between the geometry of the boundary box (maximum) and the mesh that wraps the cones of vision (minimum). As follows we can further explore the morphology of the atrium lobby using a *Mesh reduction algorithm* that reduces mesh vertices and rebuilds the mesh providing a range of triangular or smooth curved surfaces (Figure 7(g) - 7(i), Appendix A).

■ Translation of the precedent P2: Responsive facade algorithm based on outdoor landmarks

> Explore the morphology of spatial boundaries to promote visual connection with outdoor landmarks.

We use the second precedent (P2) from the list (Figure 6) to modify the boundaries of the atrium lobby (Figure 8). The precedent (P2) suggests that people tend to look outdoors even for a short amount of time and this behaviour can be taken into consideration in design by providing appropriate outdoor landmarks to navigators. Consequently, formulating the surfaces of the volume of the atrium in a way that permits visual connectivity with various outdoor landmarks may assist the navigation performance. In practice, we define three-dimensional points as outdoor landmarks as well as key positions of the indoor path (point on a curve) (Figure 8(a)), and we develop an associative geometry for the surface that covers the volume of the atrium (the existing volume is a rectangular parallelepiped). To create openings we divide the surface in a number of panels using <Deconstruct Mesh> and <Deconstruct Face> components and as follows we make the panels move in space using <Rotate 3D> component (Appendix C: Figure 13).



(a) Defined areas of interest as attractor points

(b) Create a hanging surface that is influenced by the attractor points

(c) Adjust the surface between the existing boundary box and the selected areas

Fig. 9 Design implementation of precedent P3 at the atrium, concerning spaciousness in relation to navigation performance.

Moreover, we scale down the panels depending on the distance of those panels from the selected points on the indoor route. We use the <Area> component that calculates the area of each panel and also provides a centroid point for each panel that is used to calculate the distances between the panel and the selected points of the indoor route using a <Distance> component (Appendix C: Figure 13). We also use the output centroid from the <Area> component as a scale factor, together with the output numbers from the <Re Map> component to control the size of the panels. As a result the panels are controlled by the selected key positions of the indoor path. We apply this algorithm using one or multiple points on the path and we create surfaces with openings for several viewing possibilities towards the outdoor landmarks along the navigation path (Figure 8(b), Figure 8(c), Appendix A).

■ Translation of the precedent P3: Ceiling manipulation algorithm based on busy areas of the floorplan

> Explore the morphology of the upper boundaries of a volume in the Z axis, so that it can provide the maximum height possible in positions where people tend to accumulate.

Based on the third precedent chosen from the list (P3) (Figure 6), a higher ceiling can have a positive effect on users' spatial experience. For the re-design task of the atrium lobby at the New Parkland Hospital we define busy areas where people tend to accumulate, such as entrance positions, sitting or waiting areas. Consequently, we introduce these positions in Grasshopper as *attractor points*, and we suggest a modification of the ceiling over these points so that they keep a higher level than the average ceiling height (Figure 9(a)). We start with a <Plane Surface> component that represents the ceiling of the existing atrium lobby, or the upper surface of the boundary box, and we formulate a grid. Using this grip we create a hanging rod that modifies the curve of the surface of the ceiling according to the *attractor points* (Appendix D: Figure 14). We can further adjust the surface inside the boundary box defined by the existing atrium lobby (Figure 9(c), Appendix A).

6. Alternative studies — Precedent-based morphological experimentation

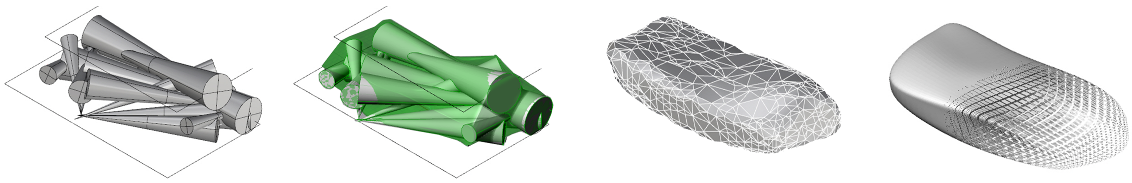
Multiple morphologies can be generated based on each one of the design precedents (Figure 6) as well as from further modifications during implementation, as it is examined in section 5. For instance, in our design case study concerning the atrium lobby at the New Parkland Hospital, a different group of landmarks, entrances or transition points, can directly influence the generation of the cones of view and result in different geometries for the atrium lobby (based on precedent P1). Additionally, changes in the routes inside the atrium lobby or the position of outdoor landmarks, can influence the openings of the responsive facade system proposed (this can include rotational sliders, ribbons, louvers, etc.), and provide a range of patterns for the same surface (based on precedent P2); while decision points or selected areas in the atrium lobby, introduced as point-attractors to the system, can manipulate the overall morphology of the ceiling (based on precedent P3).

A number of combinations of the algorithms created for the three precedents used in the design case study (P1, P2, P3), can provide a range of different morphologies. For example (Alternative study 1 - Figure 10), by adding the *Ceiling manipulation algorithm* (using precedent P3) on the result of the *Atrium volume manipulation algorithms* (using precedent P1 - Figure 10(a), 10(b)), we can further manipulate the height of the volume by defining important areas inside the atrium lobby (Figure 10(c)). As a third step we can use the *Responsive facade algorithm based on outdoor landmarks* (using precedent P2 - Figure 10(d)) on the surface generated as a result of the combination of the algorithms related to precedents P1 and P3. Another group of morphologies (Alternative study 2 - Figure 11) can initiate the design of the atrium lobby by modifying the original upper boundary of the volume (using precedent P3 - Figure 11(a)), and then add the cones of view to modify the rest of the volume (using precedent P1 - Figure 11(b)). As follows we can define a route inside the new geometry of the atrium and some outdoor landmarks so that we can investigate a range of generated perforated surfaces according to the visibility relations developed (using precedent P2 - Figure 11(d)).

To sum up, the precedents and the related algorithms defined by them, are independent. They can be used alone, or they can be combined with multiple ways in order generate a range of different morphologies that all satisfy people-centred precedent-based design principles for navigation performance.

7. Conclusion and Outlook

We call for a people-centred precedent-based parametric design approach for assisting in morphological design-space exploration during the early stages of design. As a use-case, we focus on the cognitive aspects of design composition related to user's navigation in large-scale built environments such as hospitals. We have developed a general method and exemplar for the integration of behaviour-based methods directly within parametric design technology following four steps: (a) conduct and analyse behavioural empirical studies of users experience, e.g., pertaining to navigation and wayfinding; (b) translation of behavioural observations



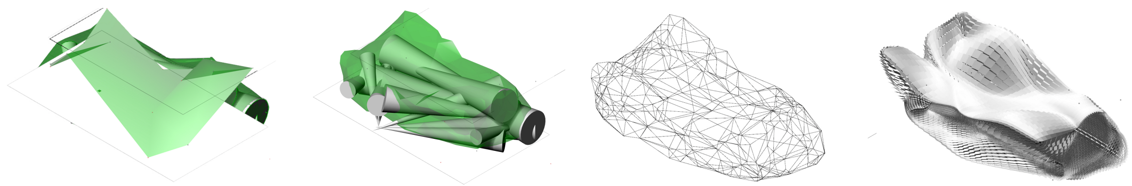
(a) Cones of vision (P1)

(b) Cover surface of the cones of vision creates a volume

(c) Modification of the ceiling (P3)

(d) Openings to the cover surface according to the outdoor landmarks (P2)

Fig. 10 Alternative study 1: Combine three algorithms based on three precedents (Figure 6) in the following order: precedent P1 (a), (b), then precedent P3 (c), and at last precedent P2 (d).



(a) Ceiling surface (P3)

(b) Cones of view (P1)

(c) Unify the ceiling surface and the cover form of the cones

(d) Openings on the final cover surface according to the outdoor landmarks (P2)

Fig. 11 Alternative study 2: Combine three algorithms based on three precedents (Figure 6) in the following order: precedent P3 (a), then precedent P1 (b),(c); and at last precedent P2 (d).

to design precedents; (c) embedding precedents into the appropriate parametric assistive design tool; and (d) generation of a range of morphologies that satisfies a combination of precedent-based design rules. The paper provides an overview of the proposed methodology and presents an example of implementation through a design case study concerning the morphological experimentation of the atrium lobby at a healthcare facility.

We selectively build on the cognitive aspects derived from a navigation study to define design precedents and present a concrete model of behaviour-based precedent integration in parametric design systems. Indeed, the precedents can naturally be further developed; a systematic collection, organization, and review of behavioural observations from a range of empirical studies can formulate design variables and constraints considering multiple target groups (e.g. elderly, children), locomotive tasks (e.g. wayfinding, emergency exit), or building types (e.g. airport, hospital, train stations) (Kondyli and Bhatt 2018). By expanding the available precedents and embedding them into parametric design systems we can promote people-centred conceptual design and morphological experimentation focusing on behavioural evidence, targeting a better user experience from the early stages of design composition. Moreover, further exploration of the opportunities that the proposed precedent-based methodology provides in different parametric design tools (e.g., Rhino 3D-Grasshopper, Rhino 3D-Python, FreeCAD, Dynamo, Maya Embedded Language (MEL)) is a topic of ongoing research with the aim to expand and encourage people-centred thinking in parametrization.

The paper demonstrates the translation of high-level (people-centred) design requirements to low-parametric design constraint using the interface of the general operations (typically) provided by parametric system (in this case, Rhino 3D-Grasshopper). Next step involves the development of general ontological elements pertaining to affordances, visibility, or mobility knowledge (Bhatt et al. 2012b, a) that can be directly included within (parametric) design systems. In this context, interpreting designers' natural language articulation of design requirements, encoding it to high-level design rules, and embedding semantic knowledge about *space* (Bhatt et al. 2013) in design systems are some steps that open up immediate research challenges at the intersection of Cognition, Artificial Intelligence, Interaction, and Design (Bhatt et al. 2017). More broadly, bridging the gap between high-level cognitive-driven design constraints and low-level quantitative / engineering centric (parametric) design methods is an ongoing design computing challenge that can lead to the development of next-generation people-centred CAAD systems (Bhatt and Schultz 2017).

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APPENDICES:

A. Operations Used in the Implementation of Precedents P1-P3 (Appendix A)

B. Implementation of Precedent P1 (Appendix B)

C. Implementation of Precedent P2 (Appendix C)

D. Implementation of Precedent P3 (Appendix D)

A. LIST OF OPERATIONS USED FOR THE IMPLEMENTATION OF PRECEDENTS P1-P3

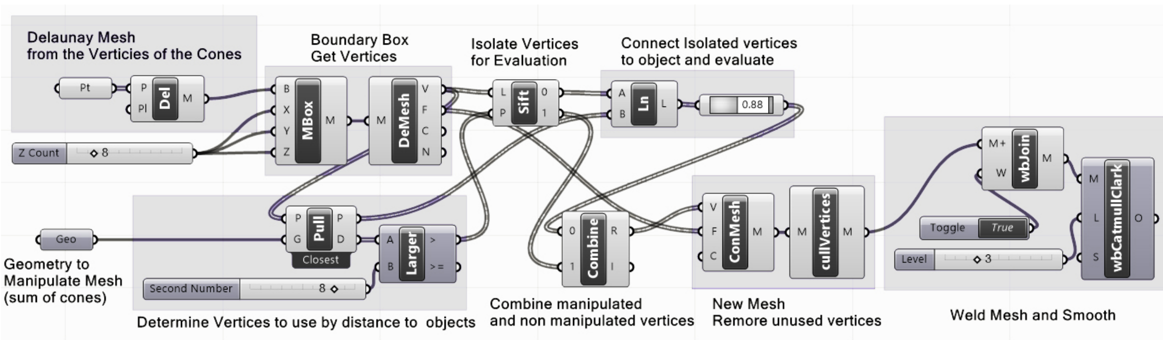
The following list includes the operations used in Parametric System Rhino 3D - Grasshopper, to implement the morphological exploration of the atrium lobby of the New Parkland Hospital. The algorithms developed using the visual language of Grasshopper for each one of the Precedents (Section 4), are presented in Figures (12 - 14).

Table 1 Operations used in the parametric system Rhino 3D with Grasshopper (Appendices B - D).

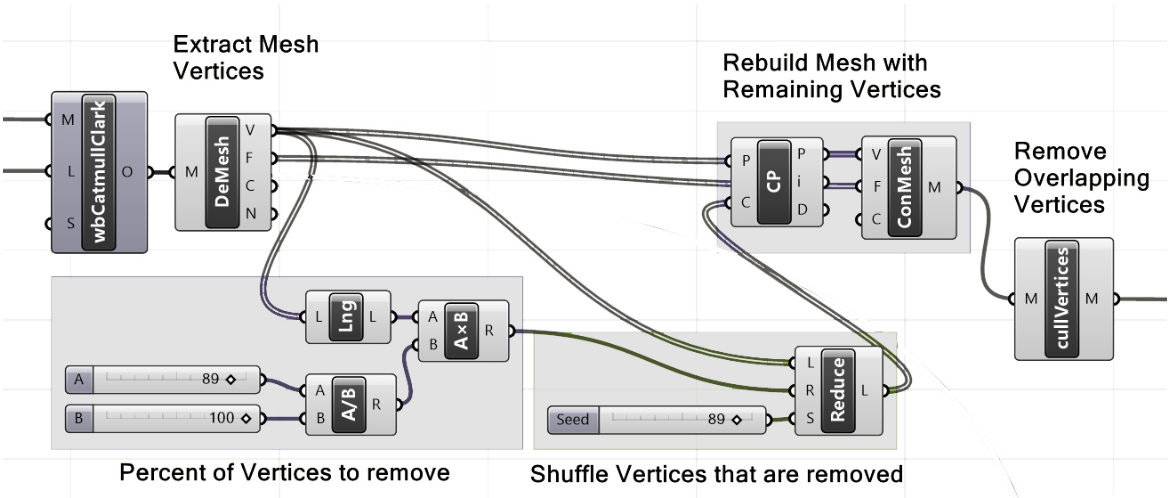
Short name	Full name	Description
A,Z,C,V Count	Number Slider	Numeric slider for single values (N, R, E, O)
AxB, A/B	Multiplication, Division	Multiplication, Division of two numbers of lists
Area	Area	Properties of breps (boundary representations), meshes
Bnd	Bounds	Numeric domain which encompasses a list of numbers
Combine	Combine Data	Combine non-null items out of several inputs
ConMesh	Construct Mesh	Construct a mesh from vertices, faces or colours
CP	Closest Point	Find the closest point in a collection
cullVertices	Mesh Cull Unused Vertices	Remove currently not used vertices
DeFace	Deconstruct Face	Deconstruct a mesh face into its four corner indices
DeMesh	Deconstruct Mesh	Deconstruct a mesh into components
Dist	Distance	Compute Euclidean distance (two coordinates)
Dom	Construct Domain	Create a numeric domain from two numeric extremes
Dots	Dot Display	Draw a collection of dots (as a preview)
End	End Point	Extract the end points of a curve
EvalSrf	Evaluate Surface	Evaluate local surface properties at a uv coordinate
Geo	Geometry	Contains a collection of generic geometry
(uv Grid)	MD Slider	A multidimensional slider
Item	List item	Retrieve a specific item from a list
Larger	Larger Than	Larger than or equal to (between two numbers)
Level	Number slider	Numeric slider for single values used for Levels
Line	Line SDL	Line segment defined by Start point, Tangent, Length
Ln	Line	Create a line between two points
Lng	List Length	Measure the length of a list
MA	Mass Addition	Perform mass addition of a list of items
MIN/MAX	List item (MIN/MAX)	Retrieve minimum/maximum item from a list
MBox	Mesh Box	Create a a mesh (shape of a polyhedral object) box
PlaneSrf	Plane Surface	Create a plane surface
Project	Project	Project an object onto a plane
Pt	Point	One point or a collection of three-dimensional points
Pull	Pull Point	Pull a point to a variety of geometry
Rad	Radians	Convert an angle specified in degrees to radians
Reduce	Random reduce	Randomly remove N items from a list
ReMap	Remap Numbers	Remap numbers into a new numeric domain
Rev	Revers	Reverse a vector (multiply by -1)
Rot3D	Rotate 3D	Rotate an object around a centre point/axis vector
Scale	Scale	Scale an object uniformly in all directions
SDivide	Divide Surface	Generate a grid of uv points in a surface
Sift	Sift Pattern	Sift elements in a list using a repeating index pattern
(Slider to Ln)	Point on Curve	Evaluate a curve at a specific location
Sort	Sort List	Sort a list of numeric keys
SrfGrid	Surface from Points	Create a nurbs surface from a grid of points
Srf4Pt	4 Point Surface	Create a surface connecting three or four points
Toggle	Boolean Toggle	Boolean True/False Toggle
u (u+1) R	Expression	Evaluate an expression
wbJoin	Weaverbird's Join Mesh and Weld	Returns a singular mesh object made out of a list of meshes (less footprint than the original meshes)

B. IMPLEMENTATION OF PRECEDENT P1

"Visual access to landmarks and signage from the entrance or a transition point can promote the navigation performance." (Section 4)



(a) Object-manipulated mesh algorithm in Rhino 3D-Grasshopper



(b) Mesh reduction by vertices algorithm in Rhino 3D-Grasshopper

Fig. 12 Two parts of the algorithm developed in Rhino 3D-Grasshopper for the implementation of the design Precedent P1. The meaning of each operation is stated in Appendix A, Table 1.

C. IMPLEMENTATION OF PRECEDENT P2

> "Transparent materials and voids extend the visual range, give access to outdoor landmarks and contribute to global spatial orientation." (Section 4)

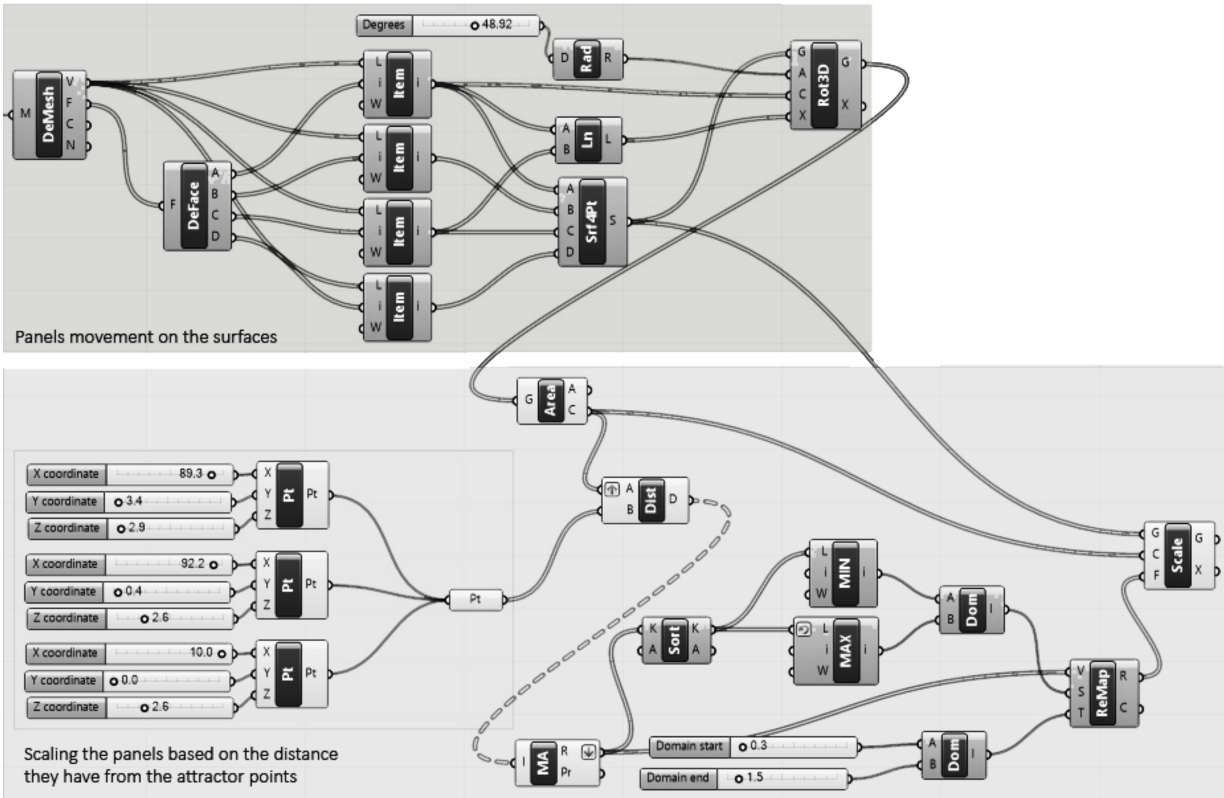


Fig. 13 An algorithm for surface rotational-segments manipulation based on attractor points, for the implementation of the design Precedent P2. The meaning of each operation is stated in Appendix A, Table 1.

D. IMPLEMENTATION OF PRECEDENT P3

> "High ceiling and wide places expand visual search and can be related to a sense of comfort and a positive spatial experience." (Section 4)

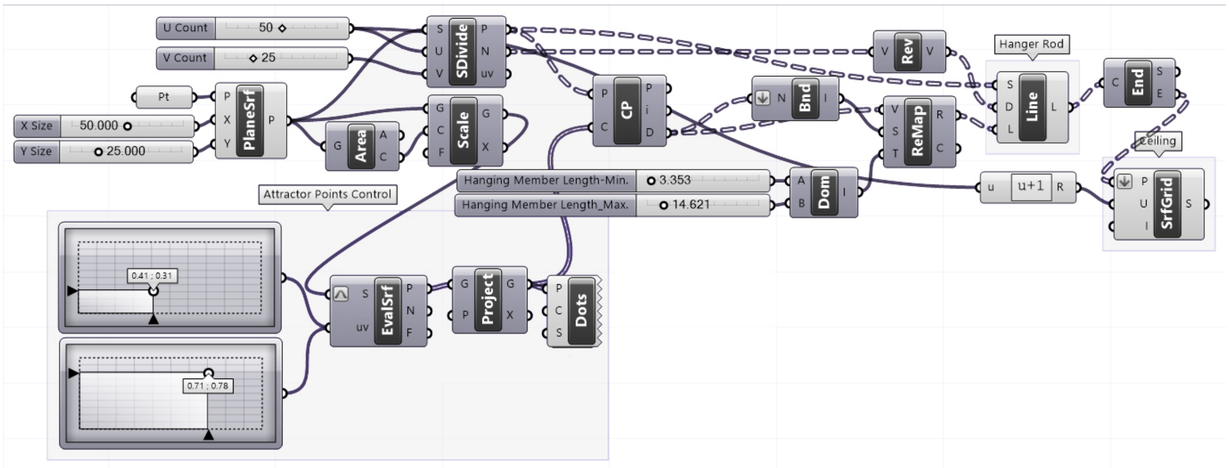


Fig. 14 An algorithm for the surface manipulation based on attractor points and a hanging rod, for the implementation of the design Precedent P3. The meaning of each operation is stated in Appendix A, Table 1.

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