New Graphic Tools for Hospital's Spatial Analysis and Design

Pilar Chías Navarro(✉), Tomás Abad, and Gonzalo García-Rosales

Department of Architecture, University of Alcalá, Madrid, Spain
{pilar.chias,tomas.abad}@uah.es,
gonzalo.grosales@gmail.com

Abstract. Mathematical concepts applied to architectural design, arise frequently from intuition. Among them, topology has proved to be particularly useful in the previous stages of the architectural projects, when location of uses and itineraries is defined. On the other hand, topology brings lots of possibilities in these phases where no dimensional definition is needed, but just to satisfy some topological properties. It becomes then a powerful easy tool to show and analyse different solutions through their spatial relationships. Concepts as continuity, connectedness, intersection, or inclusion, can be directly applied to layout schemes, setting the basis to further dimensioning. These concepts were traditionally managed and carried out in Geographic Information Systems (GIS), and now can be applied to the architectural design processes by means of the Building Information Modelling (BIM). As a particular application, the architectural design of hospitals and other healthcare facilities benefits directly from topology. This is due, firstly, to their high complexity derived from their particular technical, functional, and instrumental constraints. Secondly, topology becomes helpful to design the inner and outer itineraries of both people and logistics, paying attention to the specific problems derived from transfer points, pollution risks, and intersections.

Keywords: Topology · Space syntax · Architectural design · Architectural analysis · Healthcare facilities

1 Introduction and Main Targets

When considered from the point of view of the inner spaces design, hospitals built along the 20th century showed a definite spatial organisation. It was based on the dualism between Clinical Services and Central Units, where the late had their own specific spatial configuration with regard to the rest of the healthcare facility (Casares 2012, 8–13). Current new concepts in sustainable hospitals are related to green healthcare and imply a paradigm shift (Chías and Abad 2017b).

On the one hand, environmental and health impacts related to the design, construction, and operation of healthcare facilities, are an essential part of our research project, because in order to provide an optimal care the impacts of the built environment on human health should be determined (Frumkin and Coussens 2007, xii). On the other hand, the shape and structure of new hospitals result from the increasing

C. L. Marcos (ed.), Graphic Imprints,
https://doi.org/10.1007/978-3-319-93749-6_106

predominance of Units and Systems over Clinical Services, due to a centralised management.

A new fitting design implies to consider some new concepts, where many spaces become polyvalent and are grouped for being used by different healthcare Units. And as a consequence, there is a nonconformity between the functional organisation of the Clinical Services and the distribution of spaces where their activities take place.

Furthermore, the lack of correspondence between the indoor hospital spaces and their connections is gradually becoming more evident. Accordingly, one of the outstanding targets of our research is the definition of a methodology that considers an adequate design of adjacencies between Units and Services, and of circulation and communication spaces, and accessibility, corresponding to the need of relationships between the different areas.

In short, our research focuses on the identification of opportunities for improving the existing health facilities according to the new concepts related to green hospitals.

2 Methodology

From the starting point of the interest on mathematics and its possibilities to be graphically expressed, the capability of drawing to communicate the qualities of space must be stressed. As long as topology is concerned with the properties of space that are preserved under some continuous deformations—such as stretching, crumpling or bending—they can be graphically depicted and applied to many purposes.

The architectural project can benefit of these possibilities from the early design stages, because topology opens a big range of possible solutions that can be easily shown in a flexible manner, and comprehensive spatial analysis can be made.

2.1 Topology

As topology is concerned with the properties of space that are preserved under continuous deformations, it has proved to be particularly useful in the previous stages of the architectural projects, when the location of uses and itineraries is defined. Concepts as continuity, connectedness, intersection, or inclusion, can be directly applied to layout schemes, setting the basis to further dimensioning. As a consequence, topology becomes then a powerful easy tool to show and analyse different architectural solutions.

Topology becomes also a helpful tool to design the inner and outer itineraries of both people and logistics, paying attention to the specific problems derived from transfer points, pollution risks, and intersections (Fig. 1).

Users' movements are usually described in an abstracted form by means of their topological properties that permit to focus on the structural relationships between units while disregarding the details of phenomena. For instance, the public itineraries inside a hospital can be described using a structure of shapes and lines without considering essential details as sizes or forms, number of users or speed of movement. Such network configuration can be also referred to as a graph or diagram, which is a way to represent a network by a set of edges that connect pairs of vertices.

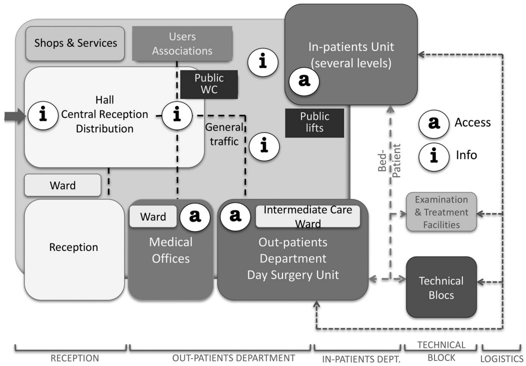

Fig. 1. Topological concepts and properties applied to design public indoor and outdoor itineraries in a hospital or a complex healthcare facility *Source* the authors

Moreover, topology brings lots of possibilities in these phases where no dimensional definition is needed, but just to satisfy some topological properties.

This is due to topology's capability to transmit the project's general order in every phase before dimensioning. All these utilities can be considered as an essential complement to other mathematical-based artistic or theoretical and speculative expressions. Thus it is important to explore a feasible way for building the connectivity relationships among spatial—architectural—features (Chías and Abad 2017a) (Fig. 2).

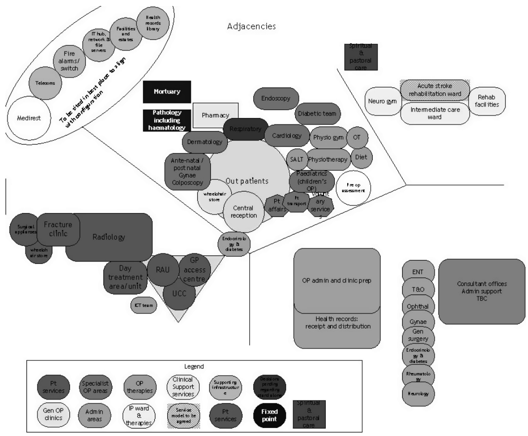

Fig. 2. Proposed adjacencies between different departments and units in a hospital. *Source* The authors

Three types of methods for topology network deviation are mainly used: the pure geometry-based (Lee 2001), the geometry-semantics based—which is our particular interest—and the pure semantics-based (Lorenz et al. 2006).

2.2 The Space Syntax Technique

As a complementary tool, we applied some network analysis techniques to indoor spaces (Kim et al 2008), and particularly the space syntax technique, that becomes particularly interesting to our case study because it has been used to derive the connectivity of urban and architectural spaces (Hillier 1996).

The space syntax theory was traditionally based on topology, and basically applied to studies dealing with accessibility and connectivity between urban spaces or complex architectural organisations (Penn et al. 1998). However, space syntax concerns geometric connectivity of spaces, and is only based on spatial links, while aspects as easiness or difficulty of indoor movements are neglected.

Similarly, spaces and departments inside the hospital are represented in space syntax as a set of connected discrete units, in spite of being a single continuous space. The concept of convex space partitioning or axial mapping is used, what involves taking a proposed spatial structure and partitioning into a set of "fewest and fattest" convex spaces (Hillier and Hanson 1984, pp. 97–98).

All these depictions are traditionally produced by means of 2D representations, which are easily checked and analysed. On the other hand, the difficulties found in spatial analysis lie in the inherent limitations of 3D models, as they were developed focusing on visualisation of buildings or towns, and fostering the appearance of reality. As a consequence, these models lack of the topological structures that are required for spatial analyses or queries, as their objects are not divided into spatial units and relationships between them are undefined.

3 Case Study: The University Hospital of Guadalajara, Spain

As a particular application, the architectural design of hospitals and other healthcare facilities benefits directly from topology. This is due to their high complex organisation which derives, on the one hand, from their particular technical, functional, and instrumental constraints. And on the other hand, from the specific problems set by the needs of their specific spatial relationships.

The research involves the study of four major Spanish public hospitals that are located in Madrid and its surrounding area: the Hospital Central de la Defensa Gómez Ulla in Madrid, the University Hospital Ramón y Cajal—also in Madrid—the University Hospital Príncipe de Asturias in Alcalá, and the University Hospital in Guadalajara.

Although all of them are University Hospitals and provide world-class clinical services, each one serves to a population with different characteristics, and responds to different healthcare needs.

As a particular case study we chose the University Hospital of Guadalajara because it is located in an interesting environment outside the town, and shows many possibilities for expansion and outdoor planning and design.

This hospital is the specialised health facility for the population of the neighbouring municipalities of Guadalajara that are located within a radius of more than 60 km (Table 1).

Table 1. Main characteristics of the University Hospital of Guadalajara

Year	No. of beds	Site surface (m^2)	Built surface (m^2)	Typology
1982–2007	380	45.024	60.101	Tower with 10 storeys, and enlargement
2018 (ext.)	771		124.786	

It is 62 km far from Madrid, and 0,600 km from the city centre of Guadalajara, at the south east of the town. The Hospital is well communicated, as it is already connected with Madrid and the city centre by means of near public transport routes—various bus lines—and an access road for both public and private transport.

From the typological point of view, it is an isolated flat roofed ten storey building, which is surrounded by a garden. It is currently crossed by access roads and used as parking areas (Figs. 3 and 4).

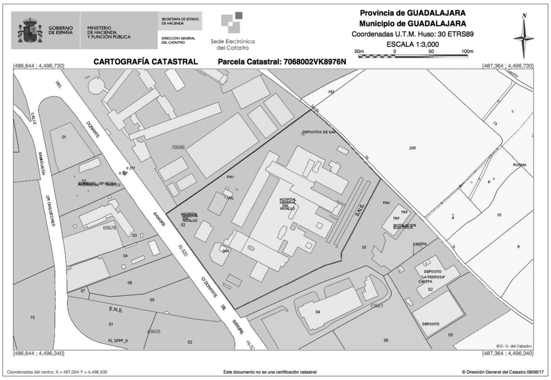

Fig. 3. Cadastral map of the University Hospital of Guadalajara. *Source* Dirección General del Catastro 2017

The procedure for generating the convex maps is iterative. It starts with the identification of the fattest of the convex spaces, and then identifies gradually the next largest ones until the entire area is subdivided into a set of convex spaces. The axial map is then drawn on the convex map by laying down the longest straight line passing through these convex spaces. It implies a different procedure with respect to the traditional way of representing a street network, that uses centre street lines and the corresponding intersections. On a graph, space syntax represents each line by a node and each intersection as an edge, while in the traditional method the situation is vice versa. It means that an intersection becomes a node, and a line connecting two nodes is an edge.

A first solution consists in constructing a 2D model and to associate the respective three-dimensional datasets. In this case, indoor spaces are composed of polygons

Fig. 4. The University Hospital of Guadalajara from the south-east. *Source* G. García-Rosales

representing hallways, wards, and all types of spaces, while their relationships can be clearly defined by means of GIS layout schemes through topology. To apply this method to a 3D building, a data model must be produced representing both rooms and itineraries using a network model composed of links and nodes, where nodes represent doors and entrances. Obviously, emergency exits take priority to other. Axial links connect nodes along the centre lines of hallways and corridors, and resistance to the flow—impedance—is categorized into different values according with different strengths. Third dimension is mapped as stair and lift links (Fig. 5).

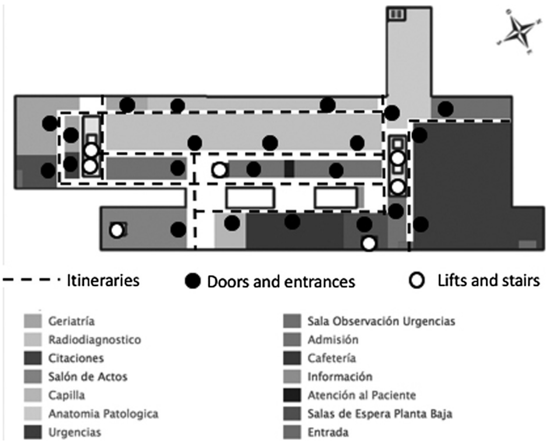

Fig. 5. Axial map of the ground floor plan. Black dots depict doors and entrances, while white dots represent vertical connections as lifts and stairs. University Hospital of Guadalajara. *Source* The authors

On the other hand, graphs do not include neither quantitative nor qualitative information, that becomes essential to identify the problems that can appear when walking along a particular itinerary. For this purpose, the main empirical method is based on formal, semi-structured interviews with supplementary document analysis, on informal meetings and discussions, on observations, and subsequent feed-back on reports. According to them, some outputs as *spaghetti* diagrams can be produced to track the inner flows and to identify users' itineraries, among other (Fig. 6).

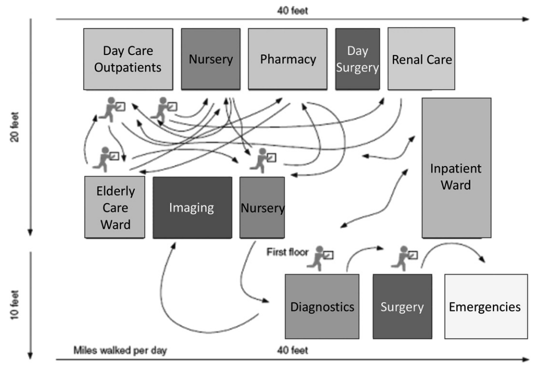

Fig. 6. *Spaghetti* diagram showing the main itineraries of the clinical staff inside a Hospital. *Source* The authors

According to functional differences in a corridor stretch, we can define five types of nodes: CrossPoint, WindowPoint, DoorPoint, StairPoint and EndPoint.

On the other hand, the inner structure of a hospital appears to be particularly complex, as there are many rooms and subrooms inside each Clinical Unit. From a functional point of view, in order to facilitate the construction of the graph structure, the first step is the subdivision of the footprint of each floor. Rooms can be virtually linked with the corridors by means of doors or windows. Subrooms can be linked to corridors only through rooms. Stairs and lifts are singular spaces, that are identified as vertical links at each level. Finally, stairs can be also virtually linked to corridors via accesses and exits.

If we consider the specific requirements for indoor navigation related to functionality and the kind of user—Indoor Navigation Ontology—the organisation of each floor layout can be represented by the corresponding graph and defined by means of the topological properties of rooms and connections, and other produced documents as surveys, etc., that will be linked to each edge or node of the graph (Evans and Minieka 1992) (Fig. 7).

In this sense, the users' profile is relevant in topological network construction because different users have specific physical and perceptual capabilities. A physically impaired user can only move from one level to another by taking the lifts, what is impossible in emergency situations. Users' location can be also tracked by means of the network analysis. In this case, the concept of event denotes every obstacle to the users' flow. It can be a physical object that blocks a corridor—particularly in emergency situations, as when a wall that collapses—but also a closed door with special requirements to be opened, or just a lift out of order.

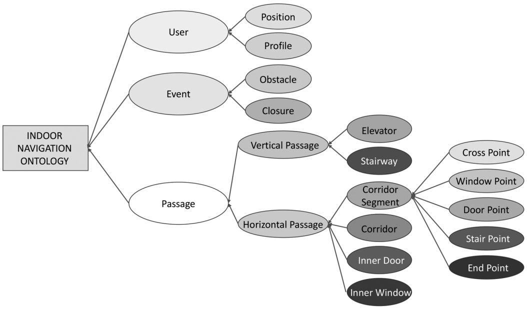

Fig. 7. The indoor navigation ontology. *Source* The authors

By means of all these tools, groups of interest will also get a better feel for the spaces, itineraries, and access points, and will visualise proposals and make comments during the meetings and discussions with the architects, leading to quicker decision-making.

4 Discussion and Conclusions

The increasing complexity of hospital design needs a deep exploration of feasible ways for building the connectivity relationships among spatial features. Traditional topology approaches for indoor spaces were previously based on 2D maps or pure geometrical models, which proved to be inadequate to manage other essential related information. The trouble caused by existing topology construction approaches can be prevented by using 3D models which contain detailed semantic and geometric information.

The utility and applicability of mathematics to architectural design is evident in space syntax and 3D modelling, as they both focus on operating objectives through analytical means such as accessibility, which are required for better spatial plans or guidance purposes for people and logistics. Topology helps to pay attention to specific problems derived from transfer points, intersections and pollution risks.

Concepts related to topology that were traditionally managed and implemented in Geographic Information Systems (GIS), now can be applied to architecture by means of Building Information Models (BIM).

Nowadays space syntax and BIM become useful tools to be applied to every architectural project with a high level of complexity, of which hospital and healthcare facilities design is just an example. Both methods support the essential involvement of hospital's users—although attaching different weight and priority—as their specific applications to the architectural project cover different fields, and can be introduced in different phases. The outcomes of interest during the whole process are the *interim criteria* and subjective assessments that can be used to make decisions.

Another conclusion to be stressed is that 2D space syntax method is cheaper and faster than BIM, because the associated information is limited. It can be applied to practical situations such as building layout project and disaster prevention. In turn, 3D models are easiest to understand due to their visualisation capabilities, making able to the clinical staff to literally walk around the facilities. But they are also more sophisticated systems and become more rigid if they have to be modified. As they must be applied since the first phases of design, they become also less versatile, and their implementation is more expensive. In turn, an early implementation can be maintained until the end of the service life of the healthcare facility.

The introduction of other factors as distance, time, resistance to the user's flows—impedance—or connections between different indoor space levels, was a step ahead to deal with spatial problems. These advances implied a conceptual and operational change from 2D GIS packages to 3D models (Kim et al. 2008)

Technologies of information and communication (TIC) as location-based services (LBS) which are space syntax-based, have been applied to car navigation or personal guidance systems. As a result, we are now facing some apps design as specific wayfinding technologies which are also applicable to indoor and outdoor hospital spaces.

Acknowledgements. This paper is a result of the research project BIA2016-78893-C3-1-R "Methodology of evaluation of comfort requirements, environmental conditions, and spatial functionality of hospitals and their surroundings. Adaptation proposals to new sanitary concepts".

We want to acknowledge the Spanish Ministry of Economy and Competitivity and the EU for their support.

The project team is also grateful for the help and support of Lucio Cabrerizo García, Managing Director of the Hospital, and Asís Jové, Medical Director.

References

Casares A (2012) Arquitectura Sanitaria y Hospitalaria. Madrid, Escuela Nacional de Sanidad. Available at http://e-spacio.uned.es/fez/view/bibliuned:500920. Accessed 7 June 2017

Chías P, Abad T (2017a) Topology for health care facilities' design. XY Digitale 3:156–169. http://dx.doi.org/10.15168/xy.v2i3.48

Chías P, Abad T (2017b) Green hospitals, green healthcare. Int J Energy Prod Manage 2(2):196–205. http://dx.doi.org/10.2495/EQ-V2-N2-196-205

Evans JR, Minieka E (1992) Optimization algorithms for networks and graphs. Marcel Dekker Inc., New York

Frumkin H, Coussens C (eds) (2007) Green healthcare institutions: health, environment, and economics. Workshop Summary. Available at http://www.nap.edu/catalog/11878.html. Accessed 12 May 2017

Kim H, Jun Ch, Cho Y, Kim G (2008) Indoor spatial analysis using space syntax. In: The international archives of the photogrammetry, remote sensing and spatial information sciences, vol XXXVII, part 2, pp 1065–1070

Hillier B (1996) Space is the machine. Cambridge University Press, Cambridge

Hillier B, Hanson J (1984) The social logic of space. Cambridge University Press, Cambridge

Lee J (2001) A 3D data model for representing topological relationships between spatial entities in built-environments. Ph.D. dissertation, The Ohio State University. Available at https://etd.ohiolink.edu/!etd.send_file?accession=osu1486399451960626&disposition=inline

Lorenz B, Ohlbach HJ, Stoffel E (2006) A hybrid spatial model for representing indoor environments. In: Web and wireless geographical information systems. 6th international workshop (W2GIS 2006), Hong Kong, China, 4–5 Dec 2006. Springer, Berlin, pp 102–112

Penn A, Hillier B, Banister D, Xu J (1998) Configurational modelling of urban movement networks. Environ Plan B Plan Design 25(1):59–84

Pilar Chias is Ph.D. in Architecture, and is Full Professor and Director of the School of Architecture at the University of Alcala. She is responsible for architecture in the coordination team of the Area of Civil Engineering and Architecture in the National Agency for Research of the Spanish Ministry of Economy and Competitiveness (Agencia Estatal de Investigación). She is the Director of Task Group 2, "Open Source in Use for the Cultural Heritage Communication Process," of the International Scientific Committee for Documentation of Cultural Heritage (CIPA), ICOMOS (International Council on Monuments and Sites), and she is also the director of the research team "Intervention in Cultural Heritage and Sustainable Architecture" (University of Alcala). She is a member of IBERCARTO, the Working Group on Spanish Spatial Data Infrastructures (IDEE), the Commission of Cartography (Consejo Superior Geográfico), and the Working Group on INSPIRE for the Spanish Cultural Heritage (Instituto del Patrimonio Cultural de España). E-mail: pilar.chias@uah.es

Tomás Abad is a Master in Civil Engineering EQF 7 and a researcher. He is a specialist in cultural heritage research and documentation, analysis and dissemination, focusing on the study of cartography as an essential tool for knowledge of territory and landscape. He is a speaker and member of the scientific committees of numerous international and national conferences and journals, and has authored 23 books together with P. Chías (several of them award-winning) and more than 100 articles. As principal researchers, he and Chías have conducted more than 50 research projects funded by the National Plan and other sources. E-mail: tomas.abad@uah.es

Gonzalo García-Rosales González-Fierro Degree in Architecture by ETSAM (Madrid). Master in Architectural Restoration by the ETSA of Valladolid. PhD Architect by the University of Alcalá, with Special Mention in International Doctorate. As a researcher, he is part of several Projects and Research Groups. Currently, he participates in the Research Team "Hospital Architecture" (UAH), directed by Pilar Chías. He is Associate Professor of the Graphic Expression Department of the Department of Architecture at UAH (Alcalá de Henares), and Associate Professor of the Department of Graphic Ideation at ETSAM (Madrid. He has participated in conferences, courses and seminars on topics related to Graphic Expression, Plastic Arts, and Audivisual Communication. In 2016 he was a member of the Organizing Committee of the XVI International Congress of Expression Architectonic Graphic at the School of Architecture of UAH (Alcalá de Henares). E-mail: gonzalo.grosales@gmail.com