SIGN-BY-SIGN

Using graph theory to develop a wayfinding decision support tool for architects in early stage design

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Abstract. Wayfinding plays an integral role in the ease of movement and experience of a place when travelling between locations. Signage is crucial to this as it helps ensure people in unfamiliar environments can successfully navigate to their destination when faced with numerous spatial decisions. The design of wayfinding strategies is complex and requires careful consideration of its effect on the overall design and legibility. This research aims to develop a decision support tool which assists the designer in the placement of directional signage within indoor spaces in the early stage of design. These positions are informed through connecting the spatial qualities of an environment using weighted graph theory with consideration of visibility, pedestrian traffic density and connectivity. This connection between entrances, points of interest (POI) and destinations brings a quantitative understanding to the how people navigate through the generation of visual maps, pathing and node values. The result from this approach is an automated system which can optimally place signage within a given Revit floor plan. The signage information is visually outputted in a plan with relevant information and analysis displayed to inform designers on possible design adjustments. The research contributes to the development of autonomous design environments, expanding the opportunities of collaboration between the designer and computer aided design tools.

Keywords. Signage, Graph Theory, Wayfinding, Automation, Decision-Making

1. Introduction: (Research context and motivations)

We live in a world of connection. Not only through the internet and mobile phones, but through numerous networks in natural complex systems from molecule interaction to human relationships, social systems and physical systems. This includes wayfinding which is a fundamental yet complex human activity which we undertake daily. Wayfinding describes how people navigate from a start point to their destination through path planning and decision-making (Weiner et al. 2012).

While urban travel has been the forefront of research in wayfinding, in recent years indoor spaces have taken a significant field of interest, particularly public buildings. This is due to the lack of external navigation support which means a reliance on the buildings structure, experience and visual aids to navigate (Holscher et al., 2007). It is through these systems that we can develop “mental maps” of our environment which helps us simplify and remember areas for future journeys (Lynch 1960). Signage is one of these visual aids which has proven to be the most effective for those unfamiliar to an environment (Huang et al. 2017; Montello 2010). “A layout with no wayfinding signs is as confusing as a maze” (Huang et al. 2017).

Signage not a new concept, but the strategies to place them within indoor spaces is lacking. Traditionally the signage strategy is a manual process which relies on the experience and intuition of the designer. This approach is time consuming and effectiveness of the design decisions can be compromised through assumption (Calori 2007). The flaws with intuitive design become more noticeable as the space becomes more complex. The layout must also be developed before any testing can be completed on its effectiveness, which is typically later in the design process through VR testing or post-construction user testing.

Understanding how signage is placed is reliant on knowledge of how people make sense of space and the decisions made when navigating from point A to B. This network of interconnection and interaction between space can be explained quantifiably through graph theory (Lakshmi 2017). Graph theory has been around for decade, though its integration with architecture, specifically wayfinding has been a recent endeavor. Using the intersection of graph edges as decision points allows them to be weighted in accordance with wayfinding metrics. The method allows for the creation of a tool that provides quick, iterative analysis for any size and shape of design, with multiple and complex routes. This provides the designer with signage placement strategies based on connections and data, complementing their understanding of signage layouts.

2. Research Aims

The aim of this research is to explore how graph theory can be applied in the Architecture, Engineering and Construction (AEC) industry to interpret wayfinding decision making in indoor spaces. This is through seeking to understand the multiple conditions and decisions people make in their everyday journeys. Specifically, the aim is to develop a workflow that collaborates with the designer to deliver an optimal signage location strategy, providing a basis for further industry development.

Taking existing research in the field of wayfinding hopes to set the foundation of knowledge which is used to achieve insight on parameter values and analysis required create a weighted graph. The integration of external Excel data on site usage anticipates a potential integration which can be used to better understand human behaviour within the environment.

3. Research Question

How can graph theory be applied to automate signage placement in the wayfinding strategy of indoor spaces?

4. Methodology

Action research is a holistic approach to problem-solving used in real situations to solve real problems where flexibility, involvement or change must take place quickly (O'Brien 2001). O'Brien (2001) differentiates action learning to other methodologies as "learning by doing". It encourages a "particular way of looking at your practice to check whether it is as you feel it should be" (McNiff 2013, p.23). The 'action' refers to what you do regarding context while the 'research' refers to how you find out about what you do through data-gathering, reflection and evidence (McNiff 2013). While there have been differing definitions and research about action research, all share the core concept of a cyclical and iterative approach to an immediate problem solution. Kemmis (2009) outlined these steps diagrammatically as planning, acting, observing and reflecting which continues until the problem is resolved.

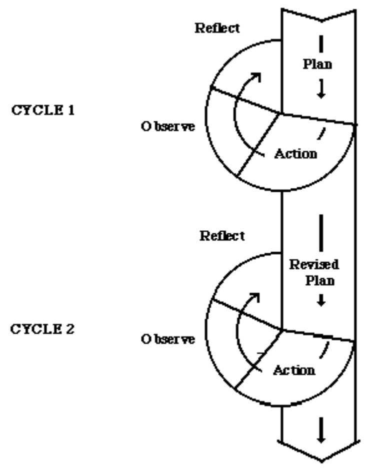


Figure 1. Stephen Kemmis' Simple Action Research Model

This cycle acts as the foundation of action research and through little modification it is capable of being able to "adapt to the context of the individual research progress" (Azhar, Ahmad, & Sein 2010, p. 97). This flexibility enables it to solve problems ranging from social science to AEC. The action research approach has been previously implemented in AEC and has proven to be "well suited to support the development and implementation of information systems" (Hartmann 2009 p. 57).

"Action research is performed collaboratively and enhances the competencies of both researchers and practitioners" (Azhar, Ahmad, & Sein 2010, p. 88). When employing new strategies and technologies into this project it involves the collaboration with industry professionals in the fields of wayfinding and computational design theory and practice. This enables the intertwine of knowledge between different fields of research with key understanding of different shortcomings, opportunities and techniques. Through this partnership ideas can be generated, tested and monitored with relevant input about its progress which modifies the overall progression.

Furthermore, the process of passing data through a system through grasshopper follows a similar iterative cycle. Prior to the initial testing, previous architectural workflows were examined, with problems identified to help determine strategies to proceed. As the script develops, tests on its accuracy and robustness are carried out, with the results reviewed in order to redevelop and refine as required. This process continues to be carried out till a solution is found which creates multiple iterative generations which inform and build from each other. The combination of iterative scripting with industry collaboration "links theory and practice to generate a solution" (Azhar, Ahmad, & Sein 2010, p. 88)

5. Background Research/Literature review

5.1. INTRODUCTION

“The true importance of signage and wayfinding systems only becomes evident when they do not work.” (Lorenz 2010). The shift in AEC processes to a performance-based approach allows for this possibility of failure to be minimised, if not removed. Wayfinding is a spatial issue encountered daily when navigating within an environment. Lynch defines wayfinding as “a consistent use and organization of definite sensory cues from the external environment” (Lynch 1960, p. 3).

Crucial to wayfinding is the system for communicating legible spatial information within a busy environment (Dubey et al. 2019). Signage has proven to be easiest to provide directional information and understanding with a demonstrated ability to attract strong eye fixations even with low visual saliency (Huang et al. 2017; Montello 2010). Automation of wayfinding strategies allows for gradual iterations and adjustments to be made easier and faster in comparison to traditional methods (Roudavski 2009).

When developing a workflow for signage placement, it is critical to be able to understand the decision-making of pedestrians in relation to their complex environment.

5.2. WAYFINDING AND SIGNAGE

Wayfinding explores and examines how people move through their environment, in essence “how living organisms make their way from an origin to a destination” (Carpman & Grant 2001). The main reasons for the failure in a wayfinding system comes down to either a deficiency of information or architectural complexity (Raubal and Egenhofer 1998). Majority of studies relating to wayfinding theories and approaches have a focus on the urban environment. While there is research on wayfinding in indoor spaces (Carpman & Grant 1993; Raubal & Egenhofer 1998), most focus on a specific setting which is indicative of predefined routes. As such, its complexity and adaptability are limited to the environment which the research is conducted in. Passini (1984, 2002) takes a more holistic approach of complex architectural systems with a focus on decision making. He presents the three fundamentals of wayfinding as decision-making, decision-execution and information processing.

To extend this definition environmental psychologists have included the introduction of visual clues that provide orientation and navigation aid. An effective signage system can increase the legibility of a complex environment (Cubukcu 2003). While there has been lots of research on environmental cues and their effect on wayfinding, there is a lack of resources identifying the effectiveness of this research in a system. The current approach to wayfinding systems involve a manual creation of a design through the understanding of theory, experience and intuition of the designer. As a result, the process of developing a strategy lasts for a lengthy period with no evaluation beyond on-site observation post-production (Calori 2007).

5.3. A COMPUTATIONAL APPROACH

As the AEC industry slowly digitally transforms its processes and practices, so does the way designers collaborate with computer aided tools for automating design tasks. Many designers have attempted to recreate the principles presented in the Image of the City (Lynch 1960) using a range of computational strategies. This has included methods of Space Syntax (Bafna 2003), selection criteria (Kavakli & Gero 2001), Inter Connection Density (O'Neill) and route-based complexity (Heye & Tumpf 2003). Each have their own findings and flaws, with some only considering the structural features within an environment. These approaches typically overlook approaches that can quantitatively derive the elements of an environment (Filomena, Verstegen and Manley 2019).

5.4. GRAPH THEORY

Graph theory is a branch of mathematics which started from the Koinsber Bridge's problem in 1735 (Sarma 2012). This concept has developed and over time been applied to more fields of research, including in the AEC industry (Majeed 2020). Graph theory deals with the study of topological relations and it forms as the basis of space syntax. Applying graph theory to architecture involves the conversion of complex spatial environments into a set of relationships of nodes and edges (Majeed 2020). The benefit of graphs in the AEC discipline is through the selection of characteristics relevant to the design problem (Roth & Hashimshony 1988). This allows for the analysis of individual spaces that come together to build a wider system (Kalay 1987).

Common forms of abstraction involve producing convex spaces, axial lines and visibility graphs (Dawes & Ostwald 2013). Michael Betty (2014) proposed an alternative approach that shifted the emphasis from lines of movement to their intersection. This is crucial to wayfinding through providing information on specific location in space which are the intersection of long lines of sight, providing an array of visual information.

Wan and Krishnamurti (2008) created a variant of the ideas presented by Lynch (1960) and Passini (1984) on the legibility problem which they defined as wayfinding manageability. The manageability of a system defines a measure for the facilitation of wayfinding within an environment. Through the development of weighted environmental cues and variables they were able to produce a route-based system which gave an expression of the manageability quantitively. Limitations to the work stem from a macro-only approach at a route level which neglects aspects of the broader environment. Huang et al. (2017) provides a more thorough approach to this which takes graphical representation, optimisations of scheme and paths and adds in an agent-based sign refinement. This additional layer provides a combination of both analytics and human behaviour which is crucial to wayfinding.

5.5. CONCLUSION

Graph theory and other computational approaches have all contributed to the development of an automated wayfinding workflow which provides insights and evaluations of indoor systems. Although the research specific to signage placement is limited and has differing approaches, they all provide useful information to a designer about the way humans understand and navigate through their environment with the help of visual cues. Future studies can be conducted that instead combine a range of optimisation and evaluation approaches like Huang et al. (2017) but for indoor spaces.

6. Case Study

The research explores how to extract decision making points for signage through the development of an interconnected graph which iterates based on wayfinding principles. The process was developed to have a seamless cross platform between Rhino and Revit, to allow for multiple stages of designs to be tested in industry standard work environments. By running through different analysis and optimisation techniques, one can get an understanding of the factors that influence human behaviour and the effect it has on the design of a signage system. Throughout each step of the process action research is undertaken to ensure the goals are being met through collaboration with industry partner.

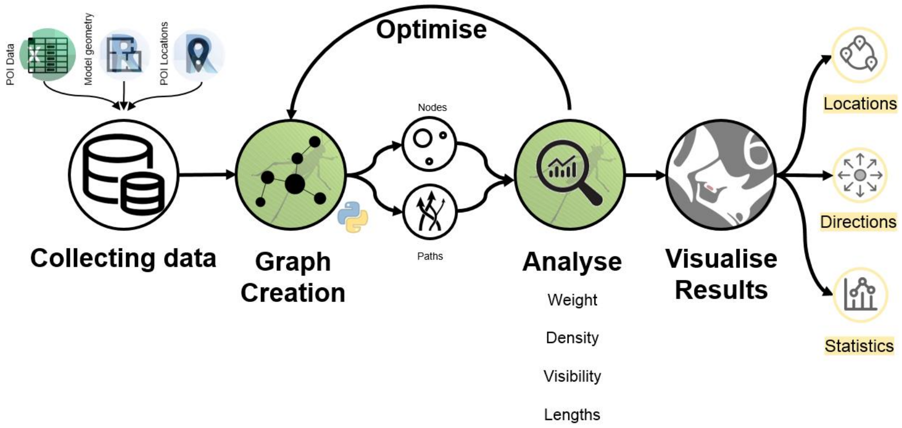


Figure 2. Complete project workflow

6.1 COLLECTING MODEL DATA

Collecting and sharing data forms the basis of the project. Data is feed into the script through two major sources. The first is the Revit model data which includes the geometry of the floor plan as well as the information attached it. The second step involves feeding existing environmental data about POI name and usage. This helps inform the start and end points and weight the graph.

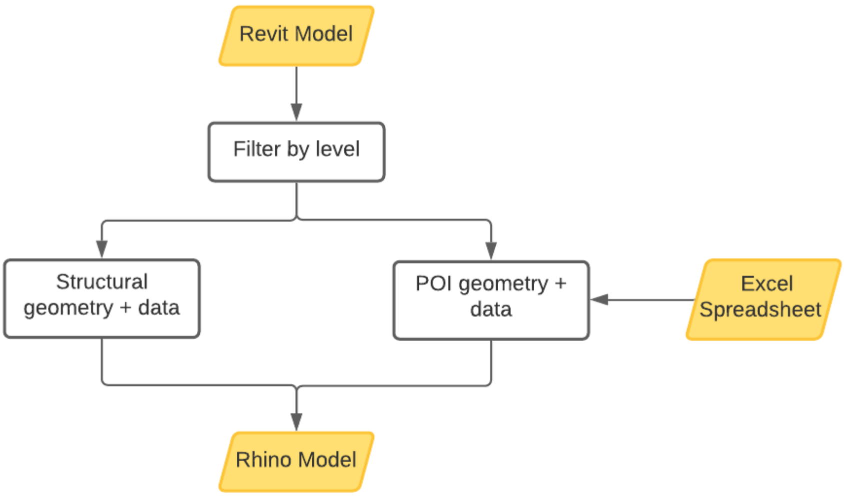


Figure 3. Workflow using Rhino.Inside and Excel

6.1.1 Rhino.Inside

The Revit data is capable of being extracted using Rhino.Inside which runs a live Rhino environment within Revit. This allows for a connected workflow in which changes can be made to the Revit environment and automatically update and integrate with the script without constant importing and exporting. The ability to link to a Revit model is valuable as it is the current industry standard for BIM. All data about Revit families and their parameter values are stored within the Revit file and by the linking this to Rhino gives direct access to its data. Information can subsequently be filtered out to extract only components required for wayfinding analysis. This includes the boundaries (walls, columns, stairs, lifts, etc.) and the POI data which varies depending on the indoor space.

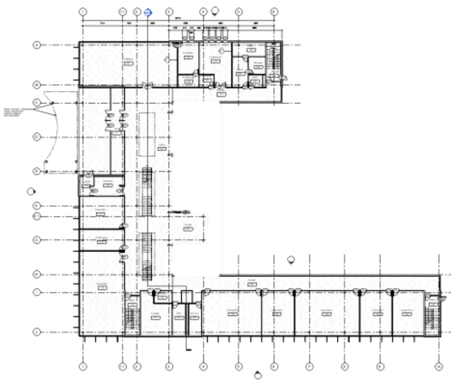


Figure 4. Revit Sample Architecture floor plan

Figure 5. Extracted information in Rhino

6.1.2 Excel Spreadsheet

The Excel data used for this research is a sample file which would hopefully evolve into separate files for different environments. This means that for a station it would include data on all relevant station POI and usage and for a shopping center it would have a separate data set that is relevant to its usage.

This Excel spreadsheet is fed into the grasshopper script and used to extract families with the terms contained in the sheet. This did cause issues as families were inconstantly named so the actual Revit family name had to be inputted from the project.

TABLE 1. Sample Excel spreadsheet data

POI	Revit Family/Tag(s)	Usage (%)
Toilet	.WC	92
Kitchen	Kitchen	26
Lift	LIFT	88
Stairs	Stair	11
Large meeting room	18P MEET	30

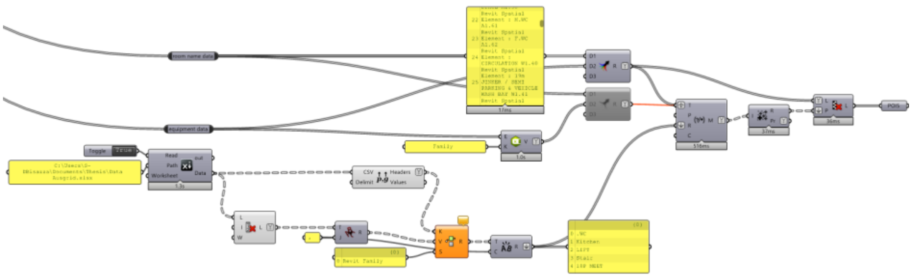


Figure 6. Script for extracting POI from Revit element data using Excel data

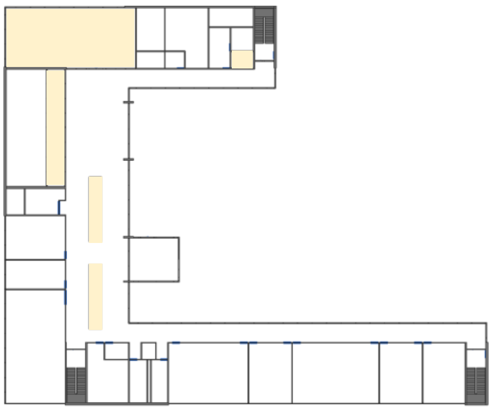


Figure 7. Sample POI geometry isolated in Revit floorplan

6.2 CONNECTING SPACES – CREATING THE GRAPH

In order to test the system, a Rhino environment was initially used. This not only helped increase the speed of development but also allows for the script to work for multiple platform input. The geometry is for initial design stage, with only a rough estimation of areas and locations with input start-destination pairs.

The first step was to create a simplified version of the environment as surfaces which serve as the obstacles within an environment. This includes items such as walls, rooms, lifts, stairs, columns, etc.

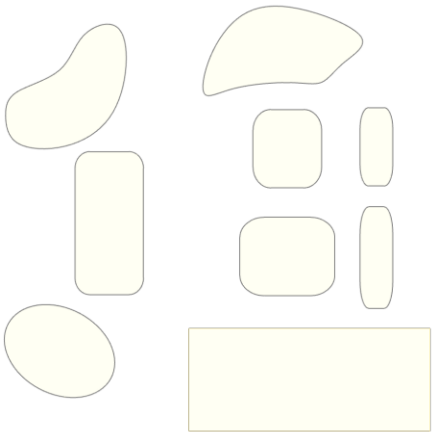


Figure 8. Obstacle Creation

In order to get a sense of how people move throughout the space a graph is created of all possible paths one could take. This was achieved through extracting the medial axis of the plan using Voronoi tessellation on divided points along all edges of the obstacles (Figure 9). The paths were then cleaned by removing any that intersected with obstacles as the path becomes invalid (Figure 10).

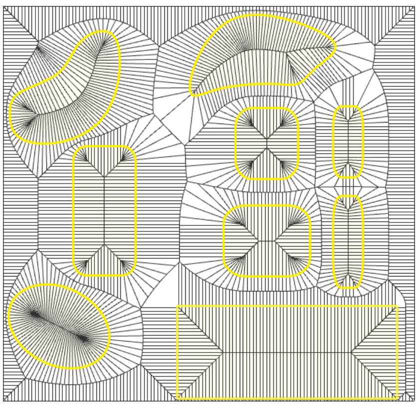


Figure 9. Voronoi tessellation of plan

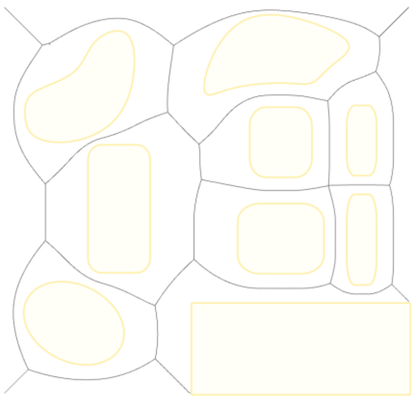


Figure 10. Graph creation of all possible paths

Start and destination points were manually placed using points within Rhino. This differs to the Revit environment where the POI data serves as the start-destination pair which are derived from Excel data. By finding the shortest walk along the paths generated from start to destination, the shortest route people would most efficiently travel between these points can be determined.

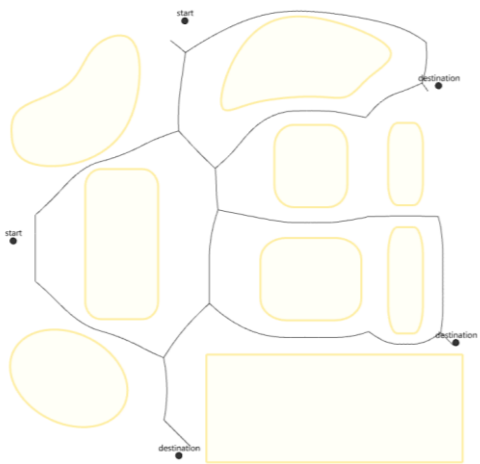


Figure 11. Shortest walk between start and destination points

Using these paths, the points where people would have to make a navigational decision can be identified by calculating if the angle of travel exceeds 45°. These points become areas for potential signage.

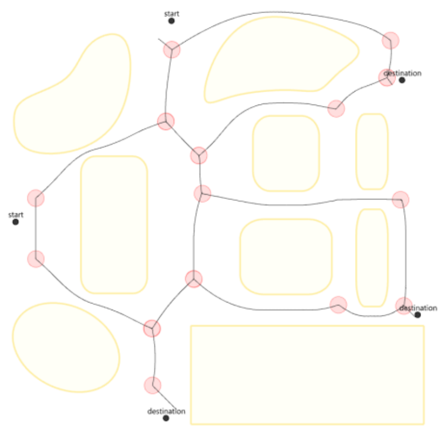


Figure 12. Decision points within paths, indicated by red circles

Using these nodes as starting point for decision making, the direction of travel from the node to the destination allows for a direction to be associated with each node which informs the signage information. In order to reduce the complexity of information provided, all angles were rounded to their closed angle within 0, 90, 180, 270 and 360 degrees.

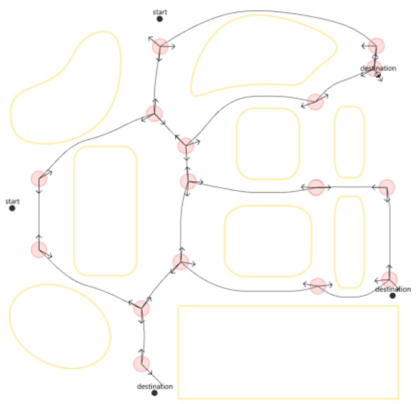


Figure 13. Arrows initially generated

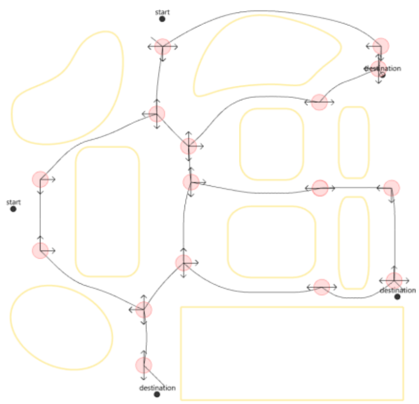


Figure 14. Simplified arrows

6.3 FINDING MEANING – ANALYSIS AND OPTIMISATION

Once the initial system was set-up, several analyses was run to determine the necessity of the sign or whether additional signage would be required. This involved calculating the number of decisions made at each node and its corresponding weighting which dictates the importance of the decision. The weighting is informed by the values from the Excel spreadsheet on the usage percentage of the POI.

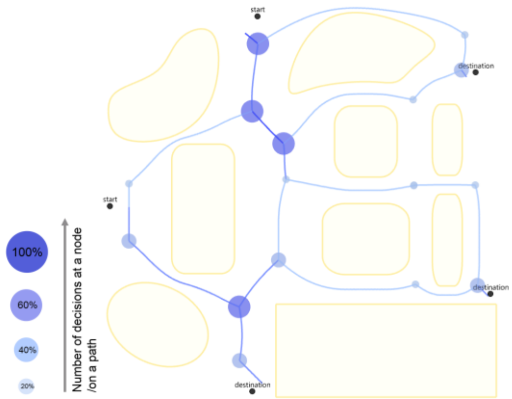
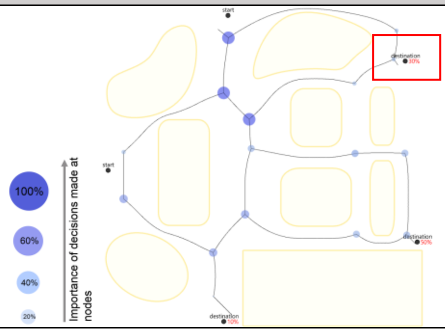
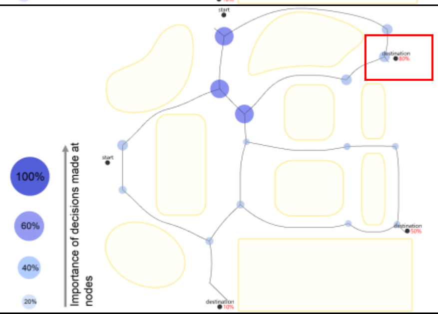


Figure 15. Nodes weighted by connectivity

TABLE 2. Effect of destination usage change on node at destination one (red rectangle)

Destination Usage (%)	Weighted Graph
30	
80	

The final set of analysis was the vision from each sign with consideration of the surrounding environment. This is tested through an isovist analysis from each node to its surrounding area. This help indicate areas with blind spots which might need additional signage as well as areas where signage is most effective and reaches the greatest number of people.

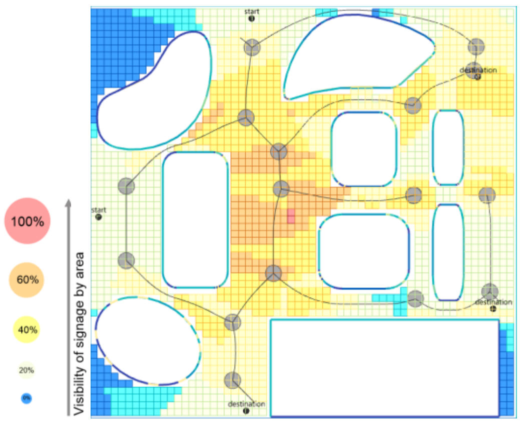
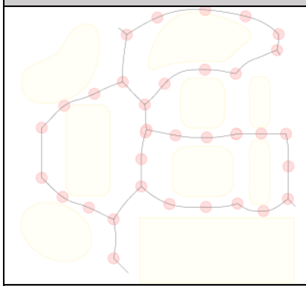
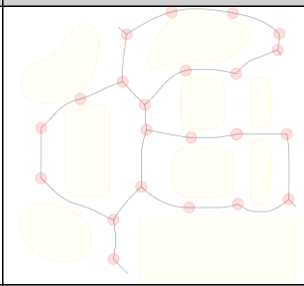
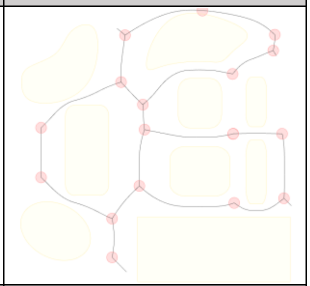
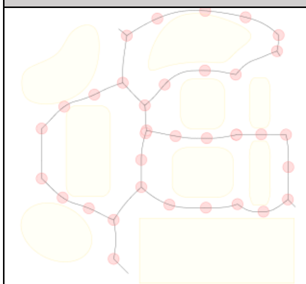
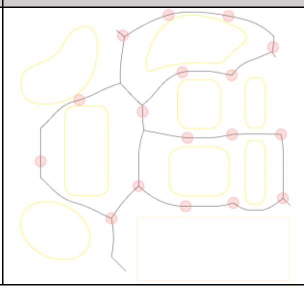
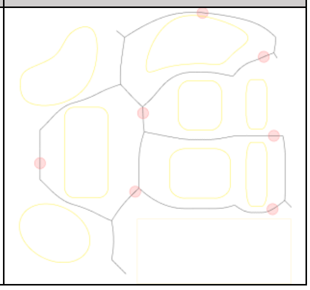


Figure 16. Visibility of area from nodes using isovist analysis

While signage is crucial, it is important that only the essential information is be relayed. Even if the environment is not complex and has good visibility, if there are too many signs it can lead to unnecessary confusion which can cause navigation errors. Likewise, if there are minimal signs which are not within a visible range, reassurance signage may need to be added. This can be facilitated for by having a min and max viewing range which alters the number and positioning of nodes to be within set range. Another factor for node necessity includes whether a sign was placed too close to a destination point where the location would already be visible and only identification signage is required.

In order to assure that new nodes were not placed in inconvenient locations like small corridors or in low traffic zones, the new positioning was weighted based on prior analysis of visibility and centrality of nodes.

TABLE 3. Nodes adjustment based on min and max distances

Max distance = 2m	**Max distance = 3.5m**	**Max distance = 5m**
		
Min distance = 0m	**Min distance = 1.5m**	**Min distance = 3m**
		

The scaling of the sample project was relatively small compared to most public spaces so determining the min and max distance for the Revit project was based on the legibility of text from distances.

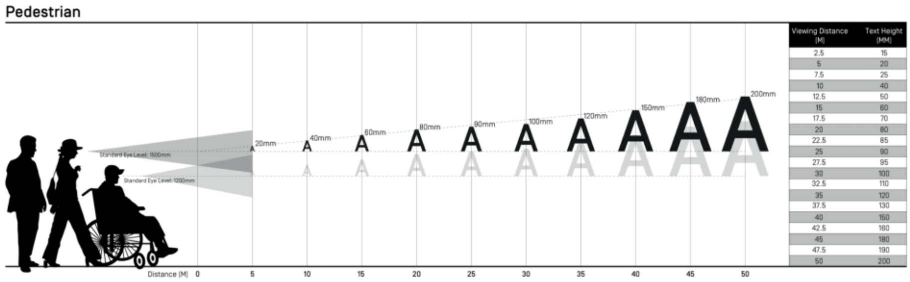
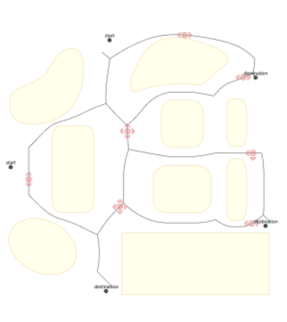
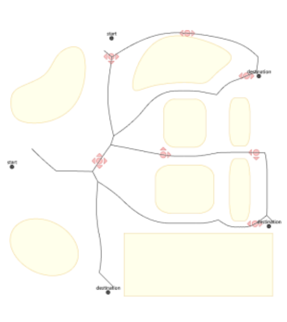
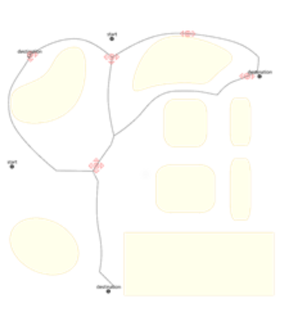
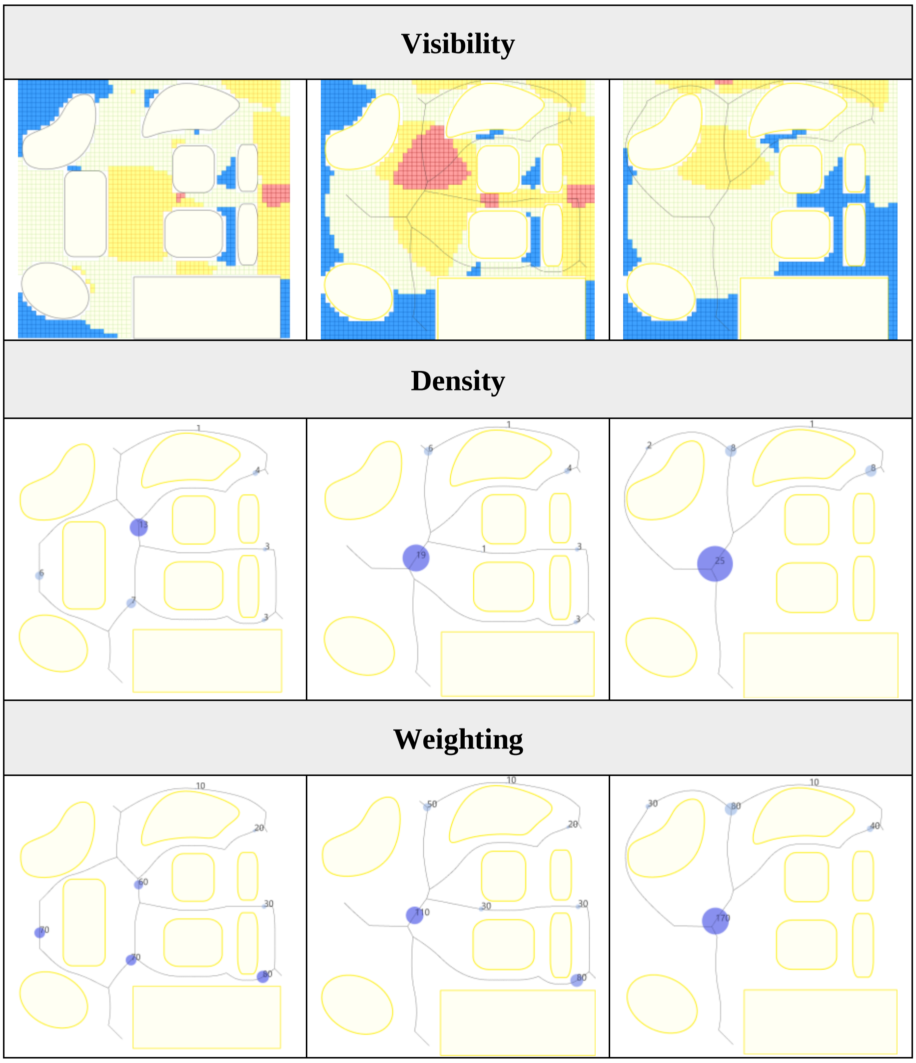


Figure 17. Letter visibility chart (Farm Architects 2019)

After iterating through possible solutions, a result is generated with statistics attached. These values change with adjustments to layout or start-destination pairs. Information on the visual analysis of the layout can also be toggled on and off. The wayfinder can use this information to input their own creative intelligence and discover how it affects the overall system.

TABLE 4. Visual and quantitative results with different circumstances

Initial results	**Change in layout results**	**Moved destination results**
		
Information Provided		
Statistics		
No. of nodes: 7 **No. of paths:** 6 **No. of segments:** 16 **Average segment length (m):** 4.5 **Average path length (m):** 1.1 **Average exit paths:** 2.6	**No. of nodes:** 7 **No. of paths:** 6 **No. of segments:** 13 **Average segment length (m):** 4.4 **Average path length (m):** 1.1 **Average exit paths:** 2.4	**No. of nodes:** 5 **No. of paths:** 6 **No. of segments:** 10 **Average segment length (m):** 3.5 **Average path length (m):** 8.0 **Average exit paths:** 2.6



6.4 TESTING IN A REVIT ENVIRONMENT

While the fundamentals of the code remain the same, the environment and complexity of a floor plan from a Revit project is much higher than a simple Rhino environment. It also allows for boundary geometry and POI data to automatically generate from inputs, removing the manual process.

Several floor plans were tested on to ensure the flexibility of the script to different spaces. The results prove to work in a similar fashion as the Rhino samples however there were some new issues that became noticeable. These involved the need for distance measurements modification due to change in scale, changing the min-max length by destination rather than having it constant and having to store data for level changes. The min-max length for destinations and how far from the destination the signs would generate changed to be based on its usage percentage. As we move into multi-level buildings, destinations exceed single floor plans, in order to try accompany for this, elements that are marked as level changes (stairs, lifts and escalators) are isolated and used to gather data about all paths passing through them. The idea was to transfer this data to the corresponding destination level based on "Base Level" and "Top Level" parameters however these did not exist for all families, so it still requires further development.

6.4.1 Sample architecture project

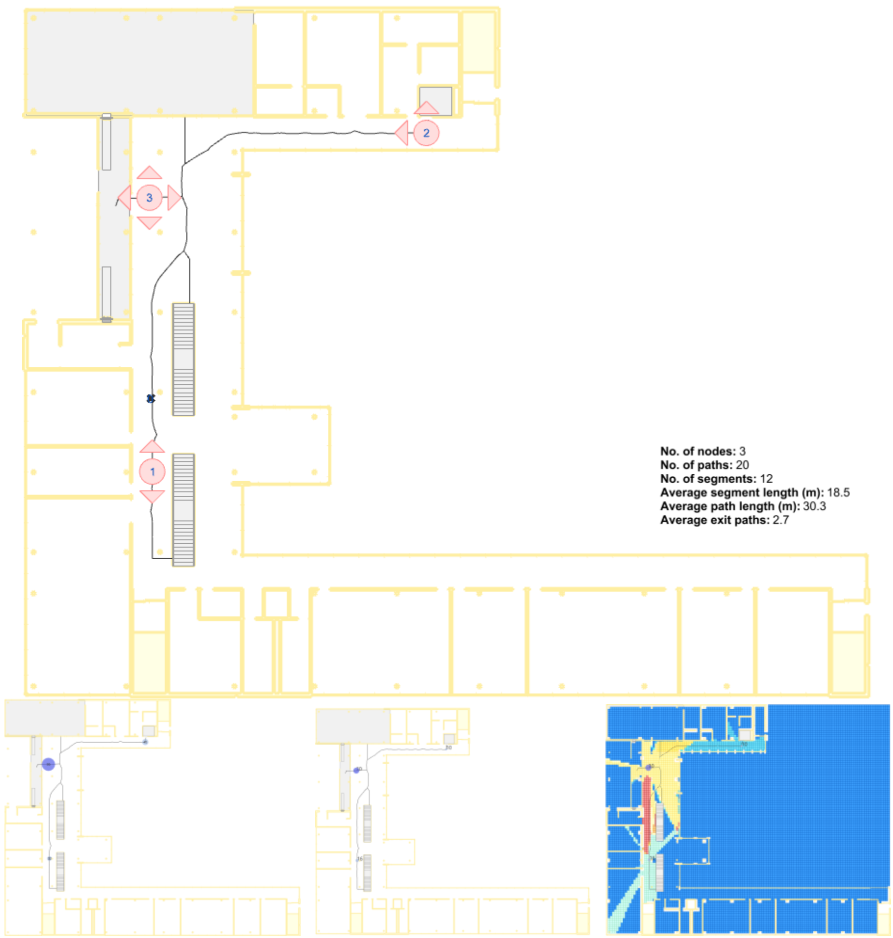


Figure 18. Sample Revit project visual results

TABLE 5. Sample Revit project results exported to Excel

NODE #	Location 1	Arrow direction 1	Location 2	Arrow direction 2	Location 3	Arrow direction 3	Location 4	Arrow direction 4	…	Node weight
1	Entrance	UP	Stairs	DOWN	Kitchen	UP			…	32
2	Toilet	UP	Entrance	LEFT					…	45
3	Toilet	RIGHT	Entrance	LEFT	Stairs	DOWN	Kitchen	UP	…	95

*Arrow direction from view orientation
*Locations descending by weight

6.4.2 Ausgrid

The next model tested on is a project COX Architecture is working on for Ausgrid. The project is divided into three buildings included an engineering/commercial office building, a logistic warehouse and workshops, and a retail café. For this research I focused on the most interesting and complex building for wayfinding, the office.

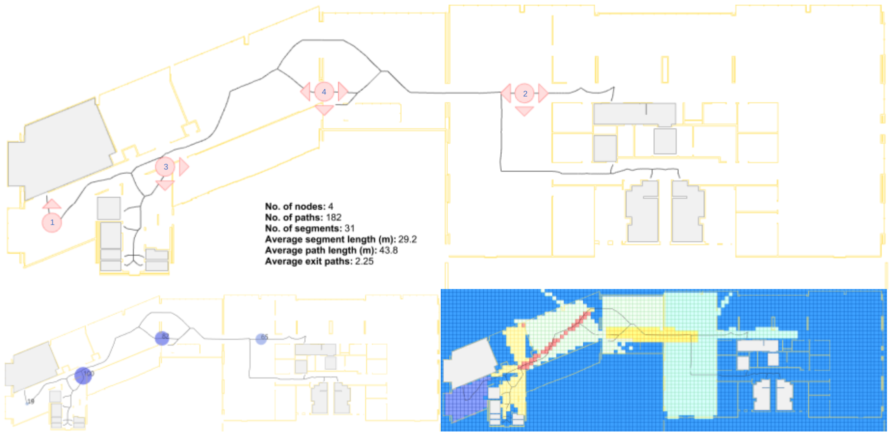


Figure 19. Ausgrid office project visual results

TABLE 6. Ausgrid project results exported to Excel

NODE #	Location 1	Arrow direction 1	Location 2	Arrow direction 2	Location 3	Arrow direction 3	Location 4	Arrow direction 4	…	Nod e weig ht
1	Large Meeting Rooms	UP							…	19
2	Lift	RIGHT	Lift	LEFT	Toilet	DOWN			…	65
3	Lift	DOWN	Toilet	DOWN	Kitchen	LEFT			…	98
4	Lift	RIGHT	Lift	LEFT	Stairs	DOWN	Large Meeting Rooms	LEFT	…	82

*Arrow direction from view orientation
*Locations descending by weight

6.4.3 Station comparison model

The final project tested on was a station model provided by COX Architecture. This model was used as a way of comparing results to an existing strategy in order to test the scripts validity.

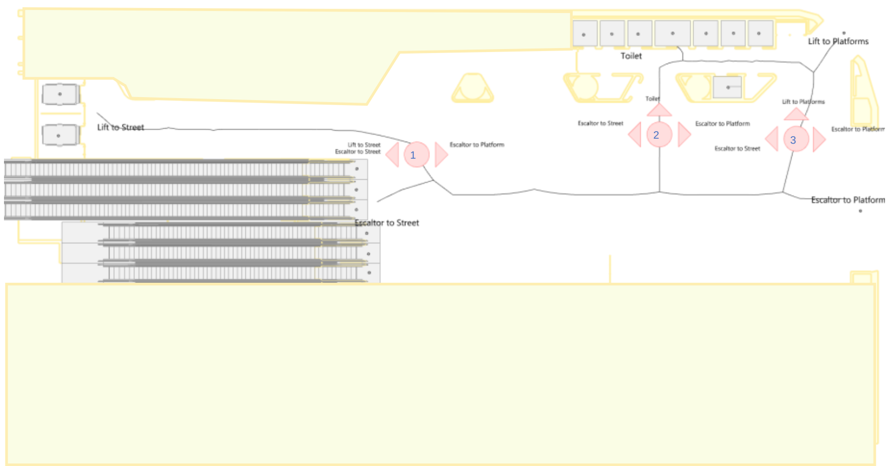


Figure 20. Station project visual and Excel results

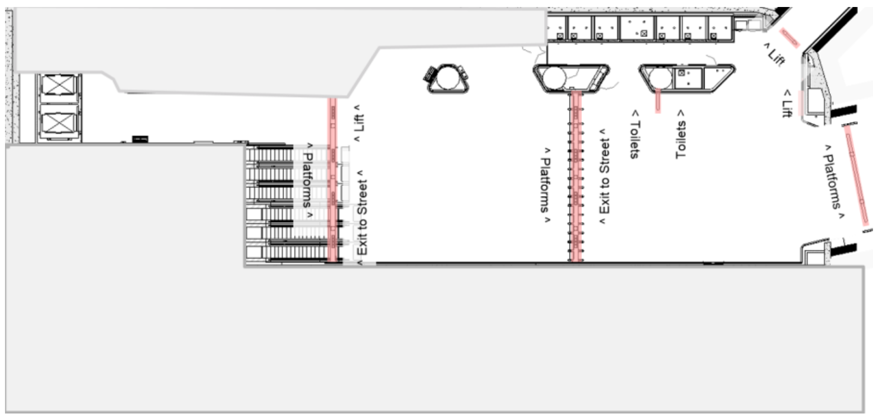


Figure 21. Station project current signage strategy for comparison

After comparison it is clear to see that the general areas of decision making are almost identical in location. The spacing and splitting of signs is not made as clear in the script and shows that the research still has room for further development.

7. Discussion (evaluation and significance)

The research successfully produced a decision support tool that works in collaboration with architects and wayfinders in early stage design. The tool can extract critical information from a floor plan in order to assist in the development of signage strategies. The interconnected workflow between the programs, Rhino and Revit, is crucial in enabling it to be accessible and flexible for multiple stages of design. Through implementing external data on the environment, it can develop a connected, weighted graph of decision-making points within an indoor space. The findings have the potential of changing the way we think about design and collaborate with computer-aided design tools.

While the project has many successes, it also falls short in some respects and has room for further development. The flexibility and accuracy of the script is reliant on the creation of an accessible database of POI and usage that must be created for each environment. There is also room for further development in terms of user group and accessible route information being integrated into the decision making. The outcomes could also be further assessed and refined through the implementation of agent-based refinement or virtual reality (VR) testing. This could help inform the effectiveness of the locations through adding in a new layer of understanding human cognition which involves the inclusion of mistakes and intuition.

While the script worked well in modifying to new environments, the result does not locate the exact position of each individual sign extremely accurately nor determine its sign type or specific graphics. Instead it serves as an assistive tool through identifying the areas of decision making and what decisions are made there. This helps advise the information that is required on signage at certain areas.

The work builds on the manual signage strategy process in decision making to create a workflow that saves time and cost. The idea of how people make their way through an environment has been heavily researched, but little is done on how this can be used to inform signage placement. Majority of the research focusing on this field tends to be regarding the urban environment rather than indoor spaces. My research transfers these principles and understandings in a manner that allows for collaboration with the designer and can modify based on data input.

The limitations of the research could be gradually worked on with more time to help develop a more accurate and reliable system. Extending from this, the research could become more interactive and accessible through a user-friendly interface that does not require grasshopper knowledge to use.

With further time and resources, the research has the potential to extend by serving as a system for advising digital signage display information through feeding real time data. This detects current usage within an environment which can inform changes in signage information at certain locations depending on hotspots to avoid clustering and guide users for certain events.

Another potential area to be explored is the way the floor plan can adapt to create a better environment for wayfinding. While the script can adapt to changes in floor plans which are manually done it has the potential to be automated to reduce architectural complexity.

8. Conclusion

The combination of graph theory and wayfinding can be used to develop a collaborative tool that can identify decision making in indoor spaces to help guide those who are unfamiliar in the most cost-efficient way. Signage strategies will no longer be created by intuition but rather guided by data driven design about how people interact with their environment. The workflow between Revit and Rhino opens greater application and potential for the tool to be integrated into industry practice.

This research has explored the viability of graph theory as a means of deconstructing how people interact with indoor spaces. By understanding this, useful results can be generated to inform designers early in the design process. Such workflow encourages the collaboration of the designer with computational tools and provides justification of decision making through data driven design. It also provokes further investigation and research into how data can be used to understand and map human behaviour.

The research provides the foundations of a data driven, human centered workflow which can by built upon and improved to redefine the way we look at the spatial design of indoor spaces. Our understanding of individuals behaviour within space is the first step to improving the design of spatial automated systems.

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